VULNERABILITY OF FRENCH NUCLEAR POWER PLANTS TO AIRCRAFT CRASH

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EXECUTIVE SUMMARY

This Review is in three Parts: **PART I** describes and accounts for the dynamics and forces in play during real aircraft crashes; **PART II** examines the probability of accidental aircraft crash and notes the unpredictability of a terrorist or malevolent act involving a commercial-sized airliner deployed as a weapon against a nuclear power plant (NPP); and **PART III** tests the present French operational NPPs against the risk and damage consequences potentially arising from both accidental and malevolent acts culminating in aircraft crash.

PART I REAL AIRCRAFT CRASHES: Three examples of actual commercial-sized aircraft crashes are assessed. These are the 9/11 World Trade Center (WTC) and Pentagon attacks, and the downing of a Boeing 747 onto Lockerbie in Scotland in 1988. Each of these incidents demonstrates that the forces imparted directly on the receiving structure can be complex in application and severely damaging.

The nature and sequencing of how these forces are generated and applied enables a relatively soft body (the aluminium alloy airframe) to cut and punch through hard and robust targets (steel (WTC) and reinforced concrete (Pentagon) built structures). The impulse loading will generate shock waves in the structure itself and these may induce damage to the body of structure, and/or damage remotely located equipment and plant. During the crash sequence, hardened parts of the disintegrating airframe may break away to act as structure-penetrating projectiles (Pentagon), and the slurry-like wave of disintegrating airframe and entrained building debris will produce a global force trying to over-topple components of (Pentagon) or the whole of the impacted building.

Also demonstrated, the devastating effects of the aviation fuel ejected from the crashing and disintegrating airframe. It is shown that, under certain circumstances, the prompt fireball accompanying the impact typically consumes less than 10% of the aviation fuel with the remainder available to burn intensely, reaching and sustaining high temperatures capable of triggering secondary and delayed collapses of the impact damaged and fire-exposed structure (WTC and Pentagon). In other circumstances, the remaining aviation fuel is violently ejected from the disintegrating airframe, forming very fine droplets of aviation fuel thoroughly mixed with air into a highly explosive fuel-air vapour, the prompt detonation of which is capable of utterly demolishing robust built structures over a wide area (Lockerbie).

PART II AIRCRAFT CRASH RISK – ACCIDENTAL AND ACTS OF WAR: The French nuclear safety regulator's (*l'Autorité de Sûreté Nucléaire* - ASN) approach to aircraft crash is examined at length, particularly how it differentiates between types of aircraft, notably small, light business jets and heavy, commercial-sized airliners, and its poles apart approach to accidents and malevolent acts involving aircraft crash.

For accidental air crash ASN considers the risk of a commercial-sized airliner crashing against a NPP to be statistically implausible, that is so infrequent to be an *incredible* event that is unlikely ever to occur. However, on much the same arithmetical reasoning, ASN accepts that a light, executive jet could possibly crash onto a NPP but for this *credible* event, it conveniently assumes that each of the 58 presently operating NPPs would survive a light aircraft crash mostly unscathed. From an entirely different standpoint, ASN defines a malevolent act, that is an intelligently driven, intentional attack that seeks out the vulnerabilities of the NPP, to be terrorism which it considers to an *Act of War*, thereby absolving itself and the operator any meaningful responsibility to plan for and mitigate against such an event.

For accidental, commercial-sized airliner crash ASN promulgates the belief that the possibility of such an event does not exist, so little or no action has to be taken to prevent or mitigate the impacts. On the other hand, ASN seems to recognise aircraft crash to be a *'known but unprepared for'* rare event because it requires precautions to be made for less severe scenarios of aircraft crash (involving smaller and much lighter aircraft). This approach of artificially limiting the scale of and, it follows, necessary response to the incident, excludes the appropriate level of technological input in framing and understanding the larger and potentially more radiologically serious incident (be it accidental or of malevolent intent) at the design and planning stages, rather than, as now, being unprepared and having to reach out for such assistance only once such an emergency occurs.

ASN's approach of discounting the risk of a seriously challenging incident of aircraft crash is not in accord with the requirements of the European Commission's post-Fukushima *Stress Tests* that are intended to test existing European NPPs against a combination of extreme initiating events, including *'indirect initiating events, for instance . . . airplane crash'*. Whereas, in May 2011 Germany summarily shut down eight NPPs mainly because of their inability to withstand commercial-sized airliner crash, three of which being of similar design and vintage to the French NPPs, ASN has taken no action in this regard even though doubts have been expressed over the surety of the primary containments (of the 900MW$_e$ series) by its own technical advisors, *Institut de Radioprotection et de Sûreté Nucléaire* (IRSN).

PART III POTENTIAL OUTCOME OF AIRCRAFT CRASH ONTO NPP SITES: Two modalities of failure triggered by aircraft crash are examined. These are a) direct impact onto a primary containment, and b) impact onto a related service, etc. within or outside the NPP Site.

France's 58 operating NPPs were designed and constructed before the accidental crash of a commercial-sized aircraft was conceived as a real threat and, indeed, at the time of the source design of many of these NPPs commercial aircraft were smaller and air traffic movements less frequent. All of France's NPPs were commissioned and in commercial operation prior to the events of 9 September 2001, a date that signalled a seed change in the motive, *modus operandi* and scale of outcome of acts of terrorism.

Events of 9/11 also changed the way in which the physical outcome of aircraft crash was considered when the target, either by accident or intent, was a nuclear power plant.

Generally, pre-9/11 analysis acknowledges that the NPP primary containment will fail, at least via localised through-rupture, and sustain deep fracturing and structural weakening radiating away from the point of impact - in the few cases where these same pre-9/11 studies have ventured into commercial-sized airliner crash, the containment damage and breaches are significant. Post-9/11 analyses that have centred on commercial-sized airliner crash demonstrate a greater resilience of structure, although this sometimes unsubstantiated gain is achieved by introduction of mitigating factors that lessen the overall damage severity. **N**one of the post-9/11 literature relating to NPP containments, incorporates the lessons learnt from the 9/11 and Lockerbie incidents: the analyses generally skirt around the complex nature of the impact damage; it is inadequate in incorporating the non-linearities that strongly featured in the 9/11 incidents; and it gives no account of aviation fuel thermal (fire) loading that resulted in the second phases of structural collapse at both the 9/11 World Trade Centre towers and the Pentagon incidents. Also, the potential for aviation fuel-air vapour mix detonation, like that which devastated the town of Lockerbie in 1988, does not feature in any of the NPP containment analyses.

On balance, particularly taking into consideration the damage severity arising from the real aircraft crashes at 9/11 WTC, Pentagon and Lockerbie, the likelihood is that a commercial-sized airliner crashing onto either the single and double shell primary containments utilised in the French nuclear NPPs, would result in at least localised through-rupture, if not catastrophically collapse part or much of the containment shell. The other radiological containments found on a NPP site, such as spent fuel, radioactive waste stores and processing plants, are equally, if not more vulnerable to aircraft crash. These containment buildings, other than localised placement of mass concrete for radiation shielding, differ little from normal commercial/industrial structures, and include no exceptional features that would bestow added resilience against aircraft crash. In particular, the spent fuel buildings (that are of common design and construction for all French NPPs) are considered to be particularly vulnerable to catastrophic collapse and, with it, unrestrained release of the radioactive contents which, at times, contain a greater amount of interim- and longer-term persistent radioactivity than the nuclear reactor itself. Much the same outcome will arise from aircraft crash on other key safety facilities on and off the NPP site: the emergency diesel generators and switchgear rooms are not specifically defended against impact; the main control rooms (for the earlier NPPs each serving two nuclear plants) are not wholly resistant to fire in the immediate aftermath of a crash, as are the radioactive waste storage buildings; and off-site, the embankments, dams and culverts serving to divert cooling water to the plant condensers, all of which would be unlikely to survive intact a near ground aviation fuel-air mix detonation as at Lockerbie, with risk of serious consequential flooding of the nuclear island at several inland NPP sites.

Accidental aircraft crash is likely to be, because of its unintended nature, completely unannounced except, perhaps, a few moments of forewarning that an aircraft is in some flight difficulty. Malevolent or terrorist driven aircraft crash will be implemented at no forewarning unless detected at, say, the hijacking stage when the destination target will be and is likely to remain unknown to the very final stages of the attack. Whatever, for both accidental and malevolent aircraft crash, the final stages will be abrupt with no time and opportunity to prepare for the impact, shut down the plant to a safe and stable condition, and to evacuate non-essential personnel from the site under attack, etc.. Moreover, damage from an aircraft crash could be severe and widespread, the array and scale of the outcome will probably cut across the *defence-in-depth* measures of redundancy and diversity germane to continuing nuclear safety of the NPP, and it will likely be *multi-facility* in effect, that is engaging and challenging several key nuclear safety features and safeguards simultaneously. If so, the complexity and severity of the outcome of aircraft crash could uniquely challenge the NPP because such engineered systems are expected and equipped to respond to well defined, single facetted initiating events.

Very certainly, the crashing of a commercial-sized airliner onto a NPP site has the potential to cause widescale, *across-the-board* and diverse disruption over the whole NPP site, resulting in the sequential loss of the lines of defence of one or more individual nuclear power plants. If not prepared for, the crashing of a commercial-sized airliner onto a NPP has the potential to overrun pre-prepared countermeasures, thereby impeding the effective implementation of immediate post-incident mitigation measures and, thus, extend a chaotic situation placing the NPP or NPPs onto a path towards a radiologically catastrophic outcome.

The Review arrives at the conclusion that each of the 58 operational French NPPs is vulnerable to commercial-sized airliner crash by, first, testing the known designs and structures against the well documented forces and post-impact environment of the WTC, Pentagon and Lockerbie incidents. Second, the Review considers the results of ASN's own *Complementary Safety Studies* (CSAs), undertaken as part of the post-Fukushima *Stress Tests*, by examining each NPP for response to external initiating events that are in excess of the prescribed *design-basis.* Where the forces and environment generated by aircraft crash appropriately match the CSA initiating event topic (eg the crash impact force matching or exceeding the safe shutdown earthquake - SSE) then the weakness and/or shortfalls of the NPP are taken to *'crossover'* and to at least equally apply to aircraft crash – in some instances, aircraft crash may encapsulate two or more CSA initiating events (for example, SSE^{+} seismic loading and fire exposure). This CSA *crossover* methodology reveals that the ASN's own requirements expose varying degrees of compromise of the *baseline safety standards* for each of the different series of NPP when subject to aircraft crash, either accidental or of malevolent intent.

Overall, the results of this Review are disturbing.

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VULNERABILITY OF FRENCH NUCLEAR POWER PLANTS TO AIRCRAFT CRASH

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INTRODUCTION & GENERAL SUMMARY

NUCLEAR CONTAINMENT STRATEGY

The surety and leak-tightness of the *'containments'* of nuclear power plants (NPPs) is absolutely fundamental to nuclear safety.

The containments are required to form failsafe barriers between the nuclear and radioactive processes underway inside the nuclear plant; they provide spatially defined and controlled environments suited the various processes in progress and materials held within; and, of course, they serve to radiologically isolate and to protect human health and wellbeing, and the environment generally.

The *primary* containment encloses the reactor pressure vessel, its coolant circuit and steam raising stages (the steam generators), being typically the cylindrical dome-like structure that dominates the NPP site architecture. As well as the role of protective barrier, the enclosed space of the primary containment of a pressurised water reactor (PWR), the type of commercial NPP adopted throughout France, serves the entirely passive role of providing sufficient expansion volume for venting into and containing a serious leakage from the reactor cooling circuit, should it fail during normal high pressure operation.

Over time and accompanying the depletion or *'burn-up'* of the fissile uranium content of the nuclear fuel in the active reactor core, the fuel accumulates intensely radioactive fission products reaching a level where the irradiated or *spent* fuel has to be removed from the reactor and placed under interim-term storage in a deep, water filled pond. The spent fuel remains immersed under water in interim storage for two to three years before it is transferred off-site using specialised rail transportation containers or flasks. The spent fuel storage pond is enclosed within a separate containment building, directly annexed to the primary containment.

These two separate containments, primary and spent fuel (FIGURE 27 – F27), make up most of the *nuclear island* of the NPP site. Other radiological containments on and around the NPP site will include pipelines and ducts transferring radioactive effluents and slurries to abatement and treatment facilities, which will also be housed in containment structures; stores and silos holding operational radioactive waste arisings; and the spent fuel transfer flasks for eventually moving the spent fuel off-site to a remote chemical separation plant or interim storage facility.

The amount of radioactivity held within the various containment structures is determined by both the function of the nuclear processes and quantity of nuclear and/or radioactive material held within.

The *'source term'* or amount of radioactivity contained within the fuel core of an operating reactor, includes short-, interim- and long-lived radionuclides and is very significant in radiological terms, comprising upwards of 100 tonnes or more of part-irradiated fuel with accumulating content of often intensely radioactive fission product species. The spent fuel pond might contain several tens of tonnes, maybe over 100t of fuel in various states of radioactive decay, depending on how recently and to what extent the reactor has been defueled. At certain times, for example when the all of the reactor fuel core has to be unloaded for inspection, the spent fuel pond has to receive the full reactor core load of about 100t of partly irradiated nuclear fuel. At some phases of the life cycle of a NPP, the spent fuel pond might hold a larger interim- and longer-term radioactive inventory than that of the nuclear reactor that it serves.

To provide effective isolation of the radioactive source terms, most of the engineered containments are *multi-barrier*, sometimes termed *defence-in-depth* meaning that there are several layers superimposed over and enclosing the source of radioactivity.

For example, the nuclear fuel in the reactor core comprises hundreds of individual low-enriched uranium (LEU) pellets stacked inside thin-walled, sealed tubes of zirconium alloy (*Zircaloy*) cladding. The fuel pins are bundled and braced together into fuel assemblies, and about 200 or more of these fuel assemblies are inserted into the reactor core. The reactor fuel core remains immersed in water within the sealed reactor pressure vessel, and this and its connected coolant circuit are entirely located within the primary containment building. So, from fuel cladding through to the primary containment, there are three successive, passive barriers safeguarding the active nuclear fuel.

The spent fuel that has been removed from the reactor and transferred to the interim storage fuel pond, is safeguarded by just two successive barriers, comprising the fuel cladding, that may have been weakened by the intense conditions of the four to five years stay in the active reactor fuel core, and the fuel building structure itself.

At certain times in the NPP maintenance cycle, usually every 12 to 18 months when the reactor fuel core is being partially refuelled and/or when the nuclear plant is under maintenance, one of the containment barriers is temporarily removed. For example, for refuelling the reactor pressure vessel lid is removed for access to the fuel assemblies, thereby removing one of the overall containment barriers. Associated with refuelling, is the underwater transfer of intensely radioactive spent fuel assemblies through to the spent fuel pond for which the temporarily water filled canal around the open reactor is indirectly linked the spent fuel pond, during which times the primary containment boundary includes the spent fuel building. At other times activities are undertaken within the containment which could jeopardise the fuel, for example should heavy objects fall into the spent fuel pond, such as the ~100t fuel transportation flasks when being handled immediately above the spent fuel pond (F20).

The other containments, including radioactive waste treatment plants, storage, transportation, etc., are not untypically located away from the nuclear island and dispersed around the NPP site (F17). Individually, these will contain much lower concentrations and overall quantities of radioactive material but, although of very much lower radiological significance than either the reactor or spent fuel pond source terms, uncontrolled release and dispersion away from the NPP site could also result in an unacceptable health detriment to members of the public in the locality.

Nuclear containments may be challenged in two ways: When the containment is threatened from within, for example from a loss of coolant accident (LOCA) in which the reactor circuit springs a high pressure leak and the containment environment suddenly pressurises at a higher than ambient temperature; or when the threat is from without, such as the subject of this review, by direct impact from a crashing aircraft. External events that do not necessarily penetrate the containment may also promote some related failure of the nuclear circuit, either directly by, say, remotely inducing failure in a component of the reactor pressure circuit thereby causing a LOCA, or by causing a crucial nuclear safety and/or control system to malfunction cascading to a *'knock-on'* failure leading to, again for example, a reactor circuit LOCA.

This Review considers both cases: that of an aircraft crashing directly onto any of the containments of the NPP site, focussed on the nuclear island containments, and an aircraft crashing onto a feature of the NPP site, or indeed, off the NPP site such as a cooling canal embankment, failure of which could lead to a serious off-site radiological situation. This latter case is illustrated by the indirect causation and cascade (*tsunami inundation - station electrical blackout - loss of cooling - fuel melt - hydrogen generation - detonation*) where a seemingly unrelated and remote off-site event led to catastrophic failures of the primary containments of Unit 1, 2 and 3 of the Fukushima Daiichi NPP in March 2011.

Similarly, aircraft crash could lead indirectly to a serious radiological situation at a NPP site. For example, the crash might leave the NPP cut off from off-site electricity supplies and, simultaneously, disable the on-site emergency generator supplies putting the plant in prolonged electrical blackout, without cooling for the reactor core fuel and spent fuel pond (as at Fukushima), and/or the crash damage may disrupt water cooling services, thereby denying the NPP of its essential ultimate heat sink, and so on and so forth.

REVIEW OF THE VULNERABILITY OF FRENCH NPPS TO AIRCRAFT CRASH

This Review is in three Parts: **PART I** describes and accounts for the dynamics and forces in play during real aircraft crashes; **PART II** examines the probability of accidental aircraft crash and notes the inevitability of a terrorist or malevolent act involving a commercial-sized aircraft deployed as a weapon against a NPP; and **PART III** tests the present French operational NPPs against the risk and damage consequences potentially arising from both accidental and malevolent acts culminating in aircraft crash.

The Review also assesses aircraft crash in terms of complete loss of electrical supplies, nuclear island flooding, and, similarly, the loss of the ultimate heat sink, as these relate to the present round of European Commission *Stress Tests* now at peer review stage. For this, the itemised outcome of recently completed *Complementary Safety Studies* (CSAs), ordered by l'*Autorité de Sûreté Nucléaire* (ASN), are retested under aircraft crash conditions (impact load, aviation fuel deflagration and detonation, etc) to determine if the *baseline safety standards* for each of the different series of NPP are exceeded.

PART I REAL AIRCRAFT CRASHES

The dynamic mechanisms involved with and generated during aircraft crash are complex.

The three examples of actual commercial-sized aircraft crashes assessed – World Trade Center, Pentagon and Lockerbie - demonstrate that the forces imparted directly on and induced to further afield parts of the receiving structure can be very high. The nature and sequencing of how these forces are generated and applied, enables a relatively soft body (the aluminium alloy airframe) to cut and punch through hard and robust targets (steel and reinforced concrete (rc) built structures).

Also demonstrated, the devastating effects of the aviation fuel released from the crashing and disintegrating airframe. First, in 12 to 20 minutes following impact, the second phase of structural collapse of the Pentagon with the fire exposure of the burning aviation fuel weakened key building structures (rc columns, walls and slabs), promoting additional building collapse because these structural elements had lost much of the fire protection concrete cover (insulation) as a result of the high levels of force generated and induced during the airframe impact (F6). Second, in the aftermath of Lockerbie, when the virtually complete wing section and fuel tanks of the Boeing 747 airliner that had broke-up in mid-air, descended to the ground, settling then to violently explode tens of seconds later as the aviation fuel converted through from deflagration to full detonation, taking with it a terrace of houses and scooping out upwards of 4,000 tonnes of subsoil and rock, to leave a massive crater (F12).

By analysis and review of authoritative literature, it is shown that the complexity of the dynamics and forces generated by a crashing aircraft are inadequately represented by the rudimentary *Load-Time* characteristic recommended by the International Atomic Energy Agency (IAEA), this crude and flawed methodology being adopted almost universally by the nuclear industry worldwide. These *Load-Time* characteristics, for different airframe types (F1), overall mass, impact velocity and approach angle are weak because, first, it is difficult to reliably model the characteristic from first principles, and the alternative approach of extrapolating the characteristic from the single demonstration of a military fighter aircraft being flown into an immobile block of concrete to a commercial-sized airliner, is not at all practicable.

In real aircraft impact situations where about only one quarter of the aircraft energy is dissipated in its own concertinaing-like compression and disintegration, the remaining energy acts destructively in a number of modes: First, the progressively disintegrating aircraft components push forward in a slurry-like wave, imparting a relatively longer-term *push-over* force to the whole target structure – this is the time-varying force that is, not particularly accurately, mirrored by the *Load-Time* aircraft characteristic. Second, as more inert and/or tied down parts of the target structure (columns, slabs, etc) encounter the high velocity oncoming aircraft, these are unable to overcome their own inertia and undergo plastic shearing, thereby enabling a relatively soft object, the airframe, to punch through otherwise hardened materials (concrete, steel, etc) of the target structure (F5). Third, towards the end of the impact sequence as the encroaching airframe slows, some structural elements are able to activate inertia, adopting bending and buckling modes, again to plastic failure of areas and components of the target structure (F8).

During the instance of impact, there are also active what might be best described as coincidental loads and forces: Some hardened parts of the airframe (undercarriage struts, wing-fuselage shear box, engine pylons and so on) detach early in the crash sequence and continue forward as free-flying projectiles – in the Pentagon crash, what is believed to have been a forward undercarriage strut, detached and was thrown forward, breaching through at least five structural walls, travelling some 90m before coming to rest (F10/11). Impacting loads might also be transmitted through the target structure as a shock wave to be induced into relatively remotes parts of the structure or objects attached thereto, failing the fixings and attachments allowing heavy and what could be safety critical components to fly-away or fall freely (F24).

The characteristic of the target structure is also an important determinant to its response to a crashing airframe. For example, a slender, low inertia structural component will absorb and dissipate much of the impacting energy by displacement and flexure, whereas a rigid, thick rc structure, like the NPP primary containment, instead of accelerating forward in response to the impact, will remain sensibly immobile. In this case, much of the impact will radiate within the concrete as a compressive stress wave, but which will convert and reflect back from the target backface as a tensile wave against which concrete has little strength, failing as spalling at the backface surface, which adds to the free-flying projectiles, and/or forming deep fractures within and weakening the structure itself.

There is also the possibility that the impact and, particularly, the fire, deflagration, detonation and blast effects of a crashing airliner onto an occupied site could result in widespread injury and fatality, as at Lockerbie, to persons in the local area. The intense aviation fuel fire and, indeed as shown at Lockerbie, blast could disperse over a large area, incapacitating personnel needed for immediate response. Put together, the cctv records of the impact fireball and following impact and fire damage of 9/11 Pentagon building incident, enable the fire time profile and high temperatures rapidly reached within the building space to be accurately determined; and the delayed detonation sequence at Lockerbie clearly, from the utter devastation of built structures and the amount of substrata removed in forming the ground crater, shows that the fuel burn transited from a deflagration to high brisance detonation.

In summary: The crashing of an aircraft into a built structure is a complex event giving rise to a diverse range of forces and structural responses. Moreover, defining and matching the airframe and target structure characteristics is fraught with difficulties; and the present practice of relying almost completely on and extrapolating from the contrived crash of a military fighter airframe (of ~20,000kg) to represent a commercial-sized airliner (of upwards ~130,000kg+), is not at all realistic or reliable.

The inadequacy of the *Load-Time* methodology is reflected in much of the published work, particularly, where the crash vulnerability of NPP primary containments have been reported upon. For example, the openly published work considering commercial-sized airliner crash directly onto a NPP primary containment rarely, and when it does poorly models the two important plastic failure mechanisms, particularly plastic shear that was active in the 9/11 WTC and Pentagon incidents. Similarly, the difficult to predict projectile impacts, generated as the airframe disintegrates and/or by scabbing and internal fracturing of target rc structures, are hardly ever modelled, yet there is clear evidence in the post-event analysis of the Pentagon incident that free-flying projectiles played a destructive role far from the point of initial impact (90m+). And, other than to rely upon the design-basis earthquake loading, there is little realism in published analysis on the potential failure and detachment of the many components, some of critical nuclear safety function (eg fire protection systems), that are housed within the NPP primary containment and, also throughout the NPP site.

Similarly, the roles of the aviation fuel released during an aircraft crash are rarely taken into account in the published literature, even though it made such a decisive contribution to the outcomes at both the Pentagon and WTC (intense fire temperatures further weakening the already severely damaged structures) and at Lockerbie (ground level detonation). Also and applied to a NPP, even if the various radiological containments survived intact, aircraft crash could quite possibly overwhelm and incapacitate large numbers of power plant personnel, leaving a part-damaged nuclear plant unrestrained and to its own devices.

PART II AIRCRAFT CRASH - *ACCEPTABLE RISK VS TOLERABLE CONSEQUENCES* AND ACTS OF WAR

Radiological containments are in the form of built structures that satisfy what, in France, is referred to as the *baseline safety standard* when the nuclear plant is subject to an abnormal event. *Credible* abnormal events are prescribed situations that might arise internally, such as a reactor component malfunction, or externally, say inundation of the NPP site by flooding, but which in severity are within the limits and conditions of the *design-basis*. Generally, if an abnormal event, like a severe earthquake, is reckoned *a priori* to occur so infrequently that it might be considered to be beyond the design-basis it is deemed to be an *incredible* event, with the risk being totally discounted.

So far as the risk and consequences of an aircraft crash onto the NPP, the French nuclear safety regulator ASN, considers the crash of a light airframe (as specified by *Règle fondamentale de sûreté RFS I.2.a* 1980) from either a mono-engine CESSNA 210 of 1.5t all-up mass and a bi-engine LEAR JET 23 of 5.7t all-up mass, although often (eg in Germany) an equivalent to an unarmed Phantom military fighter of about 20t mass is cited) to be a within the *design-basis* against which the NPP must perform within the *baseline safety standard*. Put another way, since light aircraft crash is considered to be a credible event of *acceptable risk*, its outcome and radiological *consequences* must be *tolerable*. The antonym of this *acceptable risk vs tolerable consequences* composite, is that ASN deems, again on deduction drawn from a very scarce database of past events, the likelihood of an accidental crash of a commercial-sized airliner to be so infrequent that it would be an *incredible* event. Thus since it is never likely to happen, its projected radiological consequences may be intolerable.

By such risk discounting, ASN permits the design and continuing operation of French NPPs on the basis that the response to certain external threats, like the accidental crash of a commercial-sized airliner, do not have to meet the *baseline safety standard* solely on the premise that such an event is never likely to happen.

The manner in which the aircraft crash event database is manipulated casts considerable doubt on the viability of the risk prediction. For example, in the adopted methodology, the final risk of an aircraft crashing onto a NPP site is dominated by the air traffic accident rates for high flying aircraft in transit over the region, added to which is the lower risk (so the adopted methodology predicts) associated with local airport air traffic movements. However, assessment of the air traffic movements from a nearby airfield is somewhat simplistic, carrying no additional weighting in compensation for the type of risk and hazard associated with the landing and take-off phases, low altitude manoeuvring, so called go-arounds, etc..

This is because the risk contribution from a local airfield risk is derived solely from the number of air traffic movements, taking no account whatsoever other than by national aggregation, important local contributory factors to aircraft downing by, for example, increased rates of bird strike (for example, in nearby marshland, feeding areas) and, particularly, the low altitude and shallow angle of approach that a troubled aircraft might run its unintentional and uncontrolled approach towards a NPP site. Even where an aircraft has impacted the ground, say from a bodged landing or take-off (or go-around), skidding and the throw-forward distances of aircraft components (eg complete engine assemblies) are not incorporated into the risk assessment.

Much the same laxity applies to how the NPP target is defined. For example, the NPP is defined in terms of plan and elevation areas which, for most analyses, are taken as a simple projections of only the nuclear island and dominant primary containment structure. Limiting the NPP target to the nuclear island neglects any consequences or knock-on effects should the aircraft crash onto an essential nuclear safety or services provision, such as an emergency generator or its switchgear, or crash off-site, say onto a dyke or embankment that maintains the level of the ultimate heat sink to the NPP, or that which could flood and inundate the site. This approach of considering only the risk to the immediately obvious highly hazardous part of the NPP, has a systemic weakness that it may not always capture a cascade of interrelated risks: for example, that the aircraft may plough into the ground, destroy a canal embankment, that this in turn may flood the downstream NPP site, which might then isolate the nuclear island to a fuel meltdown. The ground upheaval at Lockerbie demonstrates the potential of a crashing commercial-sized airliner to render substantial changes to the local terrain, embankments, dams and the like.

The same probabilistic-based risk discounting, however flawed some consider this to be, cannot be applied to malevolent act, such as a terrorist attack using a hijacked airliner. Instead, ASN deems that intentional aircraft crash, like the 9/11 World Trade Centre and Pentagon attacks, *'ne sont pas les chutes accidentelles, mais de vèritables actes deguerre, qui ne sont pas inclus dans la construction des installations nuclèaires'*.[1]

Neither of ASN's reasons for dismissing the crash of a commercial-sized airliner onto any one of France's 58 operational NPPs, address the vulnerability of these NPPs should such an event occur, after all accidents do happen - the unsinkable ship the *Titanic* actually sank - and individuals and groups of individuals have planned and seen through malicious intents, sometimes at ultimate sacrifice to themselves and thousands of innocent bystanders, as shown by the tragic events of 9/11. Moreover, lessons may not be learnt from past events because even though we believe that we now fully understand the *Titanic* disaster, just recently the ultra-modern, state-of-the art cruise liner *Costa Concordia* strayed and foundered in shallow waters – in this respect there can be little confidence that later generations of NPPs will have, like the *Costa Concordia*, learnt from lessons past.

An aircraft crash onto a NPP might, no doubt, fall outside the range of readily foreseeable and acceptable *'known'* events for which the nuclear industry creates a generic response – it could be, either accidental or maliciously motivated, a shock event that had not been conceived or recognised in advance as a credible threat. In this respect, denying the inevitability of aircraft crash could be regarded as a fundamental flaw in ASN's nuclear safety rationale. Put another way, if nothing can be done to mitigate the outcome, in terms of damage severity and potential radiological consequences, of a commercial-sized airliner crashing onto any one of France's existing operational NPPs, then why bother to prepare for such a *high-impact, low-probability* (HILP) event?

In effect, France's 58 operating NPPs were designed and constructed before the accidental crash of a commercial-sized airliner was conceived to be a real threat and, indeed, at the time of the design of many of

1 Underlying this reasoning seems to be the French State's assumption that only malevolent acts organised and perpetrated by a hostile foreign State could result in more damaging outcome to a NPP than that arising out of a purely accidental event, that is even if the malevolent action was under the cover of a terrorist group. Thus, it follows, such an attack would be considered an act of war, and more precisely a nuclear act of war, for which France has the capability to respond with a nuclear strike. In other words, the French reasoning is that nuclear deterrence serves to protect nuclear facilities from such acts happening, so much so that nuclear facilities do not have to be designed to withstand such events. Of course, whether a terrorist group would agree and comply with this rationale is a matter of some debate.

these NPPs commercial aircraft were smaller and air traffic movements less frequent. All of France's NPPs were commissioned and in commercial operation prior to the events of 9 September 2001, a date that signalled a seed change in the motive, *modus operandi* and the scale of outcome of terrorist acts.

Faced with this dilemma, some might suggest, aircraft crash is an event that is beyond normal expectation, being either impossible or extremely difficult to predict, and for which the embedded and generic response processes are unsuited, leading to the inherently weak argument and stance that planning for such an event is close to impossible.

On one hand, there is the sense that ASN promulgates the belief that the possibility of such an event does not exist so little or no action has to be taken to prevent or mitigate the impacts – this applies in both instances where ASN either completely discounts the risk of an *accidental* aircraft crash, or where the responsibility is shunned from by definition that terrorist attack via aircraft crash is an *Act of War*. On the other hand, ASN seems to recognise aircraft crash to be a *'known but unprepared for'* rare event because precautions have only been made for less severe scenarios of aircraft crash (involving smaller and much lighter aircraft). This approach of artificially limiting the scale of and, it follows, necessary response to the incident, excludes the appropriate degrees of technological and scientific input in framing the mechanics of the larger and potentially more radiologically serious incident at the design and planning stages, rather than, as now, reach out for such assistance only once such an emergency occurs.

And, perhaps odder still, whereas with its declaration that malevolent intent on the scale of an aircraft crash is an *Act of War*, ASN thereby releases the operator EDF from any responsibility with regard to its prevention and, in the event, its mitigation, at the same time ASN (and its security counterpart *direction de la sûreté nucléaire de défense* – DSND) is contributing to the European Commission's *Ad-hoc Group on Nuclear Security* (AHGNS) that is specifically analysing security threats arising from terrorist acts, currently running as the *Security Track* in parallel to the post-Fukushima inspired *Stress Tests* for NPPs across Europe. So, on one hand, ASN absolves itself and the operator of the requirement to plan for aircraft crash because is deems it to be an *Act of War*, but simultaneously on the other hand, it has been and continues to contribute to a specialist group analysing the prevention of, and response to, incidents due to malevolent or terrorist acts which, must by definition and recent past history, include the deliberate crashing of a commercial-sized airliner onto a NPP target.

In Summary: The past failure of the French nuclear industry (and virtually all other nations) to realistically take into account the possibility of aircraft crash has resulted in little incentive to include for what it defines to be an extremely remote event in the safeguards design aspects of NPPs. This has resulted in the French (and other European) nuclear power plants being almost totally ill-prepared for an accidental aircraft crash and, more to the point, terrorist attack from the air. Moreover, the design and construction of the NPP plants and buildings date from a period of over 60 years, many of the older buildings and containments would just not withstand an aircraft crash and subsequent aviation fuel fire, deflagration and, as shown by Lockerbie, violent near ground detonation. Much the same vulnerability applies to other less direct safety features that may be located on or off the NPP site, such as the embankments containing the cooling canals and lagoons, failure of which could cascade to equally severe radiological consequences.

PART III POTENTIAL OUTCOME OF AN AIRCRAFT CRASH ONTO A NPP SITE – FRENCH NPPS

Two modalities of failure are examined, these are:

A) Direct Impact onto a Containment: When the aircraft crashes directly onto a containment, the potential to breach the containment and/or severely damage key nuclear safety systems and components within, thereby placing the nuclear plant, spent fuel, and/or other radioactive material and substances at risk of release into the public domain.

B) Impact onto a Related Service, etc. On or Off the NPP Site: When the aircraft crashes onto an essential services facility (causing either electricity blackout, flooding, or loss of ultimate cooling sink) from which the nuclear plant is unable to recover and implement its own shutdown to a safe and stable condition, thereafter cascading to a self-inflicted containment failure, radioactive release and off-site radiological incident.

This Review does not consider in any further detail the magnitude of the radioactive release, its dispersion from the NPP site and off-site radiological consequences – example analysis of such dispersal incidents are readily available elsewhere[2] and are a matter of record.[3]

A.1) DIRECT IMPACT ONTO THE PRIMARY CONTAINMENT

TABLES 4 (Col 10) and **5** outline the primary containment structure for each of the present operational NPPs in France. Essentially, the primary containment for each of the earlier 900WMe series is a single, internal steel lined, prestressed concrete shell, whereas the later 1,300MW_e and N4 (1,450MW_e) NPPs have a double shell containment, neither of which is steel lined.

Published studies on the structural response and damage of primary containment structures when subject to aircraft crash, generally and as previously discussed, are weak on simulating the complexity of the failure mechanism invoked. Moreover, work undertaken prior to 9/11, when the focus switched to commercial-sized aircraft, are limited to the impact forces generated by light aircraft and the single Phantom fighter airframe *Load-Time* characteristic used as a basis for extrapolation to a commercial-sized airliner – these studies show a typical primary containment structure to be vulnerable to through-rupture in the immediate impact zone and propagated fracturing in the rc material radiating from the impact point. In the few cases where these same pre-9/11 studies have ventured into commercial-sized aircraft crashes, the containment damage and breaches are significant.

That said, there are a number of post-9/11 studies that have centred on a commercial-sized aircraft crashing into primary containments: these studies tend to demonstrate a greater resilience of structure, although this sometimes unsubstantiated gain is achieved by introduction of mitigating factors, for example the dissipation of aircraft energy by collision with *'sacrificial'* built structures in the path to the primary containment; generally lower impact velocities; sometimes by assuming, quite unjustifiably some would opine, that the projected aircraft engine(s) area is only of importance in the dynamic loading composition; and by assuming the airframe to strike a glancing or oblique blow on the circular shell of the containment, etc..

Both pre- and post-9/11 published study sets remain weak in modelling the full complexity and set of forces and mechanism at play during aircraft crash; the particular vulnerability of the containment to a very low-level and shallow angle of approach strike (Pentagon) is not at all recognised; of the accompanying potentially explosive fireball and prolonged fire exposure; and, importantly, of the formation of projectiles generated by the disintegrating airframe, containment enclosure contents and equipment, and of the containment structure itself.[4]

Moreover, all of the analysis reviewed considers the primary containment structure to be in an *'as designed'* condition, that is free of any degradation arising out of service and/or ageing of the materials involved (concrete and steel tendons and reinforcement bars). Although there have been considerable advances in modelling and computational analysis of shell structures in recent years, these methods are still unable to fully account for non-linear characteristics of material degradation – such ageing- and service-related weaknesses (concrete cracking, tendon corrosion, etc) remain largely unaccounted for. Also, there are the defects of a more serious nature *'non-replaceable'* primary containment alluded to by IRSN when examining the life extension options for the 900MW_e series – whether these extant defects, by nature and/or severity, would affect the structural response and resilience of the primary containment under the modalities of aircraft crash remains unknown.

On balance and particularly taking into consideration the damage severity arising from the real aircraft crashes at 9/11 WTC, Pentagon and at Lockerbie, then the likelihood is that a commercial-sized airliner crashing onto either the single and double shell containments utilised in the French nuclear NPPs, would result in at least localised through-rupture, if not catastrophically collapse part or much of the whole containment shell.

In the immediate aftermath of impact with a primary containment structure, the engulfing aviation fireball (a feature of all three 9/11 crashes) is likely consume about one-tenth, or thereabouts, of the total aviation fuel energy carried on board the crashing airframe – this short-lived, deflagrating fireball itself is unlikely to result in

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2 For example of a radioactive release from the Generation III EPR NPP currently under construction at Flamanville see Large & Associates, *Assessments of the Radiological Consequences of Releases from Existing and Proposed EPR/PWR Nuclear Power Plants in France*, R3159-3, Greenpeace France.

3 For example, i) Chernobyl 1986 and ii) Fukushima Daiichi 2011.

4 Further detailed analysis of the resilience of the primary and other NPP containments is beyond the instructed scope of this Review.

anything greater than superficial-to-moderate severe damage of the concrete primary containment structure outer surfaces. The remaining aviation fuel, formed into a fine particle (fuel-air vapour mix) mist by its sudden, high velocity ejection from the disintegrating airframe, could present an explosive risk within the containment space or, for the double shelled containment NPPs (1,300MW$_e$ and N4), within the inter-shell cavity – there is nothing published on such a *'contained'* detonation – with, possibly, a very destructive outcome.

In summary: Subject to the crash of a commercial-sized airliner, the primary containments of all 58 operational NPPs in France are at risk of failure.

The often promoted argument that these containments possess sufficient reserves of residual strength, because of the design-basis passive (internal pressure) containment role, is largely without substantiation and, indeed, it might be counter-argued that certain features required to enhance the passive role function would be impediments to, if not weaken the containment response under dynamic and explosive loading. Whether the serious extant defects in the 900MW$_e$ series primary containment structure, alluded to by IRSN, would serve to weaken the containment when subject to the dynamic force environment of aircraft crash remains unknown.

Moreover, the widespread coverage and scale of severity of damage for an NPP at full power (Reactor State A) is likely to promote multiple failure conditions across the NPP, giving rise to the so-called *Risk Reduction Category A* (RRC-A), including station blackout (SBO) and loss of the component cooling water and essential water system cooling trains. It is also possible that projectiles generated from and/or by the impacting airframe, active within the primary containment or, similarly, the collapse of an overhead gantry structure dislodged by the impact (F18), could produce at least a small break LOCA, together with loss of essential reactor circuit water makeup systems.

A.2) DIRECT IMPACT ONTO THE SPENT FUEL AND OTHER RADIOLOGICAL CONTAINMENTS

Very few studies have been undertaken and published on the resilience of the spent fuel interim storage building and, particularly, the continuing water-tightness of the spent fuel pool during and following aircraft crash. Structural design details of the spent fuel pond buildings are not generally available, although ASN has expressed doubt about the resilience of the structure, describing spent fuel building structures for all NPPs, including the yet to be commissioned EPR, to comprise a *'metal clad roof and relatively thin rc walls of less than 300mm thickness'*.

The greater likelihood is that an airliner crashing into the fuel pond building would penetrate, if not catastrophically collapse the whole building. Forces and loads imparted during the crash sequence would exceed the ultimate limit state of Eurocode 2, being the structural design standard adopted for NPP civil engineered structures such as the spent fuel building (and other containments located off the NPP nuclear island).

Failing the water-tightness of the spent fuel pond might be achieved by either a projectile puncturing the steel liner or rc wall of the pool, and/or the water cooling transfer piping (Pentagon) or, perhaps more destructively by explosion of the spilt and atomised aviation fuel (Lockerbie). Whatever the specific cause, pool failure and loss of water cover to what might be several hundred tonnes of intensely radioactive fuel would inevitably lead to an intolerable and irrecoverable radiological situation, a dire situation recognised by ASN *'. . Regarding the spent fuel pool, given the difficulty or even the impossibility of deploying effective means of mitigating the consequences of prolonged exposure of the fuel assemblies EDF (Electricité de France) is required to define and implement tightened measures to prevent the fuel assembly exposure'*.

There are several other 'radiological' containments in service on a NPP site. Although these have not been addressed in detail by this Review, much that has been noted for the primary and spent fuel building containments would equally, if not more so, apply to each of the other containments located about the NPP site.

In summary: The vulnerability of the spent fuel pond containment building to aircraft crash is a weakness common to each of France's 58 operational NPPs.

It is a matter of fact that relatively thin rc and masonry walling will catastrophically fail under commercial-sized airliner impact (Pentagon and Lockerbie) and, following this, there is additional risk of the spent fuel pool failing its watertightness and rapidly draining down to leave the fuel exposed – with possibly tens of tonnes of intensely radioactive spent fuel in any one of the 58 reactor ponds at risk of a vigorous hydrogen-liberating Zircaloy-steam cladding reaction, the off-site radiological consequences could be severe indeed.

B.1) OUTCOMES OF IMPACT ON PARTS OF THE NPP SITE OTHER THAN ON THE CONTAINMENTS

ASN has noted that, but has yet to report on, the requirement for EDF to assess aspects of aircraft crash (assumed to be a commercial-sized aircraft) to certain on- and off-site features of the operational NPPs. However, while the detailed specification of this requirement is not publicly available, it is believed that EDF has to practicably assess the resilience of certain embankments, dams and reservoirs both on- and off- certain of its NPP sites.

The above aircraft crash specific requirement is a *'bolt-on'* to the *Complementary Safety Studies* (CSAs) specified by ASN for all operational NPPs and part of the review of the Generation III EPR NPP presently under construction at Flamanville. The CSAs supplement the European Commission-ENSREG *Stress Tests* that are presently at peer review. Essentially, one purpose of the *Stress Tests* is to identify any extreme external events that could trigger a Fukushima-like loss of control and fuel melt down at a NPP, either of the active reactor fuel core, or the spent fuel in the pond, or both.

Other than the *bolt-on* specification above, ASN does not accept (publicly at least) the crash of a commercial-sized airliner, either accidental or resulting from a malevolent act, to be a credible external initiating event. This directly contradicts the scope of initiating events specified in the EC-ENSREG *Stress Tests* declaration, viz:

> *". . .*
> *the assessment of consequences of loss of safety functions is relevant also if the situation is provoked by indirect initiating events, for instance large disturbance from the electrical power grid . . ., forest fire, **airplane crash**.*
> *. . ."*
>
> *my truncation . . and **emphasis***

particularly in that ASN confines the type of initiating events to *'other extreme **natural** events'* thereby, or so it seems, disqualifying man-made incidents such as aircraft crash.

Whatever, the basis of the CSA specification is that the safety margins of existing nuclear plants should be *'tested'* against extreme external events that are beyond the design-basis. Moreover, the CSAs require the response of the plant triggered by extreme situations, to be assessed under sequential loss of the lines of defence by deterministic consideration, irrespective of the probabilistic outcome and, in addition, the countermeasures in place to manage and mitigate the event should be assumed to be progressively overrun.

Put another way, ASN requires the robustness of the *defence-in-depth* of each NPP to be tested against extreme external events that have been, hitherto, considered *incredible* and beyond the *design basis*. Surprising therefore that ASN continues to exclude aircraft crash to test the robustness of the *defence-in-depth* of all present operational and future NPPs.

It is possible to manipulate the outcome of certain of the CSAs assessments as if the initiating event was aircraft crash. For example, where the CSA specifies an *'indirect initiation event'* to be flooding, it is quite justified to introduce aircraft crash to have caused the source of flooding. For example, a commercial-sized airliner crashing onto and part destroying an embankment of the condenser intake cooling canal would result in the same initiating event outcome considered, say, by the *'flooding'* topic of the CSA. Much the same justification applies to certain of the other extreme initiating events of the earthquake, station electrical blackout (SBO), loss of ultimate heat sink and post incident CSA topics – the proviso being that an aircraft event must at least provide (replicate) a similar (in nature and magnitude) challenging and/or deleterious environment as the particular CSA topic reported upon by EDF. Moreover, because as shown by Lockerbie the ensuing disruption and damage resulting from aircraft crash can be widespread, the event itself may invoke several, simultaneous modes of failure that are not covered by the existing nuclear safety case or, indeed, by the somewhat isolated and linear fault scenarios prescribed by the CSAs.

Nevertheless, a gauge of aircraft crash resilience of the three basic NPP types of TABLE 4 can be gleaned from the published outcomes of the CSAs. For these, ASN identifies topics and areas *'in which safety could be improved'*, some which satisfy the above proviso and thus mirror a cross-linkage to the outcome of an aircraft crash.

TABLES 6 through to **10** identify and detail, so far as is practicable, this cross-linkage from the CSAs to an aircraft crash mirrored event – these cross-linkages, identifying the most probable modalities of failure should any of the 58 operational NPPs be subject to commercial-sized airliner crash, are grouped together and highlighted as *crossovers* in TABLE S1:

TABLE S1 AIRCRAFT CRASH MODALITIES AND CROSSOVERS DERIVED FROM THE CSAS

TABLE	CSA TOPIC	AIRCRAFT CROSSOVER	NPP TYPE/LOCATION
6	**EARTHQUAKE** when the peak dynamic loading of aircraft crash equals or exceed the induced SSE (and beyond) direct and induced loading	i) Loads exceed *Baseline Safety Standard* (BSS) of design-basis of the Fire Protection Systems that are at risk of being rendered part- or wholly-inoperative by aircraft crash. ii) Damage to or destruction of flood containment structures (sluice dates, weirs, dams, etc) resulting in long-term loss of the ultimate heat sink. iii) Lack of BSS robustness of reactor cavity, spent fuel cooling, WCS valves etc. to aircraft crash loading. iv) Crash impact loads caused flooding from on-site stored water held in tanks around NPP site onto the nuclear island prompting loss of safety systems.	all NPPs *Tricastin, Fessenheim* and *Bugey* sites all NPPs unidentified NPPs and *Gravelines*
7	**FLOODING** when the aircraft crashes onto a built structure retaining an embankment or similar, thereby permitting egress of floodwaters directly onto NPP site	i) Damage/destruction of water channel embankments, dams, reservoirs with a number of inland NPP Nuclear Islands at below flood level - both *Tricastin* and *Fessenheim* under particular scrutiny: *Tricastin* flooding reliant upon sluice gates and watertight screen for final protection, considered not immune from severe flooding. At *Fessenheim*, the consequences failure of Grand Canal d'Alsace embankments would be the presence of layer of water on the site, with scenario involving total loss of off- and on-site power supplies, as well as the potential loss of other nuclear island equipment. ii) Aircraft crash onto a single water cooling tower could promote multiple collapse of adjacent towers - localised flooding could affect the operation of the on-site emergency generators which ASN consider vulnerable to flooding.	Specifically *Tricastin* and *Fessenheim*, and at *Bugey, Civaux, Cruas, Nogent, St Alban* All NPPs with cooling towers, ASN awaiting RECS by 2012
8	**STATION BLACKOUT** loss of off- and on-site electrical supplies, could include intentional combination of malevolent acts by disabling incoming power grid and aircraft crash directly onto NPP disabling emergency generators	i) If NPP-specific generator lost, maintaining reactor core and spent fuel cooling requires continuing SBO generator sets switched from a neighbouring NPP on site. If all SBO sets are disabled and the single, ultimate backup diesel-generator set (GUS – $900MW_e$) or combustion turbine (TAC - $1300MW_e$ and N4 series) per site also disabled by widespread damage of aircraft crash, the fuel protection times are shortened to few hours (less than 10 hours) for all ($900MW_e$), several days for the $1300MW_e$ and N4 series, and just a few hours (unspecified) for the EPR series of NPPs. ii) For $900MW_e$ and $1300MW_e$/N4 NPPs core exposure to melt times are shorter than response time for ETA site (12 to 24 hours) by the *Nuclear Rapid Intervention Force* (FARN) – yet to be fully established. iii) For a reactor core that has been discharged completely into the spent fuel pond the discharged core exposure time is about 10 hours from onset of loss of pond cooling.	$900MW_e$ series NPPs critically at risk of fuel meltdown within a few hours (unspecified). Particularly for $900MW_e$ NPPs, ASN require EDF to install an *ultimate backup* diesel generator set (DUS), together with smaller emergency generator sets, for use in the event of a SBO total loss situation
9	ULTIMATE HEAT SINKS aircraft crash triggering one or more of a number of scenarios leading to loss of ultimate heat sink, including flooding, loss of cooling intake, SBO. etc	i) ASN acknowledge that the heat sink could be *'seriously damaged'* (see earlier), requiring EDF to consider loss of heat sink and station blackout simultaneously (H1+H3). ii) The degrees of redundancy and diversity in the intake, distribution (and exhausting) of the ultimate heat sink (water) into the NPP complex is not sufficiently known to appraise EDF's assurance that all possible scenarios of H1 can be restored before the fuel, either reactor fuel core, and/or in the spent fuel pond of a single NPP, or to all NPPs on site, becomes exposed. Fuel exposure times are reckoned in days for both reactor core, and spent fuel ponds, although ASN postulates that the reactor fuel cores ($900MW_e$, $1300MW_e$ and N4 NPPs) could become exposed *'in just a few hours'* for a whole site H1 situation. However, it should be noted that loss of coolant water levels in the fuel storage ponds seems to be confined to evaporation losses only and no account is given to a direct breach of the pond liner of failure of any part of the water transfer pipework. iii) EDF/ASN seem to limit the assessment to H1 situations where the sink has been temporally halted by blockage, localised failure, etc., whereas not readily recoverable situations have not been assessed – irrecoverable loss	EDF H1+H3 scenario assessment has yet to be submitted. All NPPs for complete H1 loss over NPP site

		might result from an aircraft crash directly onto the heat sink inlet or outlet.	
10	POST-INCIDENT EDF management of post-incident situation not sufficiently resourced, nor flexible enough to deal with diverse outcomes of aircraft crash over NPP site, with inadequacies of response and post incident mitigation and countermeasures identified by ASN, particularly in spent pool building	i) NPP emergency plans not sufficiently resourced to deal with *Multi-Facility* event which is expected outcome of air crash. ii) Pond environment designed for the SSE level and hence the structure and containment has not been tested against aircraft crash impact and projectile loading which could i) breach the containment, ii) rupture the pool and water circulation services, and iii) generation of projectiles. iii) Loss of cooling water levels in spent fuel problem, accompanied by breach of walls and/or roof gives rise to high levels of gamma *'skyshine'* as the water cover depth over the fuel reduces – this situation, could arise in an aircraft impacting directly on the spent fuel building shell, will limit access to emergency personnel endeavouring to maintain the fuel-steam environment above the Zircaloy-steam temperature at which hydrogen is liberated. iv) The spent fuel building structure for all NPPs, including the yet to be commissioned EPR, comprises a metal clad roof and relatively thin rc walls of less than 300mm thickness. Both elements of this structure would not be resilient against a crashing aircraft and any breach in the containment would enable gamma shine from the uncovering spent fuel assemblies and release of radioactive particulate matter should the fuel and its cladding become overheated (~1,000°C) and damaged – pond evaporation rates and times are specified earlier.	All NPPs

In Summary: More often than not, the regulatory definition and determination of nuclear safety centres on external challenges to the nuclear island, particularly on the primary containment enclosing the nuclear reactor plant. However, some forms of external event can apply across the whole NPP site, such as earthquake; other events might apply over certain areas of the NPP site, including the nuclear island, for example flooding; and other incidents might, as chance would have it or quite intentionally, strike particular features of the NPP site.

Aircraft crash, either of accidental or malevolent intent, falls into this last category of external initiating event.

The meltdown and radioactive releases from the Fukushima NPPs in March 2011 resulted indirectly from the undersea earthquake and, more directly, the generated tsunami wave swamping the Fukushima Daiichi NPP site. the ensuing failure of on- and off-site electrical supplies, giving rise to a prolonged station blackout, loss of cooling of the by then shut down reactors, overheating of the reactor core fuel culminated in explosion and destruction of the primary and spent fuel pond containments. In other words, if crucial aspects of the NPP plant overall are damaged, disrupted and discontinued by some external event, then left to their own devices even fully shutdown nuclear reactors are quite capable of utterly destroying their own containment enclosures.

ASN's CSA interrogation of each of the 58 operational NPPs, reveals that these NPPs are also vulnerable to external challenges that are remotely sourced from the primary and spent fuel containments. Revealed are the very short time periods of few hours, not dissimilar to the timescales at Fukushima, available for recovering of a deteriorating radiological situation following an extreme initiating event occurring somewhere on and/or off the NPP site. Somewhat disturbingly, the CSAs also reveal the failure of the operator EDF to have in place sufficiently comprehensive plans with which to adequately respond to and capture control of a *'multi-facility'* event.

Very certainly, the crashing of a commercial-sized airliner onto a NPP site has the potential to cause widescale and diverse disruption across the whole NPP site, resulting in the sequential loss of the lines of defence of one or more individual nuclear power plants. If not prepared for, the crashing of a commercial-sized airliner onto a NPP has the potential to overrun pre-prepared countermeasures, thereby impeding the effective implementation of immediate post-incident mitigation measures, and thus extending a chaotic situation placing the NPP or NPPs onto a path towards a radiologically catastrophic outcome.

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VULNERABILITY OF FRENCH NUCLEAR POWER PLANTS TO AIRCRAFT CRASH

PART I AIRCRAFT CRASH – IMPACT FORCE LOADING, EXPLOSION AND FIRE HAZARDS

Aircraft crashes are infrequent but not that uncommon events.

Three past aircraft crashes provide a useful insight into the challenging environments generated by aircraft crashing onto built structures, these are the 9/11 events at i) the World Trade Centre; ii) the Pentagon; and in 1988 iii) the town of Lockerbie in Scotland. Although all three of these incidents were terrorist driven, each provides example of the crash damage severity onto built structures that could arise from both accidental and malevolent incidents involving a commercial-sized airliner crashing onto a NPP site.

For example:[5]

1) **WORLD TRADE CENTRE - NORTH TOWER** - 11 September 2001

This incident was a high velocity collision between two thin-walled structures: the aluminium alloy skinned Boeing 767 airliner and the exterior façade (structural) columns of the World Trade Center (WTC) North Tower. The relevance here is, putting aside the eventual collapse of the Tower arising from knock-on events occurring after, but as a result of the collision, is the fact that a relatively soft skinned Boeing 767 aircraft was able to slice through the much sturdier carbon steel external facia columns of the tower.

In structure, each WTC tower consists of an inner core of columns enclosed within an open lattice array of façade columns, the whole forming a stiff hollow tube – each of the façade columns was fabricated to form a closed box cross section 356mm square of between 12.5 to 7mm thickness carbon steel depending on the height location in the tower (FIGURE 3).

The mechanism involved the cutting and stacking of the skins, frames and spars of the light airframe, concertinaing these components against each other to form a concentrated mass of sufficient energy to generate cracking and shear failure of the tower outer columns. Setting aside the two engine assemblies which are considered to be hardened projectiles, the energy absorbed by the cutting, collapsing and disintegrating airframe has been estimated to be 586MJ.[6]

Once that the concertinaing airframe had attained sufficient non-yielding mass-density, the individual façade column cross sections underwent plastic shearing and detachment of the column sections in the locality of the impact - hence, the shape of the airframe mirrored in the punched through façade (FIGURES 4 & 5) and by whole sections of the detached columns free-falling from the Tower ahead of the instant of the final progressive collapse. This shearing mechanism required a relatively modest amount of energy to complete, about 26MJ or 4 to 5% of the total energy of the impacting aircraft.[7]

The only other practicable mechanism available to punch through the column facade would have been for the individual columns to have failed in plastic bending, that is with the columns deflecting and bending inwards in the path of the impacting airframe, tearing and failing in tension at the

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5 For an introduction to the general principles for the forces, etc., created during a aircraft crash see APPENDIX I

6 Comprising i) fuselage crush 376Mj, fuselage cutting 190MJ and breakup of wings 20MJ – Footnote 7

7 Wierzbicki T, Teng X, *How the airplane wing cut through the exterior columns of the World Trade Center, Impact and Crashworthiness Lab Report #75*, International Journal of Impact Engineering, March 2002 - video

intermediate fixing locations. However, for this mode of failure to complete, the substantial column (beam) inertia (including the floor stiffening) would have to be overcome (ie the column moving itself synchronously with the collapsing airframe), this being very unlikely under high velocity impact conditions.

The WTC aircraft crash demonstrates the capability of a relatively soft missile (the aluminium alloy airframe) to cut through a hardened target (the carbon steel column façade). The high structural stiffness of the receiving target (the hollow tube WTC tower)[8] contributed to the ultimate effectiveness of the shearing of the columns because of the high inertia and inability to yield during a high velocity impact sequence.[9]

The lesson to be drawn here is that massively built structures, designed to withstand and/or contain predefined and relatively steady-state loading (such as wind loading or high pressure transients for the primary containment of an NPP) may not, by virtue of the strength in one role, be at all suitable for another role where the application is a high velocity, transient impact.

2) **PENTAGON BUILDING** - 11 September 2001

The outcome of the single aircraft crashing obliquely into the Pentagon building on 9-11 involved four separate modes of failure and illustrates the extent of *global*, *localised* and *fire* damage achieved by the crashing Boeing 757 airframe (FIGURE 6).

Overall the impact was at virtually ground level, with a horizontal approach, although skewed to the building elevation (FIGURE 7). CCTV records of the last few seconds of the aircraft's approach to the Pentagon enable the velocity of the airframe at impact to be accurately estimated at 156m/s (304 knots). Also recorded was the initial impact with the building outer façade, with one wing shearing off spilling its aviation fuel to generate a fireball that consumed about 14% of the total on-board fuel – this portion of the fuel burnt (deflagrated) as a prompt fire, leaving the remaining aviation fuel, about 14,000kg, to burn within the building as the airframe drove further inwards.

The Pentagon structure comprises a regular grillage of reinforced concrete (rc) framework (columns and beams), with exterior rc walling, interior rc floor and roof slabs.[10] The Pentagon ground plan comprises four parallel and continuous terraces reducing the pentagram projection to an inner courtyard (FIGURE 8). Being the foremost military establishment of the United States, not surprisingly details of the individual structural elements are not publicly available,[11] although for a building of this period (topped out 1943) and purpose its open-bay layout would be determined by 3 by 6m column grillage enclosed by exterior rc walling and roofing, most probably augmented with an additional blast containment steel mesh interwoven with the steel reinforcement rods (rbars). For the period of construction and, particularly, purpose the building structure would be expected to in corporate a high degree of structural redundancy and energy absorbing capacity.

First, the collapse of the entire front elevation section of the Pentagon at the point of initial impact shows the devastating failure of the various reinforced concrete (rc) wall and floor slab components in the outermost terrace building. The failure of the lower floor followed much the same shear punching mechanism as that described for the WTC Twin Towers (above), although here cutting

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8 The high stiffness of such a tall built structure is necessary for structural stability and to resist wind loading.

9 Kœchlin p, Potapov S, *Classification of Soft and Hard Impacts—Application to Aircraft Crash*, Nuc Eng Des 239(4):613-618 (2009)

10 *The Pentagon Building Performance Report*, American Society of Civil Engineers, 2003

11 For a best guess at some of the structural component dimensioning see Mlakar, P. F., Dusenberry, D. O., Harris, J. R., Haynes, G., Phan, L. T., Sozen, M. A. (2003), *Structural Damage Induced by a Terrorist Attack on the Pentagon, ASCE Technical Council on Forensic Engineering (TCFE) Third Forensic Congress*, ASCE TCFE, Reston, VA.

through steel reinforced concrete (rc) walling and completely removing all of the forward positioned columns - the aircraft's penetrating profile is somewhat masked by the collapse of the higher two floors down into the ground level void.

Further into the building, columns that had not detached were distorted into single and triple curvature in the direction of the path of the impacting aircraft (FIGURE 8). Other than the forward columns that had been removed, most of the inner columns remained attached and ductile but with some yielding and *necking* of the rbars at the fixing with the under and over rc slabs. This physical displacement of the structural columns inside the building (FIGURE 9A & B) suggests a second *'global'* failure mode being that the impact velocity slowed sufficient to activate the inertia of the rc columns, placing these in plastic bending to failure.

The third failure mode involved a hardened component of the airframe, believed to be a forward undercarriage strut, punching through three of the terraced buildings into the depth of the Pentagon blocks, forming an exit hole in the outermost wall of the third block. This spar, detached from the airframe and acting as an independent projectile, cleaved through five rc concrete and brickwork walls, travelling about 90m before coming to rest (FIGURE 10).

The fourth mode of failure sustained by the Pentagon was the thermal assault on the structure for the ensuing fire set by the aviation fuel and building contents and, possibly, from the weight of the fire extinguishing water deployed in fire fighting. Assuming that the fire was initially contained in the first floor area opened up by the penetrating airframe, the fire fuel load for the residual fuel (about 86% of the fuel carried) was about 180MJ/m^2 from the residual aviation fuel alone, added to which are the building flammable contents, increasing the overall fuel load to about 380MJ/m*2*, burning over a gross area of 3,400m^2. The fierce fire temperatures, estimated to be 850^{o}C within 30 minutes for a moderately ventilation controlled burn,[12] effectively stripped the protective but impact-damaged concrete cover protecting the rbar reinforcement to columns within 12 to 20 minutes, an endurance time that closely corresponded with the phased collapse of the building following impact.[13]

This second 9/11 example reiterates the localised shear punching mode experienced at the WTC Towers; as the disintegrating airframe slowed, the lower impacting velocity of the concertinaing airframe was able to activate the rc column inertia, displace and fail columns in plastic bending causing further partial collapse of the building; and the fierce aviation fuel and building contents fire quickly stripped the rc fire protection cover from the structural elements adding to the rate of delayed structural collapse. Quite separately, at an early stage of the disintegration, a solid member of the airframe, probably a forward undercarriage spar, detached at sufficient kinetic energy to form a projectile that broke through five rc walls before coming to rest.

The lesson to be drawn here is that ferro-concrete structures are also at risk when exposed to thermal loading (fire), particularly if the concrete cover protecting the inner reinforcement steel (rbars) has been damaged or stripped away by the initial impact, and projectile impact in itself may produce

12 Magnusson S, Thelandersson S, *Temperature-time curves of complete process of fire development: Theoretical study of wood fuel fires in enclosed spaces*. Acta Polytechnica Scandinavica (Civil Engineering and Building Construction Series 65, 1970

13 Under normal ambient temperature, the loss of concrete cover in itself does not significantly affect the structural capacity of an rc structure. However, when the reinforcement of stripped members is exposed directly to fire, as it was in this case, the load-carrying capacity of individual structural members, and therefore of the entire system, can quickly deteriorate because of high temperature exposure. This loss in capacity could lead to premature collapse of the entire structural system, particularly in one with such severe mechanical damage.

fragmentation and spalling of the concrete cover on the backface, thus producing a secondary series of energetic concrete lump projectiles projecting into a containment space.[14]

These two 9/11 incidents of a real aircraft crash, again deriving from malevolent intent but for which the outcome would not differ if the triggering event was accidental, the forces involved were colossal and utterly destructive. Now that a full analysis of the collapse of both the ***World Trade Center*** twin towers and the ***Pentagon*** has been published,[15,16] it is clear that both impact and fire phases of the crash played active roles in the destruction of the buildings. The initial impact would have destroyed or weakened the structure of the buildings and the immediately following fire was of sufficient temperature to ignite all flammable materials within, which provoked further structural member buckling and damage leading to catastrophic structural failure of each tower.

In the third example, the aviation fuel played a very different and highly energetic role during the immediate aftermath of the impact.

3) **LOCKERBIE TOWN** - December1988

On 21 December the Scottish town of ***Lockerbie*** suffered a direct hit from parts of a Pan Am Boeing 747 airliner falling from the sky. For its transatlantic flight, Pan Am PA103, carried upwards of 90 tonnes of aviation fuel some of which, upon impact, ignited into a ~100m diameter fireball setting fire to passing vehicles and setting ablaze buildings. Each of the four 747 engines, detached and falling freely as missiles, landed about the town, with one engine assembly breaking through the road surface to embed itself several meters into the road substructure. The major part of both wings, including the main fuel tanks, fell onto the residential housing of Sherwood Crescent and, after a few tens of seconds, the residual aviation fuel detonated completely demolishing housing and carving a crater some 80m long by 20m deep.[17]

It is now established[18] that the downing of PA103 was caused by a relatively small improvised explosive device that blew a ~0.5m diameter hole in the forward left side of the fuselage, after which the aircraft rapidly broke apart in mid-air with the component parts freefalling to earth.[19] Bringing these various objects to rest resulted in forces being exerted by both projectile (ie the aircraft parts) and the arresting ‘target’ (ie the buildings, ground surface, etc) – these imparted forces would have been of very high but short duration.[20,21]

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14 Thick and massive rc structures are vulnerable to backface spalling and, indeed, catastrophic failure, if of sufficient mass and fixity (ie massive, thick-walled structures) because a sharp impact will generate a compressive stress wave that radiates from the point of impact at the concrete celerity (~3,900m/s) to mostly reflect from the backface, thereby converting into a tensile stress wave under which the tensile-weak concrete is prone to failure.

15 Now published as the official report produced by the American Society of Civil Engineers (ASCE) for the Federal Emergency Management Agency (FEMA), May 2002.

16 American Society of Civil Engineers (ASCE), *The Pentagon Building Performance Report*, January 2003

17 All 259 passengers and crew on board PA103 were killed and eleven residents of Lockerbie also died.

18 *Aircraft Accident Report on the accident to Boeing 747-121, N739PA at Lockerbie, Dumfriesshire, Scotland on 21 December 1988* No 2/90 EW/C1094, Air Accidents Investigation Branch, July 1990.

19 The air accident investigation report estimated ground impact speeds of 120kts (62m/s) for the nose section weighing approximately 8,000kg, 260kts (133m/s) for the engines and pylons each of about 6,500kg, and between 440 to 500kts (225/257m/s) for the relatively intact wing of approximately 45,000kg of structure, containing an estimated 90 tonnes of fuel.

20 For example, assume a single engine-pylon assembly of 6,500kg from PA103 ploughing into the road surface at 133m/s was brought to rest in 0.5 seconds (by collapse of its and the road structures) then the force exerted F_1 relates the momentum at initial and final states $F=2F_1 = mv-mu = 0 - 6500(-133) = 864,500$Ns, so the force on the building, given an equal and opposite reaction, is $864,500/2 = 432.10^3$kN applied over a 0.5 second impulse. Here the example is for a simple uniform

However, at Lockerbie the impacting airframe parts were dispersed over a relatively wide area and these account for only localised damage. The major and widespread damage was caused mainly by detonation of the aviation fuel spilling from the virtually intact centre section, wings and fuel tanks containing 90 tonnes of aviation fuel – the wing section came to earth in a residential area, broke up and settled and then, about 45 seconds later a fuel explosion scooped out a lozenge-shaped crater some 80m by 40m by 20m deep (FIGURE 12). The blast wave and ensuing fireball completely destroyed the houses that occupied the site of the crater, in all about forty other houses were wrecked beyond repair, and buried gas and water mains were ruptured by the ground penetrating explosion.

The time lapse of ~45 seconds between the impact of the wing section and the onset of the fireball centred on the residential housing of Sherwood Crescent, strongly suggests the formation of a fuel-air mixture and subsequent free-air deflagration transiting to detonation (explosion).[22] The explosive fireball originated at some point above Sherwood Crescent, maybe just a few meters, with a major proportion of the spherical blast wave acting directly on the ground surface, transferring energy into the ground substrata, which accounts for the large volume of excavated crater debris and, remote from the crater itself, the rupture of buried water and gas mains. Built structures in the vicinity of the fireball detonation were subject to two components of force: the *overpressure* of the blast or shock wave generated by the prompt phase of the expanding fireball and, following this, a combination of phenomena of dynamic pressure, the duration and time of arrival to the surfaces of the built structures, including a comparatively long-lived negative phase during which vacuum forces were applied to building surfaces.

This example[23] demonstrates the extreme damage severity of air-vapour explosions, here in an unconfined (free) space. Similar air-vapour mixtures developing in a confined space, such as a building void, would be expected to yield greater blast pressures than the unconfined space equivalent.[24] Quite possibly, a deflagration will develop into a detonation if and when the flame front accelerating through the flammable mixture reaches supersonic velocity, at which point the deflagration transits to a detonation – a turbulent vapour flow, caused by obstacles, machinery and equipment in the path of the flame front, is more conducive to a deflagration to detonation transition, with the impacting conditions conducive the to efficient formation of an explosive fuel-air vapour mix.[25]

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collapse so that the *'Load-Time'* function is constant over the dissipation period, but for real aircraft *v* built structures the *Load-Time* function is complex, requiring case-specific derivation – see FIGURE 1

21 Redmayne D, Turbitt T, *Ground Velocity Attenuation Associated with the Lockerbie Air Crash Impact*, Seismology Research Group, British Geological Survey, 1990

22 Explosion as defined here consists of detonation and deflagration. The difference between a detonation and a deflagration is primarily the burn rate of the explosive material in question. In general, solid detonating materials have burn rates in excess of 4000 m/s. Deflagrating materials are typically in gaseous, fine mist or vapour form, particularly formed by and at the site of the incident and, in general, whether a vapour mix detonates or deflagrates depends primarily on the concentration in air of the gas or vapour, and there has to be a threshold volume of explosive gases or vapours in air before a deflagration can occur.

23 Other examples include i) Flixborough (1974) involving 60 tonnes of cyclohexane inside a process plant, exploded equivalent to 15 tons of TNT, totally demolishing the plant and killing 29 persons; ii) Buncefield or the Hertfordshire Oil Storage Depot (2005) with a series of free air explosions overwhelming twenty aviation fuel storage tanks; iii) Piper Alpha (1988) offshore oil-gas rig totally destroyed with the loss of 167 lives – as a rough rule of thumb, the complete detonation of 500lb of aviation fuel would be equivalent to about 1,000lb of TNT – *see Evaluation of Aircraft Crash Hazards Analyses for Nuclear Power Plants*. Argonne National Laboratory report NUREG/CR-2859 Nuclear Regulatory Commission (NRC), June 2002

24 Reidewald F, *Explosive Mixture*, The Chemical Engineer, 9 November 1995

25 The formation of a finely dispersed air-fuel vapour mix is enhanced by the velocity of impact, ejecting the aviation fuel into the air to form a mist of fine droplets or particles of fuel ideal for ignition – hence the accompanying fireball almost at the

The lesson to be drawn here is that the destructive forces of explosion of the aircraft fuel or existing on-site flammables, released by the impact with buildings, storage silos, etc., should not at all be dismissed and confined to a secondary, contributory role. Also, it may be that the widespread devastation wreaked by the aircraft crash itself and, particularly, the injurious range of the explosive shock fronts, radiating several hundreds of meters from the blast centre, may incapacitate and prevent the human resource response and the implementation of mitigation measures in the immediate and short-term aftermaths of such an incident.

APPLICATION TO NUCLEAR POWER PLANTS: The three aircraft crashes briefly reviewed here graphically illustrate the very high forces deriving from a combination of impact and fuel explosion, both at the instance, during and following a real aircraft crash and, considered collectively, these real incidents demonstrate the vulnerability of and severity of damage sustained by built structures.

In another respect, the aircraft involved were modern airliners, capable of high speed, carrying large aviation fuel loads and their trajectories towards the target buildings, although terrorist driven, were not uncharacteristic of the flight approach assumed in accidental circumstances. For example, the Boeing 747 free-fall descent onto Lockerbie was representative of an accidental airframe failure at high altitude say, involving an aircraft *en route*; the WTC tower impacts are representative of a high velocity and level flight approach and impact that might be adopted, as it was here, by a terrorist attack on a NPP; and the Pentagon was a slower impact virtually at ground level, a point at which most built structures are particularly vulnerable,[76] not that uncharacteristic of an aircraft running into difficulty during, say, a bodged landing approach, or following an engine-stalling bird strike, or again a deliberate attack of a malevolent nature.

Over the years there have been attempts to characterise the airframe impact parameters in order to ease the analysis of the target structure response.[26] As previously noted, the main load kinematic assumptions have been based on the interaction between target and airframe, with the impact being defined by a *Load-Time* characteristic (see FIGURE 1) for the airframe and an assumption that the target structure underwent time independent elastic deformation to its yield point, all within a generally prescribed overall impact time of about 70 milli seconds. The loading zone, a circular impact area of $7m^2$ and a maximum impact load of 110MN, derived from a normal impact onto an infinitely rigid target of a fast-flying military fighter (Phantom). Since the time of the introduction of this particular simulation (late 1970s to early 1980s), arguments have been developed to extrapolate this same *Load-Time* characteristic for the impact of a commercial-sized airliner.[27]

However, actual aircraft crashes (particularly Lockerbie and WTC 9/11), together with improved computational methods and understanding of the complex mechanisms involved, together with the interplay between the target and impact airframe, cast considerable doubt over the validity of extrapolating the fighter aircraft impact case to that of a commercial-sized airliner,[167,28,29] so much so that

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moment of impact which is reckoned to burn about one-tenth or thereabouts, turbulating the remaining fuel mist into a deflagration-detonation transition.

26 C.V. Chelapati C, et al, *Probabilistic assessment of aircraft hazard for nuclear power plants***,** Holms and Narver, 1971

27 EDF, *Démarche de dimensionnement des ouvrages epr vis-à-vis du risque lié aux chutes d'avions civils, DGSNR/SD2/033-2003*

28 In 2002, an authoritative United States Argonne National Laboratory study concluded that *"These spectra clearly show that the effect of impact by a Multi-Role Combat Aircraft at 215 m/s is considerably less severe than a modest Safe Shutdown Earthquake (SSE) as represented by the Parkfield earthquake. On the other hand, the effect due to the impact of a Boeing 707-320 at 103 m/s is clearly more severe than that due to an earthquake."* – see Evaluation of Aircraft Crash Hazards Analyses for Nuclear Power Plants. Argonne National Laboratory report NUREG/CR-2859 Nuclear Regulatory Commission (NRC), June 2002

29 In 1988 a large scale crash test was performed at the US Sandia National Laboratory in which a Phantom military airframe of 19000kg mass was impacted at a velocity of 219m/s into an essentially rigid reinforced concrete wall of 3.6m depth. The test

much more airframe-specific data, including a custom *Load-Time* characteristic, has to be developed for both the airframe and target structure.[30,31]

For the case where the target under consideration is a strongly reinforced, mass concrete structure, such as a PWR primary containment with wall thickness in excess of 0.5m, because of the great rigidity the dome is capable of transmitting considerable vibrations to the total structure and to components attached thereto or within the containment.[32,33] Isolating key nuclear safety components from such induced vibrational forces requires a fundamental design change which will not be possible with the present committed designs of the earlier series of French NPPs.

Another difficulty is in modelling the response of the target structure, particularly for reinforced concrete structures where the concrete structure has degraded over time and use. For the primary containment shell of a NPP, most analysts adopt finite element (FE) modelling to compute the response, in terms of limit state deflections of the shell under impact loading, but the application of non-linear FE analysis to degraded concrete structures is considered to be a relatively new research subject.[34] There is limited information available on non-linear behaviour of concrete, particularly under the loading regimes deriving from aircraft crash and, possibly, ensuing explosive blast and/or fire. A valid non-linear analysis depends on a constitutive model that can adequately represent the behaviour of concrete beyond its linear range, and appropriate materials data.

The key mechanisms acting in and following impact of a commercial-sized airliner with a built structure are:

a) IMPACT LOADING: As a result of impact of the aircraft, (kinetic) energy[35] is transferred from the aircraft to the building,[36,37,38,39] in two distinct phases:

- **Impact:** In the first of these phases, the impacting airframe acts as a *'soft'* projectile with energy transferred being absorbed over a time period, the length of which is determined by the inertial

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results were used to evaluate the *Load-Time* characteristic of Riera methodology for prediction of the impact force-time history of an aircraft impact on a rigid target – see Footnote 166.

30 Large J H, *Demarche de Dimensionnement des Ouvrages Epr Vis-À-Vis du Risque Lie Aux Chutes D'avions Civils*, R3159, May 2006

31 Sturm, Dietmar; Julisch, Peter; Hadrich, Hans-Juergen; Nguyen-Huy, *Dynamic Testing Techniques For Components And Large Specimens To Cover Incidents With High Energy Rate*, Con Mechanism of Fracture, Proceedings of the Fracture-Mechanism Program and Related Papers. 1986

32 Schnellenbach, G.; Stangenberg, F. *New Developments in the Design of Nuclear Power Plants Against Airplane Crashes*, VGB Kraftwerkstechnik, v 59, n 1 1979

33 Hammel J, *Aircraft Impact on a Spherical Shell*, Institut für Mechanik, Technische Hochschule Darmstadt, D-6100, 1975

34 Nuclear Energy Agency, *Finite Element Analysis of Degraded Concrete Structures*, Workshop Proceedings, NEA/CSNI/R(99), 1999.

35 The kinetic energy of a non-rotating object of mass m travelling at a velocity v is $mv^2/2$. If a rigid body is arrested then, under the conservation of energy, all of the kinetic energy of motion has to be transferred into other energy forms such as heat, elastic and plastic deformation, etc..

36 Just on the basis of kinetic energy alone the three levels of aircraft crash referred to by the STUK regulator increase from Level 1 (light aircraft) to Level 2 (Jet Fighter) to Level 3 (Commercial) airliner in the ratio 1 to 50 to 1500 or that the energy available from a crashing commercial airline (impact alone) is 1500 times that of a light aircraft.

37 For further details of the IAEA recommendations on nuclear facility resilience requirements and recommendations relating to aircraft crash see *Advanced Nuclear Plant Design Options to Cope with External Events*, Kuznetsov V, Nuclear Engineer, International Atomic Energy Agency (IAEA),

38 International Atomic Energy Agency, *External Events Excluding Earthquakes in the Design of Nuclear Power Plants*, Safety Guide, IAEA Safety Standards Series, N^o. NS-G-1.5, Vienna (2003)

39 International Atomic Energy Agency, *External Human Induced Events in Site Evaluation for Nuclear Power Plants*, Safety Standards Series No. NS-G-3.1, IAEA, Vienna (2002).

and stiffness properties of both the airframe and target structures, the striking velocity and, essentially, size of the airframe, as a finite amount of kinetic energy is transferred to and dissipated by the building structure.

The general assumption is that the building components receive this imparted energy in the form of strain energy whilst each component is deforming elastically and beyond up to the point of permanent yielding,[40] characterised by a *Load-Time* diagram (FIGURE 1) for various military and commercial airframes.[41,42] The impact energy also produces a *'pushover'* couple acting on the structure globally, particularly as the airframe disintegration advances and slurry-like wave of airframe and building materials debris progresses through the built structure.

However, the *Load-Time* characterisation of the impact force can only be that – a relatively crude characterisation. Absolute peak force levels may be much higher than assumed and may be transmitted through the structure to be induced in items of equipment fixed to the main structure causing failure of function, detachment, etc..

- **Impulse:** The second loading phase follows and involves those components of the aircraft that are sufficiently tough to form rigid projectiles that will strike and commence to penetrate, again by dissipation of kinetic energy, components of the building fabric and structure.

  Component projectiles involved in this second phase will include parts of the jet engines, undercarriage spars, and other hard inclusions in the airframe structure, such as the shear box coupling the wings to the fuselage, etc.,[43] Other projectiles may be generated by parts of the building structure,[44] and in certain situations these projectiles might be thrown forward onto the target from a crashed airframe that has been arrested short of the target.[45]

b) FIRE & EXPLOSION LOADING: Physical damage from fuel-air fire and explosion damage can be widespread and severe, there is also the possibility of large scale incapacitation and fatality of the local residents and/or workforce population:

- **Explosive Loading - Blast:** A detonation generated shock front from a fuel-air vapour mix formed from the ejected aviation fuel radiation from a point or distributed source.

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40 *Preliminary Analysis of an Aircraft Impact, G. Forasassi, R. Lofrano* Agenzia Nazionale per le Nuove Tecnologie, l'Energia e lo Sviluppo Economico Sostenibile 2010 – see also Riera, JD. *On the stress analysis of structures subjected to aircraft impact forces*, Nucl. Eng. Des. 8 (1968) 415–426

41 Bangash M Y H *Concrete and Concrete Structures – Numerical Modelling and Applications*, Elsevier Applied Science 1989 – for straight-on impact onto an infinitely rigid build structure.

42 RIERA, J.D., *On the stress analysis of structures subjected to aircraft impact forces*, Nucl. Eng. Des. 8 (1968)

43 Rambach J, Tarakko F, Kavarenne S, *Rapport DSR N° 74*, 18th International Conference on Structural Mechanics in Reactor Technology (SMIRT 18), Beijing, China, August 7-12, 2005, , c2005

44 The characteristic of the target structure is also an important determinant to its response to a crashing airframe. For example, a slender, low inertia structural component will absorb and dissipate much of the impacting energy by displacement and flexure, whereas a rigid, thick rc structure, like the NPP primary containment, instead of accelerating forward in response to the impact, will remain sensibly immobile. In this case, much of the impact will radiate within the concrete as a compressive stress wave, but which will convert and reflect back from the target backface as a tensile wave against which concrete has little strength, failing as spalling at the backface surface, which adds to the free-flying projectiles, and/or forming deep fractures within and weakening the structure itself – the sharpness or *'brisance'* of the impact force is a strong determinant in backface scabbing and spalling.

45 For military aircraft crashes, throw forward distances up to 300m if the airframe descent angle is greater than 15^{o} to the horizontal, and for descents shallower than 15^{o} throw forward distances of up to 2km are possible - *The Throw Forward of Missiles Following Low Level Military Combat Aircraft Crashes in the UK*, Byrne J P, AEA RS 5615 January 1994.

The response of a structure encountering a blast wave[46] is determined by its shape, openness, and dynamic response. When encountering an obstacle, the parent blast front results in a reflected wave that is, typically, two to four times the magnitude but of much shorter duration than its parent. As a blast wave traverses over a built structure it exerts a positive pressure on the walls and roof in its forward path, and a reflected pressure once that it has passed on the windward side – following the blast wave a dynamic *'wind'* produces a inward force on the windward wall and negative forces on the side and leeward walls – built enclosures subject to a traversing or diffracting shock front will, first, be *'squeezed'* inwards and then *'inflated'* outwards.

Parameters necessary to define the blast response and failure of a built structure include the duration of the applied load (both impact and blast) and the natural period of the structural response, as well as damping and the level of ductility during the response.

- **Thermal Loading – Fire:** Thermal loading of the structure and items of plant equipment may be quite severe, rapidly reaching and sustaining high temperatures. Hitherto fire protected structural elements (columns, slabs) may have lost fire protection cover and/or coatings during the impact phase; breaches in the containment shell may result in substantial changes to the ventilation rating of the enclosure which, in itself, may result in a more severe thermal environment beyond the fire rating of essential safety equipment (eg a 1 hour fire rating may reduce to 0.5 hours of less); and the blaze of surrounding buildings and installation may prevent emergency services personnel from taking the appropriate mitigation actions to maintain nuclear safety.

PART II RISK AND FREQUENCY OF AIRCRAFT CRASH ONTO A NUCLEAR POWER PLANT

Since 9/11 the worldwide nuclear industry has been unusually tacit about the ability of the present generation of NPPs to withstand aircraft crash. This reluctance is reflected by the failure, publicly at least, by the various nuclear safety regulatory bodies to demand that the operators demonstrate the structural and containment resilience of existing NPPs against both accidental and malevolent aircraft crash.

ACCIDENTAL AIRCRAFT CRASH

Indeed, before the terrorist act of 9/11 very little attention seems to have been given (at least published) on the vulnerability of NPPs to *accidental* aircraft crash, particularly of commercial-sized airliners.

For example, although in 1985 the United Kingdom undertook studies for the impact of a heavy military aircraft and commercial airliners onto the pressurised water reactor (PWR) Sizewell B NPP, the results were never then (nor have since been) made publicly available.[47,48] Instead in 1987, a short offprint paper was available summarising the response

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46 For application to deflagration blast waves see Baker W E et al *Explosive Hazards and Evaluations, Fundamental Studies in Engineering 5,* Elsevier 1983

47 The aircraft crash assessments formed part of the Sizewell B nuclear safety case, being a statutory requirement for the licensing of the NPP as required under the UK *Nuclear Installations Act, 1965*.

48 *Sizewell B PWR Supplement to the Pre-Construction Safety Report on External Hazards, Aircraft Crash*, CEGB Report No GD/PE-N/403, 1982, *Aircraft Impact on Sizewell B,* Part 2(a), *The Effects of Impact of Heavy Aircraft Adjacent to but not directly on Vulnerable Buildings. (b) Light Aircraft on the Vulnerable Buildings*, PWR/RX774 (Pt 2), 1987 and *Aircraft Impact on Sizewell B* Part 3 *Fire Following Aircraft Crash,* PWR/RX774 Part 3, 1987

of the steel lined, rc primary containment dome (*vessel*) of Sizewell NPP to types of fighter aircraft,[49] concluding that:[50]

". . . Upon impact the aircraft can produce two types of effect on the vessel . . . local effects are characterised by penetration, perforation and backface spalling or scabbing of the vessel material (concrete) . . overall effects are vessel stability in terms of flexural and shear behaviour of the vessel . . . using the Sizewell B parameters and the load-time functions . . during impact the (steel) liner in the local area has ruptured . . the (liner retaining) studs have ruptured and in other areas they have buckled. . . "

my truncation . . . and (added) explanation

Even so, the reluctance of the UK nuclear safety regulator[51] to acknowledge the risk and consequences of aircraft crash was, perhaps, expressed in the title of the unpublished analysis,[48] being

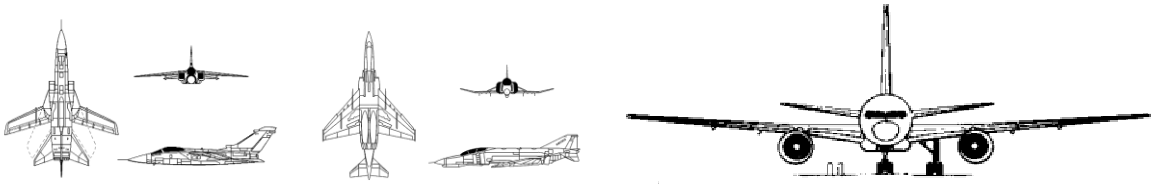
'The Effects of Impact Heavy Military Aircraft Adjacent to ***but Not Directly on*** *the Vulnerable Buildings'*

my ***emphasis***

somehow suggesting that the pilot of this hypothetical aircraft was able to retain some degree of control (and also possess the knowledge of processes and hazardous parts of the NPP) to avoid the most vulnerable parts of the plant. It is on the basis that the heavy military aircraft would not impact directly, that the Sizewell B operator claims that the likelihood of an unacceptably severe fire or explosion following the impact is sufficiently low to be discounted. At around the same time, the United States nuclear safety regulator[52] adopted a similar discounting of the risk (NUREG-0800) based analysis permitting the introduction of the mitigation that the pilot will retain sufficient control to avoid striking the nuclear plant – for military pilots this is assumed to be for 95% of the time or that, independent of all other considerations, the P_{hit} probability is equal to 0.05.

The exclusivity of this approach to military aircraft stems from the practice of these aircraft movements being under the supervision of military flight controllers and, importantly, that most state military regimes demand complete freedom of the skies for operation of military aircraft. To the contrary, civil commercial-sized airliners are required to operate at high

49 Aircraft types were multi-combat Tornado (all up 28,000kg) and strike fighter Phantom (28,030kg) compared to a Boeing 757 (123,600kg – 9/11 Pentagon) wingspan 40m for comparison.



50 Bangash Y *Aircraft Crash Analysis of the Proposed Sizewell B Containment Vessel*, Structural Mechanics in Reactor Technology, Trans 9th Int Conf Structural Mechanics in Reactor Technology, Lausanne August 1987 – 7pp.

51 Then the *Nuclear Installations Inspectorate* (NII) now the *Office for Nuclear Regulation* (ONR).

52 Nuclear Regulatory Commission (NRC), see US Nuclear Regulatory Commission Regulation (NUREG), particularly NUREG-800 3.5.1.6 (1981) and earlier D. G. Eisenhut, *Reactor Siting in the Vicinity of Airfields*, paper presented at the American Nuclear Society Annual Meeting, June 1973.

altitude within prescribed air corridors and are excluded from flying within pre-defined air exclusion zones around nuclear plants.[53]

Much the same approach differentiating between military and civilian air traffic, and the application of *risk discounting*, was and continues to be applied in the French nuclear regulatory framework with the regulator, ASN enacting the first regulation relating to aircraft crash risk in 1980,[54] prior to which there seems to have been no requirement to specifically address accidental aircraft crash at the design, construction and operational phases of NPPs. In fact, the French approach of risk discounting on the basis of the projected probability of aircraft crash, is virtually identical to that adopted in the United States and the United Kingdom. For French NPPs, three classes of aircraft are considered in terms of the projected frequency of accidental crashes at NPP-specific sites, with the data being derived from national crash records for i) overflights, sometimes referred to as *'background'*; and ii) local airport landings and takeoffs.

The pan-European approach to accidental aircraft crash is that of *Acceptable Risk and Tolerable Consequences*:

The *Tolerable Consequences* relate to the size, mass, aviation fuel load and potential impact velocity of categories of aircraft, these categories being defined[55] as light and commercial, with a special group for military airframes. In this way, although not specifically or quantitatively defined further, the size etc., of the airframe is related to the potential severity of damage to the target NPP building. The *tolerability of consequences* is usually expressed in terms of the *radiological* consequences, taking into account NPP specific features of design, size, radioactive inventory, release fractions and so on.

The *Acceptable Risk* relates to the predicted frequency of occurrence of air crash, tuned to each specific NPP site to account for local factors, yielding a projected frequency which is set against a prescribed threshold value beyond which the occurrence of an aircraft crash is reckoned to be so remote as to be an *incredible* event. The European regulators generally adopt a threshold of risk acceptability at 1.E-6 (one in a million per reactor year of operation), adding to this a further reduction of one to two orders of magnitude (1.E-1 to 1.E-2) to avoid *'cliff edge'* situations. Typically, this yields an acceptable risk of 1.E-7 to 1.E-8 (one in ten million to one hundred million) to prescribe a numerical threshold value of acceptable risk for aircraft crash.

In France, the thresholds for *credible* accidents are:

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53 In the UK, the Air Exclusion Area or Zone is regulated by the Civil Aviation Authority (CAA) under Statutory Instruments 2007 No. 1929 CIVIL AVIATION The Air Navigation (Restriction of Flying) (Nuclear Installations) Regulations 2007 5 July 2007m enacted 1 August 2007. At Dungeness NPP CAA EG R063 applies a 2 nautical mile by 2,200m altitude (3.5km radius) exclusion zone for civil air traffic – similar air traffic exclusion zones apply around French NPP sites.

54 Regulation N° I.2.a of 5 August 1980, applicable to '*nuclear sites with pressurized water reactors'* - Règles Fondamentales de Sûreté (RFS) ASN - a similar regulation was applied to other nuclear sites (fuel, radioactive waste, etc) in 1992 (Regulation N° I.1.a of 7 October 1992) – the duties and responsibilities of the various parties for nuclear safety are specified in the Article 5 of the Convention on Nuclear Safety - France, eg 5th National Report, July 2010

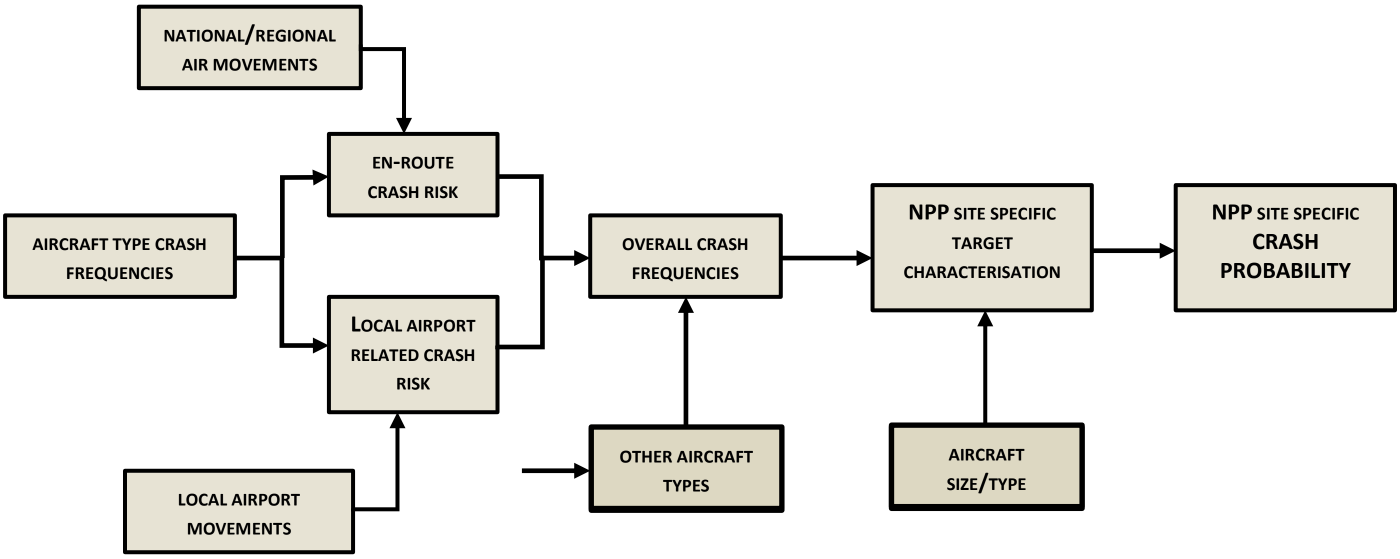
55 Now (since c2000) 5 categories of aircraft are defined as *C1* light fixed wing of <2.3t, *C2* helicopters, *C3* fixed wing of >2.3<20t, *C4* any >20t fixed wing aircraft (ie commercial airliners, freighters), *C5* military fighter aircraft – the ASN definition is slightly narrower than this and includes three aircraft categories.

TABLE 1 CREDIBLE AIR CRASH ACCIDENT THRESHOLDS

AIRCRAFT CATEGORY	TYPE OR CLASS	EXAMPLE	PROBABILITY ACCIDENT PER FLIGHT	NPP SITE PROBABILITY ORDER
GENERAL (all types)	1	SMALL <5.7 TONNES	1.E-4	~1.E-6
MILITARY	2	ANY MILITARY AIRFRAMES	1.E-6	1.E-7
COMMERCIAL	3	COMMERCIAL >5.7 TONNES	<1.E-4[56]	<1.E-8

The overall *crash rate* at each NPP site is determined by account of and summing the air traffic density, comprising i) *background* level of aviation risk; aircraft transiting the area at high altitude termed ii) *airways* risk; iii) the risk arising from *military combat aircraft* (MCA); and, where the NPP site and airfield are in close proximity, iv) the low altitude air traffic movements. The overall *crash rate* is then applied to the specific NPP site, which is defined by the distance and orientation of the target buildings from the take-off and landing runways, the height and plan form of the *safety-critical* buildings, this being usually (incorrectly it is often argued) limited to the reactor primary containment building. To determine the *NPP site specific threshold*, parts of the NPP building complex are defined as a *crash area*. The parameters relating to this are calculated from the *effective fly-in*, *footprint*, *shadow* and *skid areas* that are determined from established codes and methodologies.[57]

Applied to a commercial airliner operating at altitude and passing along a prescribed flight path, or to aircraft traffic at nearby airports, this past-event dictated, probabilistic approach adopts crash frequencies drawn from actual crash incidents, then taken through a cascade of reducing frequency, yields a very low NPP site-specific accidental crash probability.[58,59,60]



56 The equivalent data for the United States for the period 2002-2006 gives the en-route crash rate of 3.92E-7 per departure for small and large transport aircraft combined which compares to the United Kingdom crash rate value of 6.77E-7. The airframe manufacturer Boeing give a crash rate for aircraft of gross weight up to 24,000kg at 0.8E-7 per departure and, similarly, the UK's Civil Aviation Authority gives a total (all civil aircraft types) crash rate of 1.8E-7 per departure.

57 STD-3014-96, US Department of Energy, 1996.

58 For example see *Evaluation of Aircraft Crash Hazards for Nuclear Power Plants*, Kot C A, et al, Argonne National Laboratory, 1982 which gives a chance of crash into a nuclear plant 11.5 miles to the south of an air corridor at 33,000 ft to be about 2.36x10^7 per year and *Evaluation of Air Traffic Hazards at Nuclear Power Plants*, Hornyik K, Nucl Technology 23, 28, 1974.

59 *Aircraft Impact on Sizewell B, Part 1 Safety Involvement of Buildings on Site*, PWR/RX774 (pt 1) 1987.

60 Sizewell B PWR Supplement to the Pre-Construction Safety Report on External Hazards, Aircraft Crash, CEGB Report No GD/PE-N/403, 1982, Aircraft Impact on Sizewell B, *Part 2(a), The Effects of Impact of Heavy Aircraft Adjacent to but not directly on Vulnerable Buildings, (b) Light Aircraft on the Vulnerable Buildings*, PWR/RX774 (Pt 2), 1987 *and Aircraft Impact on Sizewell B Part 3 Fire Following Aircraft Crash*, PWR/RX774 Part 3, 1987.

To incorporate air traffic movements originating from a nearby airfield, since such NPP site-specific air crash risk assessments (usually undertaken jointly by the operator and regulator) are rarely made public, particularly so since 9/11, it is difficult to assess the contributory influence of this component of the overall crash rate. Again for example, for the UK NPP at Dungeness (Kent) which is located about 4km from the small, semi-commercial airport of Lydd, the last publicly available nuclear safety assessment of the risk of accidental aircraft crash for the Dungeness NPPs was undertaken by the UK nuclear safety regulator in or about 1995 for air traffic movements projected for 1997,[61,62] although for this the detailed analysis and break down of the component risks were not publicly available.[63]

However, two publicly accessible assessments[64,65] have been undertaken for a public planning inquiry relating to the risk of aircraft crash onto the Dungeness NPP using the risk assessment methodology adopted by the UK nuclear safety regulator,[66] and which is generally in accord with similar assessments internationally. Each of these analyses considers the expansion of Lydd airport, presently used mainly for club and executive jet (generally <5.7t) operations, to charter flight operations using commercial-size airliners with a relatively modest passenger throughput of 500,000 per annum, involving annually a mix about 3,500 air traffic movements of commercial-sized airlines and an additional 12,000 or so movements of small transport and executive jets (<5.7t). The crash risk for all of these air movements comparing just the nuclear island (left-hand columns - one of the two active NPPs at Dungeness) to the whole NPP site (right-hand columns – including the two active NPPs together with two recently shutdown NPPs that remain fuelled), is reckoned to be as follows:

TABLE 2 – AIRCRAFT CRASH RISKS DUNGENESS A + B SITE - INFLUENCE OF TARGET AREA[65]

	NUCLEAR ISLAND ONLY SINGLE NPP		VARIATIONS OF THE WHOLE NPP SITE			
	AIRPORT RELATED	EN-ROUTE	AIRPORT RELATED	EN-ROUTE	AIRPORT RELATED	EN-ROUTE
CRASH RATE per km2	3.09E-06	7.80E-06	3.09E-06	7.80E-06	3.09E-06	7.80E-06
EFFECTIVE TARGET AREA km^2	1 NPP containment only 0.0512		1 NPP + Services 0.1284		4 NPPs + whole Site 0.5364	
CRASH FREQUENCY/year	1.58E-07	3.99E-07	3.97E-07	1.00E-06	1.66E-07	4.18E-06
OVERALL CRASH FREQUENCY	**5.58E-07** (1 in 1,794,000)		**1.40E-06** (1 in 715,200)		**5.84.E-06** (1 in 171,200)	

61 Aircraft Impact Dungeness B – Topic Report 2.4 – Dungeness A-PSR – *C2 Assessment Report on Dungeness A External Hazards Aircraft Crash*, ARF No 15 NUC 305/67/4/3 P1 E3, Nuclear Installations Inspectorate, September 1995.

62 It seems, although it is not certain, that the NII's Dungeness A analysis of 1995 was based on the information provided by the then airport operator *Lydd Airport Group* in its 1998 application (SH/88/230) for a runway extension. This was the subject of Local Public Inquiry inspector's report of September 1992. The air traffic data is used for the *NII Case* of TABLE 1 (see later) are taken from the 1992 Inspector's report although it is understood that these projected levels of air traffic have never been achieved at Lydd.

63 The UK regulator's analysis predicts a *total* impact frequency on the NPP site at Dungeness of 1.4E-6 per year (a chance of about 1 in 715,000 years) for <u>all</u> categories of aircraft and helicopters [63] – this level of projected risk of accidental aircraft risk approximately corresponds to the ANS *GENERAL* category of TABLE 2. However, for licensing the Dungeness NPPs only the C4 aircraft category risk would be taken into account because aircraft of the other categories would not be considered to pose a threat of intolerable consequences (ie light aircraft and the generally exempt military airframes).

64 Large J H *Nuclear Safety of the Nuclear Power Plants at Dungeness as determined by the Proposed Development of London Ashford Airport*, R3136-A1 – see also *Town And Country Planning Act 1990 - Section 77 And Town And Country Planning (Inquiries Procedure) (England) Rules 2000 Applications By London Ashford Airport Ltd Site At London Ashford Airport Limited, Lydd, Romney Marsh, TN29 9QL* Key And Explanation Of The Evidence Statements of John Large, May 2011

65 AREVA, *London Ashford Airport (Lydd) Development: Aircraft Crash Risks to Dungeness Nuclear Power Stations*, WSP Group, AREVA March 2009

66 Contract Research Paper 150/1997, *The calculation of aircraft crash risk in the UK, United Kingdom Atomic Energy Authority (UKAEA)*

TABLE 2 shows the relationship between contributory air traffic movements of *en-route* (high altitude) and commercial-sized airliners and executive jet traffic movements related to the local airport at Lydd as this risk applies to the NPP site at Dungeness.

The results featured in the left-hand side of the table [■ and ■] is taken from analysis presented by the French NPP design company AREVA being, essentially, in support of further nuclear development of the Dungeness site. AREVA's analysis is presented as the substantive case [■] being with the minimal or *'bare bones'* target area, comprising just the equivalent primary containment of the AGR reactor block and excludes the spent fuel storage building and all other radioactive material containments, nuclear safety systems, etc., that support the safe and stable operation of the single reactor under consideration, In the second AREVA result [■] the equivalent site area associated with a single AGR reactor is taken into the risk projection with the outcome of increasing the overall risk by a factor of x2.5. The right-hand side of the table [■] is the work of consultants providing support for those opposed to the development of Lydd airport with the assumption that the whole Dungeness site, covering four NPPs and all ancillary features on site should be taken as the target area, thereby increasing the risk by a factor of x10.5.

The simplified comparisons of TABLE 2 shows how sensitive the overall crash prediction is to assumptions made in the definition of the target and its relationship to both high altitude *en-route* air traffic and local airport air movements.

Also, it is important to note that it is the combination of *frequency* of crash and *consequences* that is central in setting the potential of the radioactive release, primarily because the heavier and greater fuel capacity of *C4* aircraft (equivalent to ASN's Type 3 category of TABLE 2) has the potential to severely damage the NPP plant equipment and containment systems.

The *a priori* risk of aircraft crash varies with the distance and orientation of the NPP from the airport.[67] Generally, the crash rate up to 10km from the end of the runway decreases exponentially with distance, with different amplification factor for landings (greater) and take-offs (lesser), and there is variance between the various categories or classes of aircraft. Importantly, in terms of the vulnerability of the target structures, is the shallowness of the approach angle which, again, relates to the NPP to airport runway distance. The NPP target to airport runway distances relationships, together with the exposed size of the target are readily defined in formulaic terms.[68] Generally it is accepted that targets beyond 10km from the airport runway touch down/take off point are not at any added increment of risk of aircraft crash from landing and take-off air traffic movements.

Summary: Accidental Aircraft Crash Risk Rates

In France, prior to the enactment of the *règles fondamentales de sûreté I.2.a (RFS)*[54] in 1980, no regulatory specification existed for taking account of accidental aircraft crash risk in the design of nuclear installations, thus excluding *de facto* all nuclear power plants commissioned prior to the RFS enactment date of 1982 or thereabouts.

Currently in France, the risk of a crash of a commercial-sized airliner or military aircraft is deemed to be below the prescribed risk threshold and thus such high energy impacts are ruled out by this definition alone. In fact a *'plausible aircraft crash'* (the only subject of these rules) is defined as the crashing of a light aviation Type 1 aircraft (weighing less than 5.7 tonnes), with the RFS defining two types of aircraft deemed to be *'representative'*: the CESSNA 210, single-engine (propeller) aircraft (~1.5t) and the twin-engine LEARJET 23[69] (~5.7 t). Both of these representative aircraft are assumed to impact the target

67 Berg H, *Risk Assessment of Aircraft Crash onto a Nuclear Power Plant*, RT&A(20) V2, March 2011

68 US Department of Energy (USDoE), *Accident Analysis for Aircraft Crash into Hazardous Facilities.* DOE-STD-3014-2006

69 The Learjet 23 of (all up 5,670kg) compared to a Boeing 757 (123,600kg)

installation at a speed of 100m/s. This is far lower than the energy[70] of impact resulting from the three real accident scenarios involving impact velocities of 130 to 260$m.s^{-1}$ (Lockerbie) and about 200 and 280 $m.s^{-1}$ for the 9/11 Pentagon and WTC impacts, and with all three impacts including the additional hazard of the 100 tonnes or more of highly flammable aviation fuel.[71]

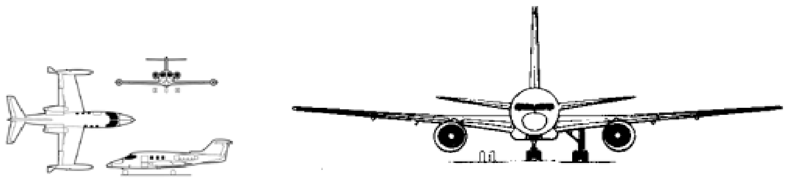
The contention is that the projected overall aircraft crash rates, particularly because of the additional risk generated by air traffic movements to and from nearby commercial airfields, is more frequent than the nuclear regulators assume. In the most recent application of the discounting risk methodology (Dungeness UK 2011), analysis by an independent expert concluded that the method used by the UK nuclear safety regulator to calculate the likelihood of crashes is *'flawed'* and could *'underestimate'* the risk by 20%.[72]

On one hand, many of the NPPs operating in France were commissioned before a specific requirement was raised to design out the vulnerability to aircraft crash and, since their commissioning very little can be practicably done, by way of modification, etc., to enhance the resilience of the existing generations of NPPs against aircraft crash. On the other hand, commercial air traffic movements of commercial-sized airliners have significantly increased; new regional airports have been developed introducing a local air traffic risk to some NPPs where none existed before; and over the last two to three decades, the airframes themselves have become larger, the quantity of aviation fuel carried greater, and the flight speeds faster.

The only opportunity available to the nuclear regulator to compensate for the increasing risk of accidental aircraft crash against existing NPPs is to stipulate improvements in the aviation side of the *risk-consequence* compact, that is in the management of air traffic movements, enhancement of aircraft performance and avionics etc., none of which the nuclear safety regulator has any direct control.

INTENTIONAL AIRCRAFT CRASH – TERRORIST AND MALEVOLENT ACTS

Because accidental crash of a civil airliner on some part of a NPP site would be reckoned, on the basis of the established assessment routines,[73] to be a very remote event it will be considered beyond the *'design basis'*.[74] However, each national regulatory framework usually incorporates a *'catch all'* that requires fault sequences within the design basis, but which have the potential to lead to a severe accident, to be considered and analysed (by bounding cases[75] if appropriate).



70 The total energy of the approaching aircraft at the instance of impact is proportional to the velocity squared (v^2), so Lockerbie x6.76 and WTC x7.84 on velocity alone, and x140 for the WTC and Pentagon impacts if mass of the Leerjet at 5.7 tonnes is compared to the Boeing airliners involved at WTC.

71 FIGURE 13 shows a comparison of the airframes considered in this Review.

72 Pitfield, D *Aircraft Accident Modelling for Lydd Airport, Kent*, LAAG/5/A, Lydd Airport Planning Inquiry, Folkstone 2011.

73 *Accident Analysis for Aircraft Crash into Hazardous Facilities*, DOE-STD-3014-96, 1996 see also for practical application *NUREG-0800, Section 3.5.1.6 Aircraft Hazards*, Nuclear Regulatory Commission, 1981 which suggests a crash rate in the absence of other data to be $3.66x10^9$ per flight mile.

74 The *Design Basis* is the performance, function, fault, abnormal condition, etc., up to which the plant is expected to function.

75 A *'bounding case'* is where the different faults and fault sequences may be grouped together in that the consequences for any fault sequence is as least as severe as every member of the groups of fault sequences to which it is bound.

In other words, if it is acknowledged that an accidental aircraft crash could lead to a very severe radioactive release then, however remote the probability of this event, there is a requirement that the consequences be identified and assessed.[76] Put another way, this is a *consequence analysis* approach that disregards any offset from the probabilistic value of a foreseeable event ever happening. So, it follows, a terrorist event beyond the rules of probability, but which deploys the same type of airliner, impact velocity, aviation fuel load, etc., will also be capable of resulting in very severe radiological consequences.

Even though this *consequence approach* drives the ASN post-Fukushima CSA requirements,[104] particularly in that

". . . Beyond the current safety requirements, . . . additional measures to prevent the serious consequences of extreme situations, on a deterministic basis, regardless of their plausibility. . ."

my . . . truncation

applied as it has been to physical features of NPPs sites, such as cooling canal embankments, ASN do not require aircraft crash to be the topic of this consequence approach. Although, that said, ASN has made an exception to this with a plant specific requirement for EDF to evaluate the damage severity of aircraft crash on the embankments of the cooling water canals, although the NPP(s) involved are not publicly specified.[143]

There are two other distinctions between an accidental aircraft crash and one driven malevolency: first is that a terrorist act is far from being accidental, since terrorist effort will be an intelligent, intentional act seeking out the vulnerabilities of the target; [77,78,79,80,81] and,

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76 In fact, a recently released but part redacted ESR Technology assessment for the UK ONR acknowledges that a commercial aircraft impact could result in a significant radiological release (including redactions thus [redacted])

> ". . *The frequency of aircraft impact with the potential to lead to significant radiological release was estimated at* [redacted]. *This risk relates to the impact of* [redacted] *causing direct mechanical damage to the bio-shield and the fuelling machine"*

see Large J H Town And Country Planning Act 1990 - Section 77 And Town and Country Planning (Inquiries Procedure) (England) Rules 2000, Applications By London Ashford Airport Ltd, Site At London Ashford Airport Limited, Lydd, Romney, Marsh, TN29 QL, *Lydd Airport Proposed Development: Dungeness Aircraft Crash Report ESRTt/D0010905* 18 July 2007.

77 The validity of ONR's redaction of the ESR Technology report (see Footnote 76) is presently being challenged via the UK Office of the Information Commissioner (OIC). The ONR gave its justification to the OIC for not removing the redactions to include *". . because it (the redacted text) establishes the likely impact of a direct hit on a reactor, and also reveals what size/type of aircraft that would be required to produce such an effect (radiological release). This would be of direct assistance to those engaged in targeting a site like this (Dungeness NPPs) . . . The accumulation of the information into a single document significantly increases the potential for access to flight paths to vulnerable areas. . "* and *". . . The location of UK nuclear facilities are well known, What is less well known are the vulnerable areas of such facilities or details of the security arrangements. . . To put it into context the formulae at a basic level for calculating the flight paths (heading, altitude and angle of attack) could be developed or used by a competent A level student of mathematics"*.

78 Attack by large airliners loaded with fuel, such as those that crashed into the World Trade Center and Pentagon, were not contemplated when design requirements for those prestigious buildings were determined. A taped interview shown September 10, 2002, on Arab TV station al-Jazeera, which contains a statement that Al Qaeda initially planned to include a nuclear plant in its 2001 attack sites, intensified concern about aircraft crashes - see Behrens C, Holt M, *Nuclear Power Plants: Vulnerability to Terrorist Attack*. CRS Report for Congress, RS21131, February 2005 – see reference to strengthen of the AP1000 NPP design *". . .Westinghouse submitted changes in the design of its AP1000 reactor to NRC on May 29, 2007, proposing to line the inside and outside of the reactor's concrete containment structure with steel plates to increase resistance to aircraft penetration."*

79 Large J H, *Nuclear Decommissioning – Openings for the Terrorist Threat*, IBC, London 2006

80 Large J H, *A Brief Assessment of the Possible Outcomes of a Terrorist Attack on the COGEMA la Hague Nuclear Reprocessing Works*, Greenpeace International, October 2006

second, the aircraft crash might be accompanied by other terrorist actions that, for example, seek to draw away and occupy key emergency services personnel; or to magnify the effect and consequences (ie down electricity grid pylons to isolate the external electricity supplies), and so on and so forth.

Set against this is the nuclear industry's strategy for defending its NPPs against natural and accidentally occurring hazards mainly on a basis of *'as chance would have it'* and, for protection against human error, the systems and equipment are designed to be tolerant and/or independent of human action (or inaction). This combined approach of gauging the risk by probabilistic assessment and treating the human operators as inconsequential dummies may have some effect in safeguarding the plant against accidents and unintentional human error, but it may prove to be woefully ineffective against intentional and intelligently driven acts of terrorism.[82] The advocacy of the probabilistic approach is strongly rooted in both design and regulatory methodologies,[83] in France stemming from the time that it was felt necessary to justify the authoritarian introduction of the *Messmer Plan.*[102]

The ASN *Information Note* of 13 September 2001[84] states that

> *". . . Elles ne sont pas construites pour résister sans dommages à l'impact d'autres avions, dont les probabilités de chute accidentelle sont extrêmement faibles . . ."*[85,86]

thereby acknowledging that no account of commercial-sized airliner crash was required in the design consideration.[87]

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81 Large & Associates, Operational Risks And Hazards of the EPR When Subject To Aircraft Crash, Further Comments Relating to the EDF Presentation, Authorisation to Construct and Operate a 3rd Nuclear Power Plant at Flamanviulle, States of Jersey, August 2006

82 Large J, Schneider M, International Terrorism - The Vulnerabilities and Protection of Nuclear Facilities, Oxford Research Group, December 2002

83 Queniart, D. et al, *Utilization of Probabilistic Methods for Evaluating the Safety of PWRs Built in France*. IAEA (International Atomic Energy Agency Proceedings Series), p 185-197, 1985

84 ANS Information Note Protection of Nuclear Facilities Against Falling Aircraft, Information Note, ASN 13 September 2001.

85 *". . . Given the likelihood of collapse (from falling aircraft on nuclear facilities}, they are built for 70 years to withstand without damage to the impact of the fall of the first aircraft family, small commercial aircraft, they are not built to withstand impact without damage to other heavier aircraft, including the likelihood of accidental fall are extremely low. In this matter, the French rules are no different from international practice. . ."*

86 ASN's assertion that its own view concurs with international practice is not factually correct inasmuch that the United States Nuclear Regulator Commission (NRC) *". . Commission believes that it is prudent for nuclear power plant designers to take into account the potential effects of the impact of a large commercial aircraft. . . "*, 72 FR 56288 although, that said, the NRC has relaxed on the application of this ruling for existing licenced designs of NPP – see 72 FR 54287, 54290.

87 There is but one specific reference to aircraft crash to be found throughout the publicly available ASN/EDF documentation which states

> *" . . The safety and radiological situations covered by the on-site emergency plan are situations where the safety of the installation is seriously affected and/or situations in which there is a risk that radioactivity might be released into the environment leading to the exposure of persons working outside the controlled area or of people living in the vicinity. The criteria for putting a safety and radiological on-site emergency plan into operation can be found in the operating procedures, the plant protection procedures (aircraft crash onto the reactor building or the fuel building) and the plant radiation monitoring system alarm sheets. The organisational structure set up when the safety and radiological on-site emergency plan is put into operation is upper bound, in other words it means that the consequences associated with both conventional risks (such as fire, personal accident etc.) and radiological risks, whether actual or potential, can be dealt with. ."*

Moreover, ASN/DSND dismiss the involvement of commercial airliners in an *accidental* crash on probability of occurrence alone and, in any event, a terrorist attack is considered to be a real *Act of War* and thus excluded from the *Design-Basis* requirement:

> *" . . . Ce qui s'est passé aux USA ne relève pas de chutes accidentelles mais de véritables actes de guerre, qui ne sont pas pris en compte dans la construction des installations nucléaires . . . "*[88,89]

In this way, ASN absolves itself and the operator EDF of the requirement to plan for aircraft crash because it deems it to be an *Act of War*. However, ASN is currently contributing, via its membership of ENSREG, to the European Commission *Ad-hoc Group on Nuclear Security* (AHGNS) that is specifically analysing security threats arising from terrorist acts, currently running as the *Security Track*[90,91] in parallel to the *Stress Tests*.

However, international acceptance of this approach to risk, that is dismissing projected infrequent events as incredible, has changed now that the lessons of Fukushima Daiichi (March 2011) are being absorbed. In Germany, where 8 NPP plants were summarily shut down (May 2011) mainly because of their inability to withstand aircraft crash,[92] Chancellor Angela Merkel opined that *"Fukushima has forever changed the way we define risk in Germany"*,[93] a conclusion echoed by Norbert Röttgen, Germany's Environment Minister that the event at Fukushima:

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see p93, France's Second Report under CNS, September 2001 – an auspicious date of publication after which this text is nowhere to be found in subsequent French CNS reports.

88 *". . . What happened in the United States is not accidental but falls as real acts of war, which are not included in the construction of nuclear facilities . . ."*

89 See also the United State definition in 10 CFR 50.13, *Attacks and Destructive Acts by Enemies of the United States; and Defense Activities***,** (72 FR 56287, 56288.)

90 The Commission and ENSREG agreed to work on two parallel tracks: i) a *Safety Track* to assess how nuclear installations can withstand the consequences of various unexpected (naturally and/or accidental occurring) events; and ii) a *Security Track* to analyse security threats and the prevention of, and response to, incidents due to malevolent or terrorist acts. While nuclear operators and the national regulators, in close collaboration with the Commission, were in charge of aspects relating to nuclear safety, it was decided that Member States themselves, assisted by the Commission, would be in charge of assessing nuclear security aspects for which the Council set up the Ad-hoc Group on Nuclear Security (AHGNS). Progress made on this security strand is reported in an unpublished annex – for further details see European Commission, *Communication from the Commission to the Council and the European Parliament on the interim report on the comprehensive risk and safety assessments ("stress tests") of nuclear power plants in the European Union*, SEC(2011) 1395 final, Brussels 24 November 2011.

91 ONR provides an insight into the secrecy mutually agreed and adopted by members of AHGNS in its e-mail response of 24 February 2012 when giving it reasons from withholding a request for information on the *Security Track* studies undertaken by AHGSN to be *"Disclosing would adversely affect our relationship as the AHGNS members have agreed that the information should not be disclosed at this stage in their deliberations"* – there is no reason to believe that ASN will also abide by this mutually imposed restriction.

92 In contrast to ASN, the German nuclear safety organisation required its operators to take account of aircraft crash when undertaking the recent round of *European Commission-ENSREG Stress Tests*, *IRRS follow-up mission Germany 2011 Supplement on the Advance Reference Material (ARM), Regulatory implications of the Fukushima Dai-ichi NPP accident*, Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (RSK), specifically noting that:

> *". . .* ***Aircraft Crash***
> - *Consequential mechanical effects due to an aircraft crash that lead to a limited loss of coolant.*
> - *Protection of the fuel pool of decommissioned plants. . . "*

93 Guardian Environmental Network, *How Angela Merkel became Germany's unlikely green energy champion*, Christian Schwägerl , 9 May 2011

"*. . . has swapped a mathematical definition of nuclear energy's residual risk with a terrible real-life experience . . .we can no longer put forward the argument of a tiny risk of ten to the power of minus seven, as we have seen that it can get real in a high-tech society like Japan . . .*"[93]

Similarly, the German governmental advisor on the Environment concurred

"*. . . The widespread view that the extent of the damage due even to major incidents can be adequately determined and limited in order to be weighed up . . . is becoming considerably less persuasive . . . The fact that the accident was triggered by a process which the nuclear reactor was not designed to withstand . . . casts a light on the limitations of technological risk assessment . . . based on assumptions, and that reality can prove these assumptions wrong . . .*"[94,95]

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APPROACH TO HIGH-IMPACT, LOW PROBABILITY EVENTS - IN GENERAL

An aircraft crash onto a NPP might, no doubt, fall outside the range of readily foreseeable and acceptable *'known'* events for which the nuclear industry creates a generic response – it would be, either accidental or maliciously motivated, a shock event that had not been conceived or recognised in advance as a credible threat. Put another way, if nothing can be done to mitigate the outcome, in terms of damage severity and potential radiological consequences, of a commercial-sized airliner crashing onto any one of France's existing operational NPPs, then why bother to prepare for such a *high-impact, low-probability* (HILP) event?

Faced with this dilemma it is, some might suggest, a *Black Swan* event[96] that is beyond normal expectation, being either impossible or extremely difficult to predict, and for which the embedded and generic response processes are unsuited, so much so that planning for such an event is close to impossible.[97]

On one hand, there is sense of the *'Magic Cloth'*[98] in that the possibility of such an event cannot (dare not) exist, so that little or no action has been taken to prevent or mitigate the impacts – this caveat applies in both instances where ASN either completely discount the risk of an *accidental* aircraft crash, or where the responsibility is shunned away from by definition that it is an *Act of War*.[99] On the other hand, ASN recognise aircraft crash to be a *'known but unprepared for'*[100] rare event because precautions have only been made for less severe scenarios (involving smaller and much lighter aircraft). This approach of artificially limiting the scale of and necessary response to the incident, excludes the appropriate degrees of technological and scientific input in framing the mechanics of the incident at the design and

94 Hohmeyer O, Holm-Müller K., Niekisch M., Schreurs M. (2011b): *Pathways towards a 100 % Renewable Electricity System Chapter 10: Executive Summary and Recommendations*, Provisional Translation, Jan 2011, SRU, Berlin

95 For further discussion on this perception of risk see Dorfman, P., & Fucuc, A. (2012): Nuclear Energy Risk Post Fukushima, In: *Late lessons from Early Warnings, European Environment Agency Report*, forthcoming.

96 Taleb N, *The Black Swan,* Allen Lane, 2007

97 Lee B, Preston F, Green G, *Preparing for High-impact, Low-probability Events Lessons from Eyjafjallajökull*, Chatham House January 2012

98 Hans Christian Andersen, *Kejserens nye Klæder (The Emperor's New Clothes)*, Reitzal April 1837

99 It is assumed that planning for Acts of War is within the remit of the recently created *La Direction Générale de la Sécurité civile et de la Gestion des Crises, au cœur des situations d'urgence.*

100 Fukushima Daiichi in March 2011 was a *'known but unprepared for'* event because the response to a less severe tsunami was planned for.

planning stages, rather than, as is present practice, reaching out for such assistance once such an emergency occurs.[101]

PART III FRENCH NUCLEAR POWER PLANTS – VULNERABILITIES TO AIRCRAFT CRASH

The French nuclear industry, including research, development, military and commercial electricity nuclear power plants (NPPs)[102] comprises a total of 150 facilities,[103] including 58 pressurised water reactor (PWR) deployed for commercial electricity generation, together with front- and back-end (chemical separation or reprocessing) fuel facilities.[104] Of the operational reactors,[105] these are located at 19 different sites in groups of two, four and six (FIGURE 14) NPP units. In addition to operational reactors, some NPP sites share or are located close to other nuclear activities. For example, at Flamanville a third PWR Generation III European Pressurised Reactor (EPR) is presently under construction, and at Tricastin the overall site complex includes a nuclear weapons research facility (*Commissariat à l'énergie atomique*), the Comurhex uranium fluoride conversion and the Eurodif uranium enrichments plants.

The presently operational PWR plants are:

TABLE 3 SUMMARY OF THE TYPES AND CHARACTERISTICS OF FRENCH NPPS[106]

NPP SITE	Nº NPP	OUTPUT MW_e	PWR TYPE	START-UP YEAR	3RD 10 YEAR EXT[107]	COMMON CONTROL ROOM	ULTIMATE HEAT SINK	PRIMARY LOOPS	PRIMARY CONTAINMENT STRUCTURE	LEVEL 1 PSA[108]	LEVEL 2 PSA
FESSENHEIM	2	880	CP0	1977-77	✓[109]	✓	RIVER	**3**	RC SINGLE WALL[110]	FIRE	
BUGEY	4	910-880	CP0	1978-79	✓	✓	RIVER	**3**	RC SINGLE WALL	FIRE	
DAMPIERRE	4	890	CPY(CP1)	1980-81	✓	✓	RIVER	**3**	RC SINGLE WALL	FIRE	
GRAVELINES	6	910	CPY(CP1)	1980-85	✓	✓	SEA	**3**	RC SINGLE WALL	FIRE	
CRUAS	4	915	CPY(CP2)	1983-84	✓		RIVER	**3**	RC SINGLE WALL	FIRE	
TRICASTIN	4	915	CPY(CP1)	1980-81	✓	✓	RIVER	**3**	RC SINGLE WALL	FIRE	
BLAYAIS	4	910	CPY(CPI)	1981-83	✓	✓	ESTUARY	**3**	RC SINGLE WALL	FIRE	
SAINT- LAURENT	2	915	CPY(CP2)	1981-81	✓		RIVER	**3**	RC SINGLE WALL	FIRE	
CHINON	4	905	CPY(CP2)	1982-87	✓		RIVER	**3**	RC SINGLE WALL	FIRE	
	34										

101 House of Commons, Science and Technology Committee, *'Scientific Advice and Evidence in Emergencies'*, 3rd Report of Session 2010–11, V1. HMSO 2011

102 French reactor design and technology has developed over the years since the first small, graphite moderated gas-cooled nuclear power plant at Chinon commissioned in 1962, followed by two other relatively small NPPs in 1965 and 1967, and a further five graphite moderated reactors (at Brennilis, Bugey and Marcoule) – all of these early NPPs have been shut down. In 1974 France adopted the *Messmer Plan* and with it the commitment to a rapid expansion of NPPs utilising light water reactor (PWR) plants under licence with Westinghouse. The presently operational PWR plants were all constructed by Framatome (now AREVA), consisting of three variations of electrical output power of 900MW_e, 1,300MW_e and 1,450MW_e (N4) – the 900MW_e series are of Westinghouse design.

103 There were 126 licensed *'basic nuclear installations'* (*installations nucléaires de base* - INB) operating as of December 2010, and an additional 57 INB listed as decommissioned or under ongoing dismantling. In total, operating or closed, there are 173 INB amongst which are the 150 INB facilities subject to the CSAs.

104 *Complementary Safety Assessments (CSA)*, ASN 03 January 2012

105 Only the 58 operational, nuclear power (electricity generating) plants are considered in this review – other nuclear facilities and decommissioned NPPs are not considered.

106 *Cinquième rapport de la France pour la CNS*, July 2010

107 Each NPP undergoes a complete review every ten years (decennial re-examination) by the end of which the ASN decides whether it is fit for pursuing operation and under which conditions. The first 10 years extension comes after 10 years of operation, the second after 20 years of operation and the third after 30 years. Thus, in TABLE 3 all the NPPs that are more than 20 years old have undergone their second decennial re-examination while the others have only undergone the first re-examination. A number of the oldest NPPs (Fessenheim, Tricastin, and Gravelines-1) have recently undergone their third decennial re-examination.

108 PSA – *Probabilistic Safety Assessment* – a purportedly systematic review assessment of the probability of arriving at unacceptable consequences – Level 1 PSAs for events that could result in fuel meltdown and Level 2 for events that could result in a radioactive release (radiological consequences) beyond the primary containment.

109 10 year life extension granted in 2001.

110 Pre-stressed tensile tendon (hoop wires) concrete containment shell, carbon steel inner liner.

Paluel	4	1330	P4	1984-86			sea	4	rc Twin Wall[111]	Fire- SF	SF
Flamanville	2	1330	P4	1985-86			sea	4	rc Twin Wall	Fire- SF	SF
Saint-Alban	2	1335	P4	1985-86			river	4	rc Twin Wall	Fire- SF	SF
	8										
Belleville	2	1310	P'4	1987-88			river	4	rc Twin Wall	Fire- SF	SF
Cattenom	4	1300	P'4	1986-91			river	4	rc Twin Wall	Fire- SF	SF
Nogent	2	1310	P'4	1987-88			river	4	rc Twin Wall	Fire- SF	SF
Penly	2	1330	P'4	1990-92			sea	4	rc Twin Wall	Fire- SF	SF
Golfech	2	1310	P'4	1990-93			river	4	rc Twin Wall	Fire- SF	SF
	12										
Chooz	2	1500	N4	1996-97[112]			river	4	rc Twin Wall	Awaited	Awaited
Civaux	2	1495	N4	1997-99[112]			river	4	rc Twin Wall	Awaited	Awaited
	4										

There are two significant sources of intense radioactivity on a NPP site:

For each nuclear reactor there is the nuclear fuel core in the reactor pressure vessel, this contains upwards of 100t in progressive stages of irradiation (burn-up); and, secondly, the spent fuel pond where depleted fuel removed from the reactor core is placed under water in interim-storage. Depending on the particular fuelling cycle, upwards of 100 or more tonnes of spent fuel might be in storage at any time. Both reactor pressure vessel, and its cooling circuit, and the spent fuel pond are enclosed within their own separate *'containment'* buildings – these two buildings, the reactor *primary* and the spent fuel containments, form much of the *nuclear island* of a NPP site – Figures 15 and 16 respectively show a schematic of the nuclear island of the EPR design and the six nuclear islands installed at Gravelines.

Figure 17 provides a detailed NPP site plant for the UK Sizewell 1,100MW$_e$ NPP,[113] with Figure 17B highlighting the nuclear island containments. Similarly for Sizewell B, Figures 18 and 18B show the primary containment and Figures 19 and 19B the spent fuel pond building. As well as the radioactive sources, respectively these two separate containments also contain ancillary components of the nuclear plant, such as the steam generators, refuelling and maintenance crane, inspection platforms, and in the spent fuel building, an overhead gantry crane and equipment relating to the continuous cooling demand of the spent fuel - Figure 20 shows the internals of a typical spent fuel building at the time that a ~120t spent fuel transportation flask is being loaded into the pool for underwater receipt of spent fuel for transportation away from the NPP site.[114]

Other containments and buildings that either contain radioactive material and/or fulfil a key nuclear safety function (again for example taken from the Sizewell B NPP) include the main control room building (Figure 21), the store holding radioactive waste arisings (solid, liquid and gaseous – only the solid radwaste store shown - Figure 22), and the standby emergency generator units (Figure 23).

Primary Containments: It is generally acknowledged the present primary containment design, together with the specification criteria of function, both for normal and abnormal operation of the nuclear plant, derive from the United States NPP programme, dating back to the 1950s.

In the United States, until 1965, there were no written criteria for design and review of all commercial power reactor licenses was on a case-by-case basis. In 1965, the US *Atomic*

111 Inner shell wall of pre-stressed tensile within, and outer of reinforced concrete – no inner steel liner to either shell.

112 Full power operation delayed until 2000-2002 because of heat removal system problems.

113 In function and general arrangement, the Sizewell B NPP details are not that dissimilar to the French PWR NPPs, details of which are not readily available – for further details see Footnote 118.

114 The spent fuel is loaded into transportation flasks from above in the CPO, CPY and P4 NPPs and from below in the P'4 and N$ NPPs.

Energy Commission (AEC) first specified the regulations[115] promulgated by the *Nuclear Regulatory Commission* (NRC) to provide for the licensing of NPPs The first five criteria of these regulations define overall requirements for quality assurance and protection against natural phenomena, fire, environmental and dynamic effects (including loss of coolant accidents), and sharing of systems, structures and components. Specifically relating to the primary containment, *Criterion 16* stated

> *". . . Reactor containment and associated systems shall be provided to establish an essentially leak-tight barrier against the uncontrolled release of radioactivity to the environment and to assure that the containment design conditions important to safety are not exceeded for as long as postulated accident conditions require. . ."*

In fact, the only external challenge to the primary containment is in the form of the outer surfaces of the containment being resilient against tornado-generated missiles with aircraft crash being completely omitted.[116]

As previously noted, regulations relating to the resilience of NPP structures to aircraft crash were not introduced in France until 1980,[54] although these were and remain restricted to aircraft of all-up weight of less than 5.7 tonnes.

TABLE 3 (Col 10) outlines the primary containment structure for each of the present operational NPPs in France. Of the three series types of PWR, the $900MW_e$ (34 units in total) primary containment comprises a single pre-stressed shell with a carbon steel plate internal liner to enhance internal gas-tightness (FIGURE 17). For the $1,300MW_e$ series (20 in total), the primary containment is double shelled, with the outer shell of reinforced concrete and the inner being of unlined, prestressed concrete. In the absence of a steel liner, through-shell leakage being collected in the annular space of the double walled containment. Details of the N4 ($1,400MW_e$) PWRs (4 in total) primary containment are not readily available, although it is believed that these containments are double shelled similar to the $1,300MW_e$ series.

Main dimensions of the primary containment structures are:

115 General Design Criteria, Appendix A of 10 CFR 50 (10 CFR Part 50), 1965 DRAFT

116 Containment *Integrity Research at Sandia National Laboratories – Overview*, Sandia National Laboratories, NUREG/CR-6906 SABD2006-227P, July 2006

TABLE 4 FRENCH PWR PRIMARY CONTAINMENT DIMENSIONS[117]

	PWR 900MW$_e$ m	PWR 1300MW$_e$ m	PWR SIZEWELL B[118] m
PRIMARY CONTAINMENT TYPE	SINGLE	DOUBLE	SINGLE
INNER RADIUS	18.50	22.50	22.86
GROUND RAFT THICKNESS	3.50	3.00	~3.5
DOME TOTAL HEIGHT	60.35	65.95	~72.00 includes secondary cap +8.00m
CONTAINMENT SHELL THICKNESS CYLINDER	0.90	0.9	1.25
CONTAINMENT SHELL THICKNESS DOME	0.80	0.95	1.00
INTERNAL STEEL LINER THICKNESS	~6mm	NONE	~6mm

Rates of materials and structural degradation for concrete structures, although age-related, are relatively leisurely in development. Degradation for concrete is shrink and carbonation (micro cracking),[119] and for the pre-tensioned steel wires making up the tendon wrap of the prestressed shells, creep particularly in combination with concrete shrinkage, is the degradation factor. Other deleterious effects for concrete, such as alkali aggregate and/or high alumina have not been reported extant on any of the primary containment installations. In some US plants the history of defects has been reported,[120,121] although the data is somewhat limited the main emphasis has been on corrosion of the ungrouted post tensioning steel wires in the primary containment, and a number of wire failures have been recoded, and since 1986 there have been 32 reported occurrences of corrosion of steel containments or liners of rc containments in US NPPs.[122]

French NPPs have been subject to, starting in 1985, the so-called *'Lifetime Project'* which includes a specific topic study group *'ageing of materials'*[123] and this has revealed corrosion problems with the inner steel liner of throughout the 900MW$_e$ series primary containment at two localities of the containment shell; at two NPPs, the prestress levels of the tendons show larger than expected losses in the prestress tension, probably due higher than anticipated concrete shrinkage over time;[124] and, somewhat intriguingly, when reviewing the long-term

117 Costaz J, Rouseelle H, Picaut J, Chataigner J, *Delayed Phenomena Analysis from French PWR 900 MW Containment Monitoring Comparison with Unforeseen Design Values*, undated. Other sources (*Post-Fukushima Nuclear Safety in France: Analysis of the Complementary Safety Assessments (CSAs)*, Makhijand A, Marignac Y, 2 March 2012) give the thickness of the containment shell cylinder and dome of N4 NPPs to be respectively 1.20 m and 0.82 m (for overall dimensions roughly identical to 1,300 MWe P4 and P'4 reactors), with the thickness of the outer shell of N4 NPPs being 0.55m for the cylinder and 0.40 m for the dome, with a 2m annular void.

118 The UK PWR at Sizewell B is included here for comparison since all of the figures showing the structural details of NPP containments are taken from fully detailed engineering plans of Sizewell B (FIGURES 17, 18, 19, 21, 22 and 23) – similar detailed plans of any of the French series of NPP are not available. Sizewell B is a single PWR nuclear plant of ~1,200MWe based on a 4-loop Westinghouse SNUPPS (Standard Nuclear Unit Power Plant System) constructed from 1987 through to 1995, although the civil engineering structural design dates from earlier being not untypical of PWR NPPs of the mid-1970s – the primary containment is not SNUPPS but a one-off, single prestressed, single shell, steel lined cylinder with the dome section provided with a secondary (non-structural) enclosure.

119 Carbonation occurs in concrete because the calcium bearing phases present are attacked by carbon dioxide of the air and converted to calcium carbonate, which lowers the pH and renders near surface steel reinforcement susceptible to corrosion, expansion and cracking of the concrete cover. The rate of carbonation depends on porosity and moisture content of the concrete, it is well understood and is usually tolerable over the design lifetime of an rc structure.

120 Naus D, Oland C, Ellingwood B, *Report on Aging of Nuclear Power Plant Reinforced Concrete Structures*, NUREG/CR-6424 US Nuclear Regulatory Commission, March 1996.

121 Naus D, Oland C, Ellingwood B, Chokshi N, Cherrt J, *Nuclear Power Plant Containment Pressure Boundary Aging Research*, ORNL/CP-102337, May 1999

122 Naus D, Graves H, *Detection of Aging in Nuclear Power Plant Structures*, NRC Research, undated c2000.

123 IAEA, *Assessment and management of ageing of major nuclear power plant components important to safety: Concrete containment building*, IAEA-TECDOC-1025, June 1998

124 Since the majority of the 900MWe series utilise grouted tensioning, the tensile losses cannot be made up by post-tensioning.

operation and lifetime extensions of the 900MW$_e$ series, the *Institut de Radioprotection et de Sûreté Nucléaire* (IRSN) noted, when referring to the *Structures, Systems and Components* (SSC) programme then underway for life extensions of the 900MW$_e$ series NPPs:[125]

*". . . The results of this work lead to identify 12 sensitive components including two among non replaceable components (reactor pressure vessel and **reactor building containment**) for 900 MW$_e$ NPPs. For each sensitive component, a detailed report has been prepared in agreement with French regulation . . ."*

*my added **emphasis***

although the *'detailed report'* referred to does not seem to be a publicly available document, nor are the particular NPPs affected identified.

Also, for the 900MW$_e$ series, the maximum pressure capability is above the extreme accident level, although this is achieved by taking into consideration augmentation by the internal steel liner; however its original design intent did not, it is believed, assume this role. The penetration equipment hatch has been identified as a relatively weak structure for which a modification and strengthening programme for all 900MW$_e$ series NPPs is currently underway.

For the double-shelled Generation II PWR primary containments (1,300MW$_e$), the design internal pressure for the outer shell is believed to be about 5 bar (abs) which is above the equivalent static pressure loading from an extreme, but nevertheless credible accident. The inner shell, not fitted with an internal steel liner, is believed to be pressure rated below 5 bar (abs) and this weakness is presently subject to review, with some augmentation of the function expected to be implemented before 2014.[126] Extensive micro-cracking of concrete shells of the 1,300MW$_e$ and N4 NPPs has been reported.[127]

The radiological consequences of a breached primary containment depend on the operational and containment state of the reactor circuit within. For example:

i) **Operational and Intact Reactor Plant:** If the nuclear plant was operational at the time of the aircraft crash, the impulse loading to the overall structure should initiate the seismic SCRAM system,[128] thereby immediately closing the nuclear activity down but with the reactor vessel and its cooling circuit remaining intact.[129] There

125 Quentin P, Couturier J, *IRSN point of view on plant long term operation assessment*, IRSN, undated c 2010

126 Raimond e, et al, *Continued efforts to improve the robustness of the French Gen II PWRs with respect to the risks of severe accidents. Safety assessment and research activities*, Eurosafe, IRSN 2011

127 *Post-Fukushima Nuclear Safety in France: Analysis of the Complementary Safety Assessments (CSAs)*, Makhijand A, Marignac Y, 2 March 2012

128 The remains some ambiguity about the extent of autonomy of the seismic sensitive SCRAM systems, particularly with ASN suggesting not *". . . problems with operator interpretation of the measurements taken by this instrumentation, and a lack of clarity in the reactor shutdown procedures. These deviations can delay reactor shutdown as specified in RFS I.3.b, or could even lead to this decision not being taken."*. Indeed, this may be a generic shortfall of NPPs installed in relatively low-seismic activity areas, for example for its *Stress Tests* appraisal, the UK ONR state that *". . . 331 Sizewell B reactor does not have automatic seismic shutdown systems. If the reactor does not shut down automatically in response to a normal trip signal, the operator is required to do so in response to a signal from the seismic monitoring system"* and automatic seismic SCRAM of the reactor is subject to much NRC discussion – see NUREG/CR-2513 UCRL-53037, O'Connell W, Wells J, *On the Advisability of an Automatic Seismic Scram*, Lawrence Livermore National Laboratory, December 1981.

129 The use of and dependence upon a seismic initiated reactor SCRAM for French NPPs is not known. The advantages of an automatic seismic SCRAM, sometimes set at 0.6 to 0.9 of the SSE level, is that the reactor shutdown gains a few seconds over a turbine (usually excessive vibration also induced seismically) and other initiated SCRAM or trip, so seismic initiated

would occur an immediate release of the containment atmosphere, mainly short-lived radioactive argon and nitrogen, and emission of gamma shine from any exposed parts of the reactor pressure vessel – gamma shine from a badly damaged containment could inhibit near proximity working by emergency personnel.

ii) Recently Operational but Damaged Reactor Plant: If, like i) above, the nuclear plant was operational at the time of impact, but the impact damaged or caused a key nuclear safety system to malfunction then, if the incident led to post-impact LOCA and fuel melt, the radioactive release through the breached containment and corresponding off-site radiological consequences could be severe indeed.[2]

iii) Shut Down Reactor Plant undergoing Refuelling – Reactor Pit Flooded: If the impact and penetration of the aircraft and/or building/equipment generated projectiles damaged the reactor pit and/or fuel transfer path to the spent fuel pond, then the loss of water could result in exposure of recently discharged nuclear fuel, temperature rise, hydrogen liberation and fire/deflagration/explosion and the accompanying significant radioactive release and off-site radiological consequences.

Similarly, loss of cooling to the water remaining inside the reactor pressure vessel, but with some natural convective circulation from the primary circuit, would, depending on the state of the fuel in the reactor core (ie the refuel cycle), take about 12 to 20 hours by evaporation and boiling to uncover the fuel core, shortly after which there is risk of triggering a zirconium-steam reaction and exothermic hydrogen liberation.

Other NPP Containments: Of the other, many containment structures located on a NPP site, the spent fuel building is the most radiologically significant.

The spent fuel discharged from the reactor core is stored under water in the pond for at least two to three years following its unloading from the reactor core. This time period of natural radioactive (and heat emission) decay is at the gain in the reduction of certain shorter-lived radionuclides, particularly the highly volatile radio-iodine-131, before transportation to the fuel chemical separation (reprocessing) facility at la Hague.[130] Also stored in the pond are activated metal components removed from the reactor core and pressure vessel, burnt-out control rods and, albeit normally small and bottled, quantities of fuel that has been damaged in the reactor core. At certain times of the reactor maintenance cycle, the entire reactor core fuel, about 100 tonnes[+], is temporarily transferred and held in the pond whilst reactor pressure vessel inspection/repairs are underway.

Structural details of the spent fuel pond buildings are not readily available, although these would not be expected to depart that significantly from the available details of the UK

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shutdown allows the residual heat decay of the reactor fuel core a few more seconds (about 50% of the stored heat in the fuel core is dissipated within 5 to 10 seconds), thereby reducing the load and thermal shock on the residual heat dissipation systems. On the other hand, a seismic SCRAM may also trip out connection to off-site electricity supplies which could lead to difficulties for multi-NPP nuclear sites.

130 As at the end of 2010, about 17,000 tons of spent fuel was in storage, most of it spent low-enriched uranium fuel but also including 1,700 tons of MOX – this spent fuel is dispersed over the 58 operational NPPs including the spent fuel transported off-site and in store at the COGEMA facility at la Hague awaiting reprocessing. In addition there were about 4,500 tons of low-enriched uranium fuel in the cores of the 58 light water reactors (LWRs), 290 tons of MOX fuel in the cores of 20 of those same LWRs, 80 tons of reprocessed and re-enriched uranium fuel in the cores of the four 900-MW LWRs at Cruas. France discharges annually about 1,200 tons of spent fuel from its LWR fleet, including MOX fuel that will increase to 100 – 120 tons starting in 2012 – breakdown of the spent fuel in interim storage at each operational reactor is not readily available although the 12 to 18 month fuel cycle and a 2 to 3 years dwell time in the pond for the operational reactors suggests a minimum spent fuel storage tonnage at each NPP to be between 150 to 200 tonnes at any one time.

Sizewell B PWR spent pool. ASN describe the spent fuel building structure for all NPPs, including the yet to be commissioned EPR, to comprise a metal clad roof and relatively thin rc walls of less than 300mm thickness.[131]

The radiological consequences of a breached spent fuel building containment depend on the severity of the breach and, particularly, the continuing surety of the water pond. For example:

- **iv) Building Breached but Pool Water Level Maintained:** If the building was penetrated it is possible that the fuel pond water cooling circuits would be rendered inoperable, in which case unless alternate means of cooling could be jury rigged, the pond water levels would lower by evaporation and, eventually boiling and, similar to Case iii) above, there is risk of hydrogen liberation. With the pool remaining intact but without cooling, evaporation and boil down times to fuel exposure, again depending on the radioactive decay state of the fuel, will be a matter of a few days. If, in addition to an average spent fuel inventory, the fuel storage pond had recently received a fresh fuel core removed from the reactor to facilitate inspection and/or maintenance of the reactor internals, then pond boil down time could be a matter of hours.
- **v) Building Breached and Pool Water Drained:** In this situation and without emergency cooling being jury rigged into the pool (ie the pool may be so severely damaged that it could not retain any water) then time to exothermic hydrogen liberation could be very short, say an hour or so. Radiation levels within the immediate area of the spent fuel building would be intolerable for any human activity (>100Sv/h)[132]

There are number of independent studies and assessments relating to spent fuel pool drain-down situations, including aircraft crash scenarios, all of which forecast significant radioactive release off-site.[133] In fact, ASN acknowledges the challenges of post-event recovery of loss of cooling of the spent fuel pond *'. . . given the difficulty or even the impossibility of deploying effective means of mitigating the consequences of prolonged exposure of the fuel assemblies'*, requiring in the CSA assessments that EDF further *'. . define and implement tightened measures to prevent the fuel assembly exposure'*.

Both elements of this structure would not be resilient against a crashing aircraft and any breach in the containment would enable gamma shine from the uncovering spent fuel assemblies and release of radioactive particulate matter should the fuel and its cladding become overheated (~1,000^{o}C) and damaged.

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131 The design of the spent fuel building (of all French NPPs) is not suited to contain the pressure rise emanating from the pool if the pool water should boil and, at elevated temperatures the hydrogen deflagration should the Zircaloy-steam reaction occur in the coolant emptied (boiled away) pond.

132 *Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants*, p. A1A-1

133 For example i) US Nuclear Regulatory Commission, *Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants* NRC, NUREG-1738, 2001, ii) Robert Alvarez, Jan Beyea, Klaus Janberg, Jungmin Kang, Ed Lyman, Allison Macfarlane, Gordon Thompson, and Frank von Hippel, *Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States*, Science & Global Security, vol.11, no.1, 2003. Iii) V.L. Sailor, K.R. Perkins, J.R. Weeks, and H.R. Connell, *Severe Accidents in Spent Fuel Pools in Support of Generic Safety*, Brookhaven National Laboratory, NUREG/CR-4982; BNL-NUREG-52093, 1987

For the Generation III NPPs, essentially the EPR, ASN and other regulators[134] have considered and, to some extent, augmented the design-basis requirements with the recognition that protection against *'external hazards'* shall include for '. . *notably earthquakes, airplane crashes and explosions* . . .*'* and that

> ". . .
>
> *Protection of the safety systems has to be considered with regard to the* ***direct impact (penetration)*** *as well as to the indirect impact by induced vibrations.. . ."*
>
> *my added* ***emphasis***

The structural response of the primary containment shells is expected to comply with the ultimate limit state of Eurocode 2 (Part 1)[135] for equivalent static structural loading and, for withstanding an external explosion (such as an aviation fuel-air detonation) a maximum overpressure of 100mbar for a duration of 300 milliseconds, and up to a maximum peak of 200mbar in account of blast wave reflection. This explosive blast overpressure limit in significantly below the (unmeasured) overpressure generated at Lockerbie which, by observation of the damage,[136] probably exceeded 400 to 600mbar.

In summary: Existing single and double shell primary containment buildings are, by virtue of the internal pressure containment and radiation shielding functions, robust structures. Direct impact from a commercial-sized airliner would be unlikely to topple the entire structure, either by dynamic impact or aviation fuel-air detonation blast overpressure, but previous studies have shown such mass concrete structures to be vulnerable to localised through rupture, backface spalling, and penetration by detached, *'hardened'* parts of the crashing airframe. The rigidity of the single shell containments, may result in high levels of induced loading and displacement of equipment within the containment, such as toppling of the heavy, overhead gantry cranes used for refuelling and maintenance which, in themselves, have considerable potential to damage nuclear safety equipment and the primary coolant circuit.

The spent fuel building containments, for each of the 58 French NPPs and the yet to be commissioned EPR at Flamanville, are vulnerable to aircraft crash. Application of aircraft crash global forces is likely to generate structural collapse of the building. Aviation fuel-air detonation, as at Lockerbie, could be structurally catastrophic, and combined the imparted forces, overpressure and fire environments would likely overcome all of the *Defence in Depth* layers relied upon.

The vulnerability of the various containments and essential services of the operational NPPs in France is summarised as follows:

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134 See the Franco-German plenary meetings of 19 and 26 October 2000 involving the French *Groupe Permanent chargé des Réacteurs nucléaires* (GPR), *Technical Guidelines for the Design and Construction of the Next Generation of Nuclear Power Plants with Pressurized Water Reactors*, October 2000 – for origin of the Codes of Practice adopted see *Gemeinsame Empfehlungen von RSK und GPR für Sicherheitsanforderungen an zukünftige Kernkraftwerke mit Druckwasserreaktor*, 1994)

135 Eurocode 2, as amended – the definition of ultimate limit state in Eurocode 2, Pt 1, is *". . associated with collapse or with other forms of structural failure which may endanger the safety of people"*.

136 Montgomery, Ward, *Facility Damage and Personal Injury from Explosive Blast*, 1993

TABLE 5 SUMMARY OF NPP CONTAINMENT/SITE VULNERABILITY TO AIRCRAFT CRASH

	RADIOLOGICAL CONTAINMENT			ESSENTIAL SERVICES		
CRASH MODALITY	PRIMARY (mainly 900MW$_e$ Series)	SPENT FUEL (all operating Series)	RADWASTE FIGURE 22	GENERATOR FIGURE 23	CONTROL ROOM FIGURE 21	EMBANKMENTS insufficient detail
IMPACT	localised through rupture	partial or complete demolition	partial or complete demolition	partial or complete demolition	partial or complete demolition	partial or complete demolition
IMPULSE	in-wall fracturing and spalling – induced damage to affixed equipment	spalled concrete projectiles – risk of crane and overhead equipment collapse into pool	spalled concrete projectiles – risk of crane and overhead equipment collapse	switchgear vulnerable local equipment failure	local equipment failure	unlikely
PROJECTILE	penetration at low level of containment, equipment and entry hatches vulnerable	penetration at all levels and, particularly, roof	penetration at all levels	penetration at all levels	local equipment failure penetration at all levels	unlikely
AVIATION FUEL FIRE	unlikely to affect if external but in double shell containments fire in annular void could be compromising	render pond cooling systems inoperative, structural beam degradation	could breach local containment and shielding (ie drums and overpacks) – spent resin ignition	diesel day tank contents adds to total flammables	main control room would have to be evacuated and emergency, standby control room manned – high ventilation fire rating	fire unlikely to persist
AVIATION FUEL-AIR DETONATION	1300/N4 fuel-air vapour in inter-shell annulus	all operating reactor types - partial or complete demolition	partial or complete demolition	partial or complete demolition	partial or complete demolition	could result in serious channel embankment destruction and loss of condenser inlet/outlet stream
POSSIBLE EXTREME OVERALL OUTCOME	primary containment severely breached LOCA incident triggered and corresponding severe radiological situation in public domain	containment breached and pond drained – fuel clad to ignition temperature, exothermic hydrogen liberation and detonation within hours and corresponding severe radiological situation in public domain	loss of local containment, destruction of building leads to significant off-site radiological situation	most NPPs have generators located at different localities but main switchgear could be sensitive – leads to complete SBO if off-site electrical supplies also isolated	on-site personnel incapacitated, loss of crucial for post-incident mitigation response	flooding of nuclear island or loss of condenser cooling – with simultaneous denial of auxiliary shutdown cooling could lead to reactor core fuel melt situation

ASN Complementary Safety Assessments (CSAs)

In addition to the PSAs that are undertaken periodically (every 10 years), ASN has recently required the operator EDF to undertake further assessments introducing a requirement for the *Complementary Safety Studies* (CSAs), first introduced and undertaken during 2011.[137]

In scope, the CSAs applied to all French nuclear facilities, including the 58[138] NPPs to be examined, particularly, for the integrity of the reactor primary containment and resilience of the spent fuel storage ponds for the following initiating events that exceeded the *baseline safety requirement*:[139,140]

137 Resolution N°. 2011-DC-2013 ASN. 4 May, 2011

138 Also includes the EPR under construction at Flamanville – this Generation III NPP has not been considered in any great detail in this Review.

139 These extraordinary triggering events, including accidental and malevolent aircraft crash, are not at all considered in the comprehensive Institut de Radioprotection de Surete Nucleaire (ISRN) and the French Atomic Energy Commission (CEA) report *Research and Development with regard to Severe Accidents in Pressurised Water Reactors*, Rapport IRSN-2007/83, 2007.

140 Sometimes this post-safety case reassessment is referred to as *'Fragility Analysis'* or *'Safety-Margin Analysis'*, being essentially a technique for assessing the capability of a structural system to withstand specified (sometimes referred to as *screening* or *review-level*) events in excess of the *design-basis* event. For example, here ASN are using the CSAs to determine the capability of NPP structural components and systems to withstand *review-level* earthquakes of a prescribed

- Earthquake
- Flooding
- Other Extreme Natural Events (not further defined)

As previously noted, under the general and ill-defined category of *'other extreme natural events'*, ASN has chosen to dismiss the occurrence of commercial-sized airliner crash[141,142] on the basis of, for accidental air crash:

i) its projected infrequency of occurrence (ie not a *credible* event);

and, quite separately and adopting an entirely different rationale, for malevolent or terrorist driven attacks on the basis that such are

ii) Acts of War and thus beyond the *Design-Basis*.

However, ASN acknowledge that it has set the requirement for EDF to assess aspects of aircraft crash (assumed to be of commercial-sized aircraft), although nothing of the requirement or outcome of this EDF assessment has been made publicly available.[143]

Aircraft crash, either accidental or resulting from a malevolent act, is in fact one of the possible causes (equipment failure, natural hazard, human activities) of a loss of electrical power and/or cooling which could lead to a severe off-site radiological situation (nuclear accident). Moreover, although ASN claim that the loss of electrical power and cooling, regardless of the cause, are specifically covered by the CSAs it declines to identify any fault scenarios that could arise from a commercial-sized airliner crash.

However, a gauge of aircraft crash resilience of the three basic NPP types of TABLE 4 can be extracted from the published outcomes (although scant in detail) of the CSAs. For these, ASN identifies topics and areas *'in which safety could be improved'*,[104] some which mirror a cross-linkage to the outcome of an aircraft crash. This is because equipment which is required to function during abnormal external events has to be qualified for the range of parameters assumed to occur during such events – the loading environment accompanying a commercial-sized airliner crash share features of the loading profiles assumed for external events that have been reassessed by the CSAs.

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magnitude in excess of the safe-shutdown earthquake. If the system can be shown by such an analysis to perform safely to this excessive seismic event, it might be judged sufficient for public safety regardless of what the actual (unknown) hazard might be – in this way the CSA topic (ie review level earthquake) might be used as a benchmark for and crosslinked to aircraft crash.

141 A search of the ASN Annual Reports dealing with Radiological Emergencies and the exercises conducted annually does not reveal any exercises that simulate the potential scale of disruption and devastation resulting from a commercial-sized airliner crash onto a NPP. For example see ASN Annual Report 2008, although the search should not be considered to be exhaustive.

142 The French regulatory framework for radiological protection implements European Directives 96/29 and 97/43 and is centred around five decrees with the intervention in radiological emergency situations by local and emergency plans Décret N° 2003-295 31 March 2003 *relatif aux interventions en situation d'urgence radiologique et en cas d'exposition durable et modifiant le code de la santé publique;* the implementation of local and emergency plans Décret n°88-622 6 May 1988 *modifié relatif aux plans d'urgence pris en application de la loi n°87- 565 du 22 juillet 1987 relative à l'organisation de la sécurité civile, à la protection de la forêt en cas d'incendie et à la prévention des risques majeurs.*

143 At this time EDF is assessing the behaviour for channel embankments and reservoirs to a number of external hazards, including aircraft crash – see 11.1.1 of Footnote 104.

For example, in the event of an earthquake certain seismically unqualified equipment might become detached and fall onto key nuclear safety equipment disrupting the safety function. The likelihood is that the same (or similar) equipment might fail when subject to the extreme forces generated by the impact or ensuing aviation fuel detonation of an aircraft crash.

The following further examples taken from the CSAs, illustrate deficiencies, shortcomings and failings that have been determined by ASN/EDF themselves in their analysis of the triggering events of earthquake, flooding and post-incident management in the aftermath of a severely damaging external event:

TABLE 6 CSA TOPIC: 10 EARTHQUAKE **SEISMIC RISK TRIGGERED EVENTS AIRCRAFT CRASH MIRRORED EVENTS**

ASN REQUIREMENT	AIRCRAFT CRASH CROSSOVER	APPLIES TO NPPS
Fire Protection: Basic safety function equipment is fire protected in the event of an earthquake – main measures against fire are not at all designed to withstand the baseline safety requirement of the SSE threshold.	Forces and excitation response of the building structure and equipment within during aircraft impact not dissimilar to earthquake transient loadings, fire risk introduced by free projectiles and presence of aviation fuel and external ignition sources	Probably all NPP types
Ground/Retention Works: Seismic robustness of dykes and other structures, bunds, etc., installed to protect facilities against flooding and to prevent the consequences of failure of these structures resulting in a loss of site ultimate heat-sink (emergency situation H1).	Direct impact by aircraft could damage or destroy flood containment structures and long-term loss of ultimate heat sink and, separately, deflagration to detonation transition of aviation fuel-air could scoop out/undermine structures (as say Lockerbie)	Probably all NPPs but expecially Tricastin, Fessenheim and Bugey sites, including the heat sinks and (condenser) intake channels, pumping station and network
Indirect Effects of Earthquake: In addition to the *design-basis* earthquake resistance equipment and structures, the assurance against direct mechanical damage or forming projectiles of systems, structures and containments (SSCs) forming hazards to separate seismically qualified equipment, etc – the knock-on effect of non-qualified components, etc.,[144] has not been fully considered.	The creating of localised failure and formation of projectiles of affected equipment, etc., apart from projectiles emanating from the disintegrating airframe, could develop into *independent* hazards such as fire.	All NPP sites – ASN identify the need for a two part approach to remedying the present unsatisfactory situation: Local and National
Loss of Emergency Generators: The total loss of electrical supplies, on- and off-site (emergency situation H3), although included in the base-line safety case on the proviso that switchboards can be restored and electricity supplies backed up from alternative generators on site. The CSA identifies a number of specific plants at risk of dam and/or channel retention embankment/wall failure.	The impact of an aircraft crash across the site area could be widespread (see Lockerbie), quite possibly introducing a common mode failure of key safety equipment (here on-site emergency generators and switchboards and loss of external off-site electricity supplies).	At all NPP sites there is the capability to cross connect generators from one unit to another but the smaller sites comprising 2 NPP may not have sufficient reserve redundancy to overcome a widespread common mode failure caused by aircraft crash
Hydrogen Presence Detectors: Hydrogen detectors, hydrogen carrying pipes and shut-off valves etc., located outside the reactor containment building do not meet the Safe Shutdown	SSE levels for all reactor types are relatively low (typically 100 to 200gal compared to ~550gal for Fukushima Daiichi NPPs. Main common cause failure at Fukushima Daiichi was hydrogen deflagration/explosion and, for	In progress on the N4 series (2 NPPs) and delayed for completion for the $900MW_e$ and $1{,}300MW_e$ NPPs in 2019 and 2023 respectively.

144 ASN identifies these items to include potential hazards identified in particular includes the structures and items (weighing more than 10 kg) not designed to withstand an earthquake (unfixed loads, handling machinery not tied down, cabinets, fans, civil engineering structures, tanks, large equipment on small piping, equipment running through the premises, false ceilings, piping with a diameter larger than 50 mm, etc.).

Earthquake (SSE) requirement.	Unit 4 cross seepage of hydrogen from Unit 3 via the common hydrogen venting systems.	
Station Black Out: ASN require a Seismic Margin Assessment to be undertaken to study the robustness of the facility to an earthquake greater than the design-basis earthquake. Deficiencies (lack of seismic robustness) were identified in the reactor cavity (PTR) and spent fuel cooling and treatment system; the demineralised water systems (SER); and the valves of the circulating water system (CFR).	These are critical components and functions in maintaining the reactor fuel core cooled (eg the PTR acts as a tank for the safety injection system into the reactor cooling circuit). Although the EDF reporting related to the seismic margins, these in themselves are a good indication of robustness of the various components and systems when subject to impact and blast loading, particularly in that EDF's approach was considered to required to be '*taken further and in greater detail'*.	All NPP sites.
Flooding from Site Stored Water: The release of the total volume of all water held in tanks onto the nuclear island platform exceeded the flooding levels for which a number of the NPP sites were designed	It may be that aircraft crash could have much the same effect in uncoupling pipes, rupturing tanks etc., to cause excessive flooding of the nuclear island platform.	Several but unidentified NPPs and, in addition, Gravelines the retaining walls forming the condenser intake channel (the ultimate heat sink) are required to remain intact to maintain cooling.

TABLE 7 CSA TOPIC: 11 FLOODING[145] **FLOOD RISK TRIGGERED EVENTS AIRCRAFT CRASH MIRRORED EVENTS**

ASN REQUIREMENT	AIRCRAFT CRASH CROSSOVER	APPLIES TO NPPS
Water Retention Structures: Damage to structures upstream/downstream of the nuclear island such as channel embankments, reservoirs, dams, tanks, etc. as well as damage to systems or equipment, such as pumping stations, the circulating water intake and discharge channel and the circulating water system (CRF) which could lead to the presence of large volumes of water on the site platforms. A general and widespread failure and total collapse of an embankment is recognised as a possible failure mode developing from a localised breach.	Direct impact (possibly specific terrorist targeting) of dam/channel structures resulting in collapse (see Lockerbie earthworks disruption and crater), including from dam bust or collapse (REB) with a number of nuclear islands offering no height defence against flooding. Flooding of the nuclear island and general site could disrupt key nuclear safety services and equipment, such as emergency diesel generators, switchgear and could render the nuclear island inaccessible to emergency services and key nuclear safety personnel. The potential consequences of the canal embankments feeding both Tricastin and Fessenheim[146] have come under particular scrutiny: Tricastin NPP flooding is reliant upon	Tricastin should account for failure of the Vouglans dam when the headstock water levels are higher than the 50% assumed by. EDF. The following NPPs are identified to be at risk of dam or channel failure (REB): i) Bugey ii) Civaux iii) Cruas iv) Nogent v) St Alban vi) Fessenheim Certain other NPP sites rely upon

145 In a flood situation, equipment able to guarantee the safety of the reactors must remain operational, so the necessary protective devices must remain functional and engage, whenever necessary, to safeguard against the various unforeseen circumstances that could lead to flooding or to maintain essential functions whilst and should the plant become flooded. This protection is based on several lines of defence (embankments, walls, water drainage networks, etc.), including volumetric protection which encompasses the buildings containing equipment able to guarantee reactor safety.

146 The National Association of Local Information Committees (CLI) reviewed the reports submitted on Fessenheim by EDF and the Fessenheim CLI submitted a study on the risk of flooding at Fessenheim in June 2011 – this latter report does not seem to be publicly accessible.

At this time, for the channel embankments and reservoirs, EDF is studying their behaviour in response to the following hazards: earthquake, airplane crash and off-site hydrocarbon explosion.	the sluice gates and watertight screen for final protection and is considered not to be immune from severe flooding. At Fessenheim, the consequences of a failure of the Grand Canal d'Alsace embankments would be the presence of a layer of water on the site, liable to lead to a scenario involving total loss of the off-site and onsite power supplies, as well as the potential loss of other nuclear island equipment.	elevated walls and embankments for flood protection,[147] and, of these, Cruas and Tricastin could remain isolated in the event of a flood. Also, the flood risk of the previously flooded NPP at Le Blayais is currently under review by ASN and L'Institut de Radioprotection et de Sûreté Nucléaire (IRSN). Due for completion in May 2012
Damage to and Flooding from Water Cooling Tower: The inland NPP sites supplement the ultimate cooling sink with water cooling towers which are contained, at ground level, by raised bunds or walls.	Aircraft crash onto a single water cooling tower could promote single or multiple collapse of adjacent towers (see Ferrybridge 1965).[148] Localised flooding could affect the operation of the on site emergency generators which ASN consider vulnerable to flooding.	This most likely applies to all inland NPP sites with cooling towers – presently EDF have in hand a complementary safety assessment report (RECS) due for submission to ASN by the close of 2012.

TABLE 8 CSA TOPIC: 13 STATION BLACK OUT LOSS OF ELECTRICAL SUPPLIES H3 AND CORE COOLING AIRCRAFT CRASH MIRRORED EVENTS

ASN REQUIREMENT	AIRCRAFT CRASH CROSSOVER	APPLIES TO NPPS
Reactor Fuel Core and Spent Fuel Pond Cooling: In the event of a loss of off-site electrical power supplies and on-site conventional supplies, core make-up (cooling) water is taken, first from the spent fuel pond, and then make-up is from the reactor cavity and spent fuel pond cooling tank (PTR) – in the absence of further external intervention, the 900MW$_e$ series of NPPs the core fuel will become exposed more than a day from the onset of the incident; and for the N4 and 1300MW$_e$ series NPPs the core fuel will become exposed several days after the start of he incident. For the spent fuel pond, make-up water	Maintaining the reactor core and spent fuel cool seems to depend on continuing supplies for the station blackout (SBO) generator sets if necessary poached from a neighbouring NPP. If, however, the SBO sets are disabled and, in addition, the single. ultimate backup diesel-generator set (GUS – 900MW$_e$) or combustion turbine (TAC - 1300 MW$_e$ and N4 series) per site is also disabled by widespread damage of an aircraft crash, the fuel protection times are shortened to few hours (less than 10 hours) for all (900MW$_e$), several days for the 1300MW$_e$ and N4 series, and just a few hours (unspecified) for the EPR series of NPPs.[149] For the 900MW$_e$ and 1300MW$_e$/N4 NPPs the core exposure to melt times are shorter than the	All 900MW$_e$ series NPPs critically at risk of fuel meltdown within a few (unspecified) hours from the onset of the incident. Particularly for the 900MW$_e$ NPPs, ASN are to require EDF to install an *ultimate backup* diesel generator set (DUS), together with smaller emergency generator sets, for use in the event of a SBO total loss situation – this ASN requirement is yet to be issued. ASN has announced that it considered the present time lapses before core exposure to be too

147 **TABLE F1 DEPENDENCY NPP SITES ON EMBANKMENTS AND OTHER ELEVATED STRUCTURES FOR FLOOD PROTECTION**

	EXISTING PROTECTION	COMMENTS
BLAYAIS	Embankments	
BELLEVILLE	Peripheral embankments	
BUGEY	Protective embankments and walls	
CHINON	Flood gates (cofferdams)	
CRUAS	Banks of the Rhone + Northern periphery wall	Peripheral protection works required
DAMPIERRE	East and South protection embankments	
FESSENHEIM	Bank and Embankment	
SAINT ALBAN	North and East wall	
TRICASTIN	Stream protections and Donzère canal embankments	Peripheral protection works required

148 The progressive and interlinked collapse of 3 cooling towers (of 8) at the Ferrybridge (UK) coal fired power station on 1 November 1965 – the collapse was triggered by vortex shedding of the windward leading towers, resulting in excessive vibration and collapse of the leeward towers.

149 Why there is so much variance in the fuel protection time is not at all explained in the ASN documentation.

is drawn from fire-fighting reserves and/or pumps of the neighbouring reactor to prevent the spent fuel becoming exposed.	response time for response time (12 to 24 hours) to site by the Nuclear Rapid Intervention Force (FARN).[150] For a reactor core that has been discharged completely into the fuel pond the discharged core exposure time is about 10 hours.	short and measures must be implemented to effectively increase the before-exposure times.

TABLE 9 CSA TOPIC: 14 ULTIMATE HEAT SINK LOSS OF ULTIMATE COOLING SINK - H1 AIRCRAFT CRASH MIRRORED EVENTS

ASN REQUIREMENT	AIRCRAFT CRASH CROSSOVER	APPLIES TO NPPS
Loss of Ultimate Heat Sink: The CSA submissions made by EDF provide its assurance that the ultimate heat sink would be recovered within the 100 hours for which the NPP has to remain autonomous. On the other hand, ASN acknowledge that the heat sink could be *'seriously damaged'*, requiring EDF to consider loss of heat sink and station blackout simultaneously (H1+H3).	The degrees[151] of redundancy and diversity in the intake, distribution (and exhausting) of the ultimate heat sink (water) into the NPP complex is not sufficiently known to appraise EDF's assurance that all possible scenarios of H1 can be restored before the fuel, either reactor fuel core, and/or in the spent fuel pond of a single NPP, or to all NPPs on site, becomes exposed – exposure times are reckoned in days for both reactor core, and spent fuel ponds, although ASN postulates that the reactor fuel cores (900MW$_e$, 1300MW$_e$ and N4 NPPs) could become exposed *'in just a few hours'* for a whole site H1 situation. EDF/ASN seem to limit the assessment to H1 situations where the sink has been temporally halted by blockage, localised failure, etc., and not by the severe levels of physical damage that might result from an aircraft crash directly onto the heat sink inlet or outlet. Also, it should be noted that loss of coolant water levels in the fuel storage ponds seems to be confined to evaporation losses only and no account is given to a direct breach of the pond liner of failure of any part of the water transfer pipework.	Not assessed because of insufficient detail. EDF H1+H3 scenario assessment has yet to be submitted.
Loss of Cooling of Equipment Rooms, Equipment, etc: Loss of the ultimate heat sink H1 is accompanied by loss of ambient ventilation and forced cooling of the equipment rooms, equipment, electrical distribution systems, etc.. At present there is no assessment of the temperature sensitivity of the equipment, etc., necessary to manage the NPP site.	Aircraft crash severely damaging the ultimate heat sink intakes, etc., could be accompanied by aviation fuel fire and a raising of ambient internal temperatures that could exacerbate equipment failures.	Most probably all NPPs.

150 *FARN* has yet to be established.

151 All of the operating NPPs depend on a single heat sink – there is no alternate heat sink available. The EPR presently under construction at Flamanville will have an alternate heat sink provided by two redundant channels in the heat sink pumping station.

TABLE 10 CSA TOPIC: 14 POST INCIDENT SEVERE ACCIDENT MANAGEMENT AIRCRAFT CRASH MIRRORED EVENTS

ASN REQUIREMENT	AIRCRAFT CRASH CROSSOVER	APPLIES TO NPPS
Multi-Facility Event: The Fukushima accident demonstrated that a single external hazard, the tsunami, could affect several facilities on a given site simultaneously. ASN considers that the EDF's current emergency organisation does not take sufficient account of this possibility. EDF is required to supplement its emergency organisation so that it can manage a *multi-facility* event. Moreover, ASN considers that at present the means of limiting releases in the event of core meltdown '*are not sufficiently robust'* for the levels of risk extant. Regarding the spent fuel pool, *'given the difficulty or even the impossibility of deploying effective means of mitigating the consequences of prolonged exposure of the fuel assemblies'* EDF is required to define and implement tightened measures to prevent the fuel assembly exposure. Also, ASN acknowledge that the heat sink could be *'seriously damaged'*, requiring EDF to consider loss of heat sink and station blackout simultaneously (H1+H3).	With high impact forces and the possibility of an aviation fuel fireball, if not detonation, aircraft crash could require a *multi-facility* response over a wide range of operating equipment and functions.	All NPPs.
Main and Secondary Control Rooms, Emergency Equipment Stores, Etc: The on-site emergency rooms (security block (BDS), emergency equipment stores, etc.) were designed without a specific regulatory requirement relative to flooding and earthquake, yet pragmatically these places are required to remain operational in the event of external hazards.	The physical devastation created by an aircraft crash could be severe and widespread, affecting emergency operation and storage area that presently do not form part of the *'hard core'* defence in depth of the NPP nor site – the impact of a commercial-sized airliner (ie >5.7 tonnes) was not part of the design-basis of all of the presently operating NPPs.	All NPP sites – at certain sites the main control rooms are particularly vulnerable to aircraft crash – insufficient detail is available about the location, vulnerability and continuing habitability of the secondary control room.
Spent Fuel Pond Integrity: The EDF CSA did not consider the possibility of a loss of integrity of the fuel pond and uncontrolled drain down of the pond water, including times when large loads (ie fuel transport flasks), are suspended over the pool.	The pond environment is designed for the SSE level and hence the structure and containment has not been tested against aircraft crash impact and projectile loading which could i) breach the containment, ii) rupture the pool and water circulation services,[152] and iii) generation of projectiles. Loss of cooling water levels in the spent fuel pool, accompanied by a breach of the walls and/or roof gives rise to high levels of gamma	Spent fuel building vulnerability at all NPPs. At Fessenheim and Bugey (and all CPO, CPY and P4 NPPs) there is an added vulnerability of fuel damage from a falling spent fuel transport flask during loading/transfer handling. For the P'4 and N4 NPPs in

152 Large J H, *Sizewell A – Cooling Pond Recirculation Pipe Failure Incident of 7 January 2007 Assessment of the NII Decision Making Process*, R3179-A3, June 2009

	'skyshine' as the water cover depth over the fuel reduces – this situation, that could arise in an aircraft impacting directly on the spent fuel building shell, may limit access to emergency personnel endeavouring to maintain the fuel-steam environment under the Zircaloy-steam temperature at which hydrogen is liberated. The spent fuel building structure for all NPPs, including the yet to be commissioned EPR, comprises a metal clad roof and relatively thin rc walls of less than 300mm thickness.[153] Both elements of this structure would not be resilient against a crashing aircraft and any breach in the containment would enable gamma shine from the uncovering spent fuel assemblies and release of radioactive particulate matter should the fuel and its cladding become overheated (~1,000^{o}C) and damaged.	which spent fuel is transferred to the flask from under the pond, there is risk of a breach of the vertical transfer canal and rapid drain down of the pond cooling/shielding water.

In January 2012, ASN published a further edict[154] on the Complementary Safety Assessments stating that the actions placed upon the NPP operator EDF were *'high priority'* noting that for the NPPs it considers that

> "*. . . their continued operation requires an increase in their robustness to extreme situations beyond their existing safety margins, as soon as possible . . .*"

ASN also requires a strengthening of the current *'baseline safety standard'*, particularly

> "*. . . reinforcement of the safety requirements for nuclear facilities, in particular with regard to the "earthquake", "flooding" and "risks linked to other industrial activities" aspects . . .*"

It is the catchall *"risks linked to other industrial activities"* that should include the potential outcome of both accidental and malevolent aircraft crash directly onto the nuclear island or nearby onto a key safety structure (a dyke, sluice, or similar containing the ultimate heat sink).

As demonstrated in **PART I**, the forces generated during the impact and potential aviation fuel deflagration/detonation would be more than capable of leading to a combined station blackout and loss of the ultimate heat sink scenario (H1 + H3). This outcome may be abrupt and without warning, and of greater damage severity and diversity than the *earthquake* and *flooding* events specified for the CSA assessments:

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153 The design of the spent fuel building (of all French NPPs) is not suited to contain the pressure rise emanating from the pool if the pool water should boil and, at elevated temperatures the hydrogen deflagration should the Zircaloy-steam reaction occur in the coolant emptied (boiled away) pond.

154 Nuclear Safety Authority (ASN) opinion N° 2012-AV-0139 3 January 2012 *concerning the complementary safety assessments of the priority nuclear facilities in the light of the accident that occurred on the nuclear power plant at Fukushima Daiichi*, January 2012

Lack of Warning/Abruptness: Accidental aircraft crash is likely to be, because of its unintended nature, completely unannounced except, perhaps, a few moments of forewarning that an aircraft is in some flight difficulty. Malevolent or terrorist driven aircraft crash will be implemented at no forewarning unless detected at, say, the hijacking stage when the destination target will be and is likely to remain unknown to the very final stages of the attack.

Whatever, for both accidental and malevolent aircraft crash, the final stages will be abrupt with no time and opportunity to prepare for the impact, shut down the plant to a safe and stable condition, and to evacuate the site under attack, etc..

The lack of forewarning is consistent with a seismic event. However, in the few seconds or tens of seconds time period over which an earthquake develops, the seismic transducers should commence reactor SCRAM[but see 128] and closedown ahead of arrival of the potentially damaging higher amplitude components. This is because at the NPP design stage (and for the Periodic Safety Reviews undertaken to date) earthquake was not a plausible severe accident initiating event so, it follows, reactor shutdown and engagement of various residual heat recovery systems should be assured for equivalent loading at or in excess of the safe shutdown earthquake (SSE) level at which the building structures and nuclear safety systems should remain essentially undamaged and functioning.

Generally, flooding from natural causes (excessive rain) is a forewarned event and the danger of inundation more typically develops progressively providing adequate time for plant shutdown, although not at the Le Blayais NPP of 1999.[155]

Damage Severity and Diversity: The damage from an aircraft crash can be severe and widespread and it is likely to be diverse, that is producing a variety or range of outcomes. At Lockerbie the falling airframe debris acted over a widespread area, it resulted in diverse outcomes ranging from demolition of buildings, fatalities of people on the ground, rupturing of underground mains, and so on. Although earthquake and flooding events can be severe and beyond the baseline safety requirement, the built-in plant design margins for earthquake and the expected time delays for flooding provide opportunity to implement mitigation and countermeasures, thus limiting the severity and diversity (knock-on) damage – there is no such opportunity with aircraft crash.

Finally, ASN (along with certain other national safety regulatory bodies) is at odds with the international nuclear agency, particularly relating to safeguard new-build NPPs against aircraft crash. For new-build NPPs, the International Atomic Energy Agency (IAEA) is cognisant of the risks and hazards of aircraft crash (both accidental and malevolent) in both judging the suitability of the nuclear facility site and its location, recommending in 2003[156] that

155 Flooding of the Le Blayais nuclear power plant in December 1999 was a International Nuclear Event Scale (INES) 2 that also involved loss of offsite electrical power but not SBO with the emergency diesel generators starting at the loss of the 400kV power supplies and there was loss of one of the two (diverse) essential service water system (ESWS) pumps. Although the NPP operators received adequate forewarning of the flooding and then loss of 400kV supplies they failed to close down the three affected NPPs at the earliest opportunity.

156 *Site Evaluation for Nuclear Installations*, IAEA Safety Standards Series, Safety Requirements N°. NS-R-3, 2003

"*. . 3.44 The potential for aircraft crashes on the site shall be assessed with account taken, to the extent practicable, of characteristics of future air traffic and aircraft.*

3.45. If the assessment shows that there is a potential for an aircraft crash on the site that could affect the safety of the installation, then an assessment of the hazards shall be made.

3.46. The hazards associated with an aircraft crash to be considered shall include impact, fire and explosions. . ."

and relating[157] to the imparted forces and resilience of the target structures

". . 4.54. Since impulsive loads associated with a design basis aircraft crash may exceed those associated with most natural phenomena or other human induced events, the potential for damage to any item important to safety should be assessed. In general it cannot be conservatively assumed that protection provided for other reasons will suffice to protect against an aircraft crash. . . .

6.6 Explosions of gas or vapour clouds can affect the entire plant area. Therefore the postulated gas or vapour cloud should be the most severe credible gas or vapour cloud relevant to the site. An analysis of the ability of plant structures to resist the effects of a gas cloud explosion can normally be limited to an examination of their capacity to withstand the overpressure (direct and drag) loading. Other effects should be considered: fire, smoke and heated gases, ground and other vibratory motions, and missiles resulting from the explosion. . ."

However, the IAEA's recognition of the risk and potential damage wreaked by an aircraft crash into a NPP is post 9/11 so NPPs designed and commissioned before this time did not necessarily include any particular degree of structural resilience focussed against aircraft crash. This is because the built structures of NPPs, the reactor plant containment, spent fuel storage ponds, equipment halls and control rooms, etc., very much reflect building technology, both in design and the materials of construction, contemporary with the time of their respective design and commissioning which, for some currently operational NPPs, dates back to the mid-1960s.

For these existing NPPs (essentially the French 900MW$_e$ series), since it is impracticable to implement any major structural and/or material changes to improve the resilience, these plants continue in operation with much the same levels of protection against aircraft crash as was the original design intent. Or, as the Finns would interpret it, the position of the world's nuclear safety regulators is given by the Director General, Jukka Laaksonen, of the Finnish Radiation and Nuclear Safety Authority (STUK),[158] who accepts that the lightest level of defence against aircraft crash continues to be acceptable for Finland's two existing, twin reactor nuclear power stations and its proposed fifth power reactor on Olkiluoto Island:

". . . [The] World's nuclear plants are designed on three levels against airplanes. First, against kinds of light airplanes, then against starfighter-type airplanes and then against large commercial airplanes. This design depends primarily

157 International Atomic Energy Agency, External Events Excluding Earthquakes in the Design of Nuclear Power Plants, Safety Guide, IAEA Safety Standards Series, No. NS-G-1.5, Vienna (2003)

158 Transcript of interview by Finnish Broadcasting Company, A-Studio 12 November 2001 – the transcript is in English and there is no authority on the accuracy of any translational/transcription.

on how close to flight-routes these plants are sited and our plants are far from flight routes and we have no fly zones to all planes in the proximity. We have considered the lightest level to be sufficient as a design basis.

. . .”

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APPENDIX I

ESSENTIAL PRINCIPLES OF AIRCRAFT CRASH AND ITS AFTERMATH

Impact Loading: As a result of impact of the aircraft, (kinetic) energy[159] is transferred from the aircraft to the building,[160,161,162,163] in two distinct phases:

a) **Impact:** In the first of these phases, the impacting airframe acts as a *'soft'* projectile with energy transferred being absorbed over a time period, the length of which is determined by the inertial and stiffness properties of both the airframe and target structures, the striking velocity and, essentially, size of the airframe, as a finite amount of kinetic energy is transferred to and dissipated by the building structure. The general assumption is that the building components receive this imparted energy in the form of strain energy whilst each component is deforming elastically and beyond up to the point of permanent yielding,[164] characterised by a *Load-Time* diagram (FIGURE 1) for various military and commercial airframes.[165,166]

b) **Impulse:** The second loading phase follows and involves those components of the aircraft that are sufficiently tough to form rigid projectiles that will strike and commence to penetrate, again by dissipation of kinetic energy, components of the building fabric and structure – the components involved in this second phase will include the jet engines, the spars of the undercarriages, and other hard inclusions in the airframe structure, such as the shear box coupling the wings to the fuselage, etc.,[167] – in certain situations these projectiles might be thrown forward onto the target from a crashed airframe that has been arrested short of the target.[168]

Fire & Explosion Loading: Physical damage from fuel-air fire and explosion damage can be widespread and severe, there is also the possibility of large scale incapacitation and fatality of the local residence and/or workforce population:

c) **Blast:** A structure encountering a blast wave[169] results in a reflected wave that is, typically, two to four times the magnitude but of much shorter duration than its parent. As a blast wave traverses over a built structure it exerts a positive pressure on the walls and roof as it passes, a reflected pressure on the windward side – following the blast wave a dynamic *'wind'* produces a inward force on the windward wall and negative forces on the side and leeward walls.

d) **Blast Resistant Structures – Damping & Ductility:** Parameters necessary to define the response to failure of a built structure include the duration of the applied load (both impact and blast) and the natural period of the structural response, as well as damping and the level of ductility during the response.

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159 The kinetic energy of a non-rotating object of mass *m* travelling at a velocity *v* is $mv^2/2$. If a rigid body is arrested then, under the conservation of energy, all of the kinetic energy of motion has to be transferred into other energy forms such as heat, elastic and plastic deformation, etc..

160 Just on the basis of kinetic energy alone the three levels of aircraft crash referred to by the STUK regulator increase from Level 1 (light aircraft) to Level 2 (Jet Fighter) to Level 3 (Commercial) airliner in the ratio 1 to 50 to 1500 or that the energy available from a crashing commercial airline (impact alone) is 1500 times that of a light aircraft.

161 For further details of the IAEA recommendations on nuclear facility resilience requirements and recommendations relating to aircraft crash see *Advanced Nuclear Plant Design Options to Cope with External Events*, Kuznetsov V, Nuclear Engineer, International Atomic Energy Agency (IAEA),

162 International Atomic Energy Agency, *External Events Excluding Earthquakes in the Design of Nuclear Power Plants*, Safety Guide, IAEA Safety Standards Series, N^o. NS-G-1.5, Vienna (2003)

163 International Atomic Energy Agency, *External Human Induced Events in Site Evaluation for Nuclear Power Plants*, Safety Standards Series No. NS-G-3.1, IAEA, Vienna (2002).

164 *Preliminary Analysis of an Aircraft Impact, G. Forasassi, R. Lofrano* Agenzia Nazionale per le Nuove Tecnologie, l'Energia e lo Sviluppo Economico Sostenibile 2010 – see also Riera, JD. *On the stress analysis of structures subjected to aircraft impact forces*, Nucl. Eng. Des. 8 (1968) 415–426

165 Bangash M Y H *Concrete and Concrete Structures – Numerical Modelling and Applications*, Elsevier Applied Science 1989 – for straight-on impact onto an infinitely rigid build structure.

166 RIERA, J.D., *On the stress analysis of structures subjected to aircraft impact forces*, Nucl. Eng. Des. 8 (1968)

167 Rambach J, Tarakko F, Kavarenne S, 18th International Conference on Structural Mechanics in Reactor Technology (SMIRT 18), Beijing, China, August 7-12, 2005, Rapport DSR N° 74, août 2005

168 For military aircraft crashes, throw forward distances up to 300m if the airframe descent angle is greater than 15^o to the horizontal, and for descents shallower than 15^o throw forward distances of up to 2km are possible - *The Throw Forward of Missiles Following Low Level Military Combat Aircraft Crashes in the UK*, Byrne J P, AEA RS 5615 January 1994.

169 For application to deflagration blast waves see Baker W E et al *Explosive Hazards and Evaluations, Fundamental Studies in Engineering 5*, Elsevier 1983

e) In blast wave loading, it is the initial peak pulse[170] that dominates the failure mode so damping is not a significant factor contributing to the blast resilience of the structure which is quite unlike the response to cyclic seismic (earthquake) induced loading, in which damping plays an important energy absorption role with significant effect contributing to the resilience and survival of the structure.

The effective explosive blast loading on a structure, ie the dynamic load factor, depends much on the ductility capacity of the structure. This is particularly so where the natural frequency of response of the structure is separated from the major (exciting) frequency of the load, so that no significant dynamic response is excited, in this case structures with greater overall ductility have greater resilience under blast loading.[171] Ductility is an important but often neglected parameter in the design of hazardous structures, such as nuclear power plants (NPPs), with the major nuclear safety components having structural ductility ratings of typically:

TABLE F1 COMPARATIVE DUCTILITY & FAILURE MODES DUE TO EXPLOSION BLAST

STRUCTURAL ELEMENT	FAILURE† kPA	DUCTILITY† BRITTLE = 1	FAILURE MODE	TYPICAL NPP APPLICATION
Glass window	1	1	shatter	Base comparison
RC§ block Walling	14	3	rupture	Office & General Buildings
Brick Walling Tied	5	2	shatter/overturn	Office & General Buildings
Brick Walling Reinforced	10	3	rupture	Some Fuel Pond Buildings
RC Slabs & Shear Walling	20	5	NLLB∫	RPV Containment Spent Fuel Pond
RC Columns	13	4	NLLB	Spent Fuel Pond Buildings
Sheeted Walls/Panelling	3	3	rupture	Some Diesel Generator Sheds
Anchored Switchgear	14	2	displaces/overturns	Throughout
Pumps, Valves Pressure Vessels	70 70	3 3	dislodges/ overturns	Throughout
HP Piping LP Ducting Cable Conduit	20 7 14	6 2 3	dislodges/ overturns	Throughout

† HCLPF or a high confidence of 1% probability of failure with 50% confidence.
§ RC or reinforce concrete
∫ NLLB or No Longer Load Bearing, ie a total failure in the structural role

Essentially, the target structure responds to the combined impact and blast wave in three ways:

i) **Global:** This includes excessive structural deformation and/or displacement, structural collapse, overturning, etc., of the main structure, particularly the outer and exposed structures of the target, mostly from the impact phase of the strike, in account of both structural (impact) and blast (TABLE 1) imposed loading.

The damage regime involves quasi-impulsive loading,[172] so the response of the structure is obtained by equating the work done by the impacting load to the strain energy produced in the structure. Setting aside localised damage in which individual structural components are removed (blasted away), the most probable failure mode of the structure overall is that of buckling and collapse in response to the global impact.

170 When the front of an air blast waves strikes the face of a building structure, a reflection occurs. As a result the over-pressure builds up rapidly to at least twice, and generally several times, that in the initiating incidence wave front. The pressure increase (load) on the structure is due to the kinetic energy of the air behind the shock front into internal energy as the rapidly moving air behind the shock front decelerates at the face of the structure. As the blast wave is being diffracted around the structure, because the back face of the structure is at ambient pressure, there a net overturning or toppling 'diffraction' load applied. In a built structure that has no weak openings (ie windows), like the primary containment, during the diffraction phase there is a net compressive or squeezing action pushing inwards trying to implode the building.

171 For example, a ductile compared to a total inductile (brittle) structure, say a factor of x5, would typically require only about one-third the load capacity of a brittle stricture in order to survive the same explosion. Compared to glass, which is inductile and brittle and which shatters under blast loading, the reinforced concrete structure of a typical PWR containment dome is, in these terms, a relatively ductile structure.

172 The maximum impact before yielding commences is given by

$$i_r = [2Lim/En]^{0.5}\, \partial_y/Ah$$

which (adopting conventional notation) for the a typical rc construction, with a roof slab load per column assumed at 35t, the structure yields at about 1,750 Pa-s. The impulse force arising from a crashing aircraft of, say 200 tonnes all-up weight considered impacting over its projected front end fuselage area (about 30m^2) with the event lasting over the entire collapse of the fuselage length, gives an impulse force of about 20,000 Pa-s or about x10 the yield strength of the typical rc structure described above.

ii) **Localised:** Arising from the hardened component (engines, etc.) strikes, leading to penetration and failure of specific structural elements of the built structure. For impact damage the aircraft, more particularly parts and components of it, have to be considered as inert projectiles.

The energy transfer upon impact relates to the kinetic energy (KE) and the key parameter in determining the target (building component) response is the kinetic energy density which relates the KE and the projected area of the projectile. In terms of projectile velocity, a diving or free-falling civil airliner is unlikely to exceed 500 knots so the damage mechanism falls below the so-called hydrodynamic regime where the intensity of the projectile-target interaction is so high that a fluid-to-fluid damage mechanism prevails (as utilised by tungsten tipped and depleted uranium scarab or long rod penetrator armour piercing rounds).[173] In the sub-hydrodynamic regime more conventional strength of materials characteristics (ie strength, stiffness, hardness and toughness) will determine the penetration mechanism and its effectiveness.

For uniform, elastic materials, such as low carbon steel used in steel-frame industrial buildings, a good first estimate of the penetrating power and breaching distance of a projectile can be obtained from the *Recht* equation which, for certain hard components of the aircraft engines, could be as high as 200mm.[174] For a steel framed industrial building structure, typical web and flange thicknesses of the steel section girders and beams is typically about 20 to 40mm so, even with penetrator break up, this and other projectiles would be more than sufficient to structurally damage, if not catastrophically collapse the building steel frame.

The failure of reinforced concrete (rc) to ballistic loading applies to the different ways in which this common building structural material is used: For very thick walled structures the concrete is considered to be a semi-infinite mass, for concrete walling and flooring (and roof) slabs the account has to be taken of the flexure of the slab, and to prevent scabbing (where the back face of the concrete surface detaches) the reflective characteristics have to be modelled. The first two of these applications are important in respect to the whole structure remaining intact, and the last that even where complete penetration is not achieved, the detached scab can form a missile in itself, projecting into and damaging and/or disabling safety critical plant within the concrete containment.

The derivation of the ballistic loading of ferro-concrete (steel reinforced concrete) structures is a little more empirically derived,[175] although even with broad brush assumptions about the detailed design of the ferro-concrete structures, a hardened

173 At projectile impact velocities below 1000m/s all impacts are sub-hydrodynamic – at 500 knots the closing velocity at impact would be approximately 260m/s.

174 After R F Recht, *Ballistic Perforation Dynamics of Armor-Piercing Projectiles*, NWC TP4532, 1967. which, for a blunt nose ogive, is

$$x = 1.61M/(bA)[V-a/b\ln([a+bV]/a)]$$

where *a* and *b* relate to the material properties of the target, M is the mass of the projectile and V the projectile closing velocity. For an aircraft impact, if it is assumed that a sufficiently robust penetrator will present itself in the form of a main turbine shaft of an aero engine which, with its blades and other attachments, might represent a mass of 0.25 tonnes of 150mm projected diameter (stub end of shaft), typical strength of materials properties give $a = 2.10^9$ and $b = 10.10^6$, so that the final penetration thickness into a steel element (ie a building stanchion) is about 200mm.

175 *MOD Assessment, Strengthening, Hardening, Repair and Demolition of Existing Structures*, Army Code No 71523, MoD 1992 which, for the same missile adopted for *Footnote 174* the slab penetration is about 1,100mm.

projectile striking most of the concrete structures of a nuclear power plant would achieve full penetration. For example, a glancing impact on a typical rc framed building would be sufficient to possibly penetrate the rc roof slabs which are not practicably greater than 100 to 150mm thickness (the thickness being limited because of selfweight loading considerations over the 4m spans).

iii) **Propagated & Remote:** Dynamic effects transmitted to structures and components that might be situated remote from the direct area of impact within the target enclosure, particularly the fixings and frames of machinery, linings, etc..[176] The outer walls of the reactor primary containment building, the fuel building and two of the four *'safeguard'* buildings of the European Pressurized Reactor (EPR – see FIGURE 2), as well as earlier PWR generations, claim to compensate against penetration and excited transmission of impact loading by isolating a second barrier within. For these buildings, the internal structures are decoupled from the outer walls in order to reduce induced vibrations, and the fixing of sensitive or safety relevant systems onto the outer walls is avoided.

176 The impact at Lockerbie was recorded as equivalent to a 1.6 Richter scale earthquake of about 12+MJ total energy – see Footnote 18.