Large and ASSOCIATES

STATES OF JERSEY

APPLICATION FOR
AUTHORISATION TO CONSTRUCT AND OPERATE
A 3RD NUCLEAR POWER UNIT
FLAMANVILLE

FURTHER COMMENTS RELATING TO THE EDF PRESENTATION

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OPERATIONAL RISKS AND HAZARDS OF THE EPR WHEN SUBJECT TO AIRCRAFT CRASH

Summary

The EdF presentation relating its proposal to build, commission and operate a Generation III EPR nuclear power plant at Flamanville includes just a single text reference to how the plant is to be protected against terrorist attack.

Essentially, EdF claims that the EPR system and its design provisions *'helps limit the consequences of an act of malice . . . to ensure that the installation returns to the safe state'* and that the radiological consequences of any terrorist act will not go beyond those assumed for the reference design accident. In other words, so far as terrorism relates, with this involving intelligently driven, intentional acts that seek out the vulnerabilities of the plant and its safety systems, it is claimed that the damage and consequences will be no more than that of an *'acceptable'* accident as triggered by a prescribed (accidental) fault event.

A deeper insight into EdF's rationale on this important aspect of nuclear safety is to be found in a previously confidential statement that EdF prepared in or about 2003 and submitted to the Direction Générale de la Sûreté Nucléaire et de la Radioprotection in response to its request to demonstrate the safety of the EPR design against the deliberate crashing of a large civil aircraft onto the nuclear island. The resulting EdF document endeavours to prove the adequacy of the plant to withstand such attack and it claims to do so by comparing the footprint and time sequencing of the impact of a small military (fighter) aircraft to that of a large, fully fuelled commercial airliner.

However, this leaked EdF document shows the claim to be flawed in a number of important respects: First, in that the impact signatures of the small military fighter and very much larger commercial passenger aircraft are unlikely, contrary to the reckoning of EdF, to be sufficiently similar in both time span and magnitude for the design resistance of the EPR to an accidental military aircraft strike to equally apply to a passenger airliner intentionally targeted the nuclear island of the plant – indeed, the basis of reckoning the resistance of the built structures is so grossly simplified that it is inapplicable to a real impact situation. Second, the EdF assumption that the 100 or more tonnes of aviation fuel spilt during the moment of impact would ignite and burn itself out within 2 minutes or so is entirely without justification and unproven, with there being a good possibility that highly explosive vapour would be formed within and around the structures, the deflagration of which could be severely damaging to the EPR building structures and nuclear equipment within and, of course, key operating personnel could perish or be incapacitated. And, quite incredibly, one line of mitigation proposed by EdF is that the terrorist would have insufficient skills to pilot the aircraft onto the intended target, this being quite contrary to the dedicated training undertaken by the terrorists who masterminded the 9/11 attacks.

The EdF rationale draws on a poorly constructed argument of the resilience of the EPR design against the international terrorist threat – it has been derived on the basis that the terrorist has limited knowledge of the EPR plant, little capability to acquire the necessary skills to launch and successfully see through the attack, and that a determined terrorist group will not intelligently and intentionally seek out the vulnerabilities of the EPR design. Not only is it an entirely unjustified postulate that the present military aircraft accidental crash safety case is adequate to cover the damage severity caused by an intentional attack with a large passenger airliner, also the claim that the resulting radiological consequences to the public will be within the existing prescribed statutory limits for accidents cannot be demonstrated to be at all sound.

Indeed, it has to be hoped that considerably more valid thought and preparation has gone into improving the resilience of the EPR design since the 2003 date of the EdF document and, one might muse, if the paperwork design of the EPR is showing such shortcomings, what of the resilience to terrorist action of the many operational nuclear plants scattered across France and elsewhere in Europe?

In Conclusion: Nuclear plants are almost totally ill-prepared for a terrorist attack from the air - the EPR design proposed for Flamanville is no exception to this.

The EPR design evolution is of successive, being based on the previous generation of pressurised water reactors, all of which were developed before terrorism became such a threat. Indeed, the EPR design is pre-9/11 and since 2001 there has simply not been sufficient time to modify the design of the buildings, plant, equipment and the all-important containment in account of the terrorist threat. If the building containments had been modified then the external appearance of their form and structure would be so obviously tell-tale of this.

If a terrorist group planned to intentionally crash an aircraft onto a nuclear power station then the probability approach adopted for the nuclear safety case no longer applies, the composite of *Acceptable Risk and Tolerable Consequences* can no longer apply - the risk reduces to intent and the consequences resulting are contrived, that is engineered and maximized by the terrorist and not, as with the present safety rationale, restricted to a foreseeable and hence controllable outcome. Considering an intentional, terrorist driven aircraft crash as a certainty, rather than as some remote probability, requires the event to be assessed in terms of its consequence management alone and this consequence management is the only form of mitigation available.

In other words, there are no practicable measures that might be implemented on site to provide a defence in depth to avert such an event. Claiming, as EdF does, that the present EPR design will automatically manage all conceivable adverse events and that the consequences of any one of these will not exceed the design basis is fundamentally flawed.

Finally, it should be noted that this review has considered terrorist attack by aircraft crash, a mode of sabotage that was inconceivable just a few years or so past. We now know that deliberate aircraft crash has to be defended against but what of the next attack, what shape and form will that take and how will plants like the proposed EPR be defended against it and, indeed, what of the adequacy of the two existing nuclear power plants at Flamanville?

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Additional Comments and Observations on the Presentation Note of the Application for Authorization to Create a 3rd Nuclear Power unit at the Existing Flamanville Site

Risk and Hazard Assessment

Obviously, real risks threatening any hazardous plant must include malicious acts (terrorism, sabotage, etc) that intelligently and intentionally seek out the vulnerabilities of the plant and its protective and safety systems. Nuclear plants are no exception to this and, moreover, it might be convincingly argued, that such plants could be considered by those of ill intent to be attractive targets by reason of the public's perception, sometimes and in some respects ill-judged, of radiation and by the extent of psychological, economic and societal damage that such an attack might create. Although and however misguided public perception might be, this should not detract from the fact that a well thought-out attack on a nuclear power plant could, if successfully implemented, result in very severe radiological consequences.

The so-called worst case incident for the EPR nuclear power plant proposed at Flamanville culminates in the melting of the 150 or so tonnes of intensely radioactive fuel held in the reactor core, a small fraction of which is assumed to disperse to atmosphere. The overall target for an *accidental* core melt failure is 10-5 for each reactor for each year of operation for every type of failure and hazard (or initiating events),[1] which being drawn from probabilistic (*a priori*) considerations it cannot possibly relate to malicious acts. Other accidental situations that result in a radioactive release relate to the containment of the irradiated (or spent) fuel held in storage in the nuclear power plant storage ponds; release from the stores that hold the radioactive waste that arises during normal operation of the plant; and/or from transportation incidents involving the delivery of new, unirradiated fuel or with the dispatch of spent fuel from the power plant.

Probabilistic Approach to Nuclear Safety

So, put simply, the risk to a nuclear power plant is a combination of the

risk of incident ~ severity of the initiating event

If the risk is unacceptable then, it is assumed by the nuclear safety case, the consequences must be tolerable, but if the risk is acceptably low (say one in one million chance) then, because the incident is unlikely to happen by chance, then the consequences can be severe and intolerable. This composite of *Acceptable Risk -v- Tolerable Consequences* is the basis adopted for the probabilistic safety reasoning and engineering design of nuclear power plants worldwide.

If, however, the incident is contrived and not accidental, that is it is a deliberate act, then it is not possible to determine the chance that it will or will not happen so, for malicious acts, the probabilistic risk approach cannot be absolutely relied upon. Similarly, if the initiating incident is contrived to seek out the vulnerabilities of the plant and, perhaps, interfere with the restoration countermeasures to restore stability to the plant, and/or impede the mitigation actions to minimise radiation dose during the aftermath of the incident, then the measure of the consequences cannot be reliably determined.

In effect, malicious acts are beyond the domain of the probabilistic reasoning adopted for the safety and design of nuclear plants. In order to account for malicious acts either the nuclear plant has to be substantially amended in its physical and safety system design and construction or a new order of rigorous and failsafe management to ensure the absolute security of the plant has to be implemented.

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1 Initiating events, including external hazards, are classified into four groups of *Plant Category Conditions* (PCCs) with each being defined (D-IV.1.2.2.1) PCC1 to PPC4) with PCC4 reckoned to be lower than one chance per million per reactor per reactor year of operation with, similarly, malicious acts seemingly excluded from this fault categorisation. The severity of damage and the magnitude and impact of the radioactive release are defined in terms of three levels of *Radiation Risk Category* RRC-A, RRC-B and Specific Accidents of 3 categories (D-V.1.2.4.1.1).

APPLICATION TO THE PROPOSED FLAMANVILLE EPR PLANT

There is, perhaps quite justifiably, a general reluctance for the nuclear industry worldwide to release any information whatsoever about the vulnerability of and installed defences to protect against terrorist attack of nuclear installations.

Indeed, the defence against terrorist and other malevolent acts is not so obvious in the EPR design. This is most probably because the EPR structural design and layout was committed to well before the September 11 2001 acts of terrorism that highlighted the need for the engineered design of hazardous plants to be resistant against malevolent acts such as deliberate aircraft crash. In this respect the anti-terrorism features will comprise, one has to assume because details have been withheld, mainly:

- means by which ill-intended approach to the plant is restricted by security cordon and, specifically, to safeguard against for commercial aircraft attack, absolute security at national and international airports; and
- by the robustness of the plant generally to withstand physical intrusion (by explosive device, crashing aircraft, truck bomb, boat launched missile, etc);

A second anti-terrorism line of defence is the claim that any reasonably foreseeable malevolent act would not result in severity of damage and consequences greater than that of the nominated design basis accidents.

However, the present state of the first EPR now under construction at Olkiluoto in Finland[2] does not suggest that the original (pre-9/11) structural design and layout of the key nuclear safety issue buildings and plant have been significantly modified to resist acts of terrorism. This is not surprising since major structural engineering amendment to the original design would necessitate fundamental revisions of the buildings, plant and layouts which, in themselves, would require a time consuming review of the detailed and overall nuclear safety cases.

Instead, the original EPR design is largely substantiated to be 'terrorist-resistant' by reliance upon increased security at national and international airports and by the recently introduced concept of '*segregation*'. For segregation the so-called *safeguard* buildings clustered around the most sensitive parts of the plant (reactor, spent fuel, emergency diesel, and seawater intake buildings) that, in themselves, do not fulfil a nuclear safety critical role.

Obviously, to safeguard against intentional aircraft crash the only effective measure (other than security at the departure airports) is to physically enhance the structure of the building enclosures although, since the fundamentals of the building design are committed to at an early stage of the design process, other than a radical change of the building structures and/or layout (for example, building underground), little can be done to improve the resilience of the existing EPR containment design. There are no apparent signs that the post 9-11 EPR designs have undergone such a radical enhancement[3] and, even for the *safeguard* buildings, no details of how these sacrificial structures have been enhanced to protect the nuclear safety critical plants are available.[4,5]

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2 European Pressurised Reactor at Olkiluoto 3, Finland - Review of the Finnish Radiation & Nuclear Safety Authority (STUK) Assessment, Large J H, R3123-A2, July 2005 - http://www.largeassociates.com/R3123-a2%20final%20Issue.pdf

3 That is simply thickening the concrete of the structures would not apply for aircraft impact and major changes would be required to strengthen the internal structures (equipment and its supports) to resist shock loading from the considerable impact forces transmitted through the built structure.

4 The concept of arranging a ring of protective buildings around the key nuclear enclosures, ie segregation, seems to be a new design concept in the EPR introduced since 9/11 2001, although that said, there does not appear to have been any major design and layout changes.

5 The only example of a specific aircraft-crash resistant reactor design now progressing through the construction stage is the relatively small radioisotope production reactor at Lucas Heights in Australia. In this design the secondary containment dome is augmented with a visually striking frame of triangulated beams which receive and dissipate the impact of a crashing aircraft.

Although, on the basis of not revealing to would-be attackers any aspect of the plants resistance to aircraft crash, accidental or otherwise, EdF excludes any reference to or detail of the measures included in the EPR design and construction that safeguard it against aircraft attack. However, in a leaked document relating the EPR resistance to aircraft impact,[6] EdF argues that the existing nuclear safety case for the *accidental* crashing of a small (fighter) military aircraft is of sufficient severity and damage outcome to cover an *intentional* crash of a fully fuelled, large commercial passenger aircraft.[7] Not only is this postulate is unproven by EdF but there are considerable weaknesses in the argument for the robustness of the EPR plant to survive a crash even of a small military aircraft. The adoption of the military aircraft case in justification of the EPR design is seriously flawed for a number of reasons,[8, 9] but particularly in the assumptions that

i) the impact footprint (against the building structures of the EPR) of a military aircraft is sufficient to adequately represent the impact footprint of a much larger commercial aircraft;

ii) that the total energy dissipated into the building structure by the impact of a commercial aircraft (of say of around 250 tonnes fully fuelled deadweight) would generate no greater induced shock and oscillatory loading into the building and, particularly, to the installed reactor equipment within than that generated by a military fighter aircraft (of 2 to 5 tonnes total deadweight); and

iii) that the very much greater volume of aviation fuel[10] released upon impact of a commercial aircraft would burn in a predictable manner and not form an explosive fuel-air mixture or be forced into the building enclosure where the vapour could ignite with explosive and severely damaging results.

EdF goes further to mitigate the consequences of an aircraft mounted terrorist attack against a nuclear island by arguing that

iv) the four levels of safety system intervention and passive containment levels of the EPR would be sufficient to provide complete surety of the nuclear island.

Further justification that the EPR design is sufficiently resilient against attack by a large commercial aircraft is taken from the assertion that the would-be terrorist pilot is unlikely to have the skills necessary

v) to fly the aircraft at the low angle of attack required to crash into the EPR complex of buildings; and vi) to manoeuvre around various obstacles present on and around the power station site.

Of EdF's claims and assertions:

v) and vi) Terrorist Pilot Skills

The international nuclear industry's approach to *accidental* aircraft crash generally derives from the guidelines and principles set out by the US Department of Energy. Essentially, this approach

6 *DGSNR/SD2/033-2003, EDF-SEPTEN CONFIDENTIEL DEFENSE* together with an appendix (*Annex 1/Appendix 1*) in all totalling 9 pages - so far as I can tell, the leaked EdF document is genuine and has not been altered or tampered with from its original

7 In this respect there is some confusion over test work conducted in the United States wherein a small aircraft was crashed against a monolithic concrete block. The purpose of this test was not to determine the strength of concrete structures but to enable the dynamics and thus the generation of impact forces of a crashing aircraft (its progressive crumpling) which could be then applied to the mathematical modeling of an aircraft impact with a building structure (concrete or otherwise).

8 The nuclear industry's approach to aircraft crash generally derives from the guidelines and principles set out by the US Department of Energy *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

9 For example, on page 8 of the EdF Document there is reliance upon past experience (REX - *retour d'experience* or feedback) yet there is no reference cited for the data relied upon.

10 For example a fully laden Boeing 747 has a 173,477 kg fuel capacity at take-off, and similarly a Boeing 767 72,831 kg, a Boeing 777 135,360 kg, an A340 108,000 kg and an A330 74800 kg.

assumes some form of loss of control of the subject aircraft, its subsequent deviation from the intended flight path and the chance of it crashing into the target nuclear plant. The nuclear plant is defined as a *crash area* and the parameters relating to this are calculated from the *effective fly-in*, *footprint*, *shadow* and *skid areas* that are determined from established codes[11] - it is these aspects of a terrorist attack that form the basis of approach of EdF rationale.

The argument that the shallow glide path necessary to home in on the nuclear island would not be available to a terrorist pilot is not particularly convincing because it is quite clear from the recently released film of the 9-11 Pentagon attack that the aircraft approaching the Pentagon was at very low altitude and maintaining a very shallow flight path up until the moment of impact.[12]

Similarly, the necessity to manoeuvre to avoid building and other obstacles nearby or on the nuclear site could be mainly overcome by approaching most nuclear islands from the seaward side, with it unobstructed and direct line of vision into the plant from 30 km or more.[13]

Indeed, the fact that the 9-11 terrorists were dedicated to their objectives, so much so that they specifically trained in pilot skills for more than a year does nothing to presuppose that the terrorist intent on attacking an EPR installation (or indeed any other existing nuclear reactor installation) would undertake similar intensity of specific training to meet that objective.

i**v) EPR Safety Systems:**

The assumption is that the four levels (safety equipment and containments) intervening would be sufficient to isolate the key nuclear safety functions, etc., of the EPR from failure and/or loss of control during and in the aftermath of an aircraft impact.

The delineation of the nuclear safety case for the EPR comprises four groups according to the projected frequency of occurrence of the initiating event, these being i) *Anticipated Transients* at higher than 10-2 per year (frequency per reactor year of operation),[14] ii) and iii) *Classes 1 & 2 (Design Basis) Accidents*[15] at between 10-2 - 10-3/y and less than 10-3/y respectively, and iv) *Severe Accidents*. [16]

11 STD-3014-96, US Department of Energy, 1996

12 The EdF Document Appendix refers to the need for a 'horizontal stabilised flight at a very low altitude (less than 50m) for a successful attack – this seems to be about the approach pattern adopted for the Pentagon attack of 9-11 and, in any case, large commercial aircraft are extremely stable at the low (typically 3.5o) landing approach descent.

13 The studies for the impact of a heavy military aircraft and commercial airliners, although cited for the Sizewell B assessment were not then and remain unavailable to the public domain. However, it is interesting to note that the title dealing with the military aircraft scenario refers to

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

with the emphasis suggesting that somehow the pilot of this hypothetical aircraft was able to retain some degree of control (and also possess the knowledge of the critical parts of the plant) 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. In other words, the nuclear industry considers there to be little justification in installing additional features (ie beefing up) to provide aircraft crash resistance. In fact the NUREG-0800 based analysis permits 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.

14 10-2/year is a chance of one in one hundred years for each year of reactor operation.

15 These are the definitions of the Finnish regulator STUK for the Olkiluoto EPR - *Class 1 & 2 Accidents* are defined by severity with, for example, loss of coolant accidents (LOCA) of less than 20cm2 breach being *Class 1* and breach areas larger than this being *Class 2* – the largest LOCA is assumed to be a double guillotine failure of a main primary coolant circuit pipe. Similar *Class 1 & 2* classification of accident severity is applied to reactivity excursions, etc., reactor scram failures, and so on.

16 These are as described for the Finnish Olkiluoto EPR but are most probably applicable to all other EPR designs originating from AREVA – see also Footnote 1 of the EdF document – *'This definition, consistent with the EPR classification, corresponds normally to the term « design extension » which is found in some countries'*. - Under the Finnish nuclear regulatory system, extraordinary situations such as *accidental* aircraft crash require separate assessment and certain event circumstances are not classified solely on the predicted frequency of the initiating event, being considered to be *'Design Extension Conditions'* (DEC).

The point here is that the four levels of safety and containment systems (redundancy and diversity) relied upon by the EdF document are justified in terms of probabilistic occurrence which includes for the remote possibility of an *accidental* aircraft crash. In fact, the possibility of an accidental crash of a commercial aircraft is reckoned to be so remote that there is no need to prepare for it,[17] being that the chance of an untoward *accidental* event is reasonably foreseeable, whereas potentially severely damaging the possibility of occurrence is so remote that it may be discounted.

The point here is that a terrorist attack is a planned event, so it cannot fall within the risk-damage severity composite relied upon for *accidental* events. That is although the airborne terrorist attack is reasonably foreseeable (9-11), its frequency of occurrence cannot be reckoned *a priori*, so its potential radiological consequences cannot be dismissed on an assumed low frequency of occurrence.

Again as a reference to the EPR design, for the Finnish Olkiluoto EPR[18] the assessment of the plant to large commercial aircraft impact has been withheld for, according to STUK, security reasons. However, it is interesting to note that the *design extension aircraft crash* is an 'add-on' to the EPR safety case, suggesting that the original EPR containment design, being pre September 11 2001, was not specifically designed to resist any impact loading greater than a light aircraft crash which was then (pre 9/11) the universally accepted design basis case drawn from the improbability (pure chance) of a civil airliner accidentally crashing onto a nuclear power plant.

This is much the same reasoning applied by EdF that the design of the safety and containment systems for a light military aircraft impact, just by chance, are sufficient to cater for the impact of a large commercial aircraft. In fact, the EdF document goes further by stating that impact of a large, fully fuelled passenger aircraft would not result in radiological consequences that would exceed the present Category 4 level of foreseeable *accident*.[19]

iii) Aviation Fuel Burn:

EdF claims that the aviation fuel released during the impact would result in a fire ball of 90m diameter, a temperature of 1,200oC which would be completely exhausted and extinguish within 2 minutes.

There are a number of difficulties with this claim with, for example, unless ignition is immediate and efficient, the fuel is likely, indeed almost certain, to form a vapour which will be available for dispersion and explosive ignition and deflagration which has to be set against the overriding EdF assumption that all of the fuel spill will be uncontained (in open air) and that ignition will be uniform.

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17 Applied to a civil airliner operating at altitude and passing along a prescribed flight path, this *a posteriori* probabilistic approach adopts rates drawn from actual crash incidents, yields a very low accidental crash probability. Essentially, the whole probabilistic assessment outcome is determined by the chance of a very small missile, the aircraft, accidentally hitting a small target, the nuclear plant, located in a very large geographical space. Applying this to nuclear plants suggests that <u>accidental</u> aircraft crash rates are sufficiently low (<107 per year) to satisfy the requirements that the hazard of occurrence is so remote that it cannot be expected to affect the plant. In application this means that for the UK Sizewell B pressurised water reactor (PWR) safety case (of 1987) aircraft crash onto the power station site was identified and considered as an external hazard that had the potential to initiate events that could lead to an accidental release of radioactivity. The expected frequency of impact of all classes of aircraft onto identified vulnerable areas of the power station site was reckoned to be extremely low, at around 7x10-7 per year and, of these, impact of aircraft and helicopters less than 2.3 tonnes was not expected to penetrate the containment structures. Thus the design criteria for Sizewell B translated into a construction that provided defence against only the first and lightest level of aircraft impact, that from a small aircraft such as a Piper Cherokee.

Of course the probability or chance of the occurrence of a malicious human act, such as the terrorist attack of 11th September, cannot be determined by classical *a priori* probabilistic means. Thus, it is only realistic to apply chance to the success of the attack once it has been initiated. Put another way, applied to the terrorist attack of 11th September the *Phit* or <u>success</u> rate was 3 out of 4 airborne aircraft, (*Phit* = 0.75).17 If the aircraft that crashed in Pennsylvania is discounted, the *Phit* for those aircraft on their target run was 3 out of 3 or 100%. In other words, the hijackers had obtained sufficient flying skills to ensure that, once that the aircraft has been commandeered, the mission would have a high, almost certain rate of achieving its objective. Whereas the military or civil pilot would not be expected to have been trained to identify the vulnerable parts of a nuclear plant (even though it is assumed that the pilot will strive to avoid certain parts of the plant), it would be in the hijacker's interest to identify the most vulnerable parts of the selected target. Hence, the same NUREG-0800 mitigation applies, but in this case in reverse with the terrorist intent of striking the plant with, perhaps, a *Phit* of 95% of success once committed to the final run to the target.

18 Again there is no reason why this should not apply equally to a French AREVA EPR.

19 See p1. Footnote 1 of the EdF document.

These relatively crude EdF assumptions have to be examined in the light of how past fuel fires have developed and burnt through to completion with, for example the recent fuel complex fire at Hemel Hempstead in the UK which initiated with a massive air-vapour explosion.

Although it not entirely clear from the EdF document how the EPR structures are intended to resist pressure waves generated by vapour deflagration, it seems that an inappropriate impulse model is deployed to determine the structural response of the building containments to an explosive overpressure, particularly for comparing the structural response of military and civil aircraft impacts.

i) and ii) Impact Loading and Penetration:

Obviously, the effect and outcome of an aircraft crash and fuel explosion/burning on any one of the active plant buildings of the EPR nuclear island will be subject to how each of the individual target buildings would perform under the impact and fire conditions.

As a result of impact (kinetic) energy is transferred from the aircraft to the building[20] by being absorbed in the building components in the form of strain energy whilst each component is deforming elastically and beyond up to the point of permanent yielding. The impact can be segregated into two regimes: First, at the moment of impact the aircraft can be considered to be a very large but relatively 'soft' projectile which, by self-deformation' will dissipate some fraction of the total kinetic energy being transferred during the impact event. Second, some components of the aircraft will be sufficiently tough to form rigid projectiles that will strike and commence to penetrate, again by kinetic energy, components of the building fabric and structure.

The first of these damage regimes involves quasi-impulsive loading, so the response of the structure is obtained by equating the work done by the impacting load to the strain energy produced in the structures. 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 impact. The types of building structure featured at nuclear power plants, for example the radioactive waste and particularly spent fuel buildings, would not withstand the impulse magnitude delivered by a crashing commercial aircraft.[21]

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 civilian aircraft 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).[22] In the sub-hydrodynamic regime more conventional strength of materials characteristics (ie strength, stiffness, hardness and toughness) will determine the penetration mechanism.

For uniform, elastic materials, such as low carbon steel used in steel-frame construction such as diesel generator sheds, radioactive waste stores and, sometimes, irradiated fuel storage buildings, a good first estimate of the penetrating power of a projectile can be obtained from the Recht equation

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20 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.

21 The maximum impact before yielding commences is given by

$$ir = [2Lim/En]0.5\ \partial y/Ah$$

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 30m2) 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.

22 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.

which, for certain hard components of the aircraft engines, could be as high as 200mm.[23] 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 in even where complete penetration is not achieved, the detached scab can form a missile in itself 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,[24] although even with broad brush assumptions about the detailed design of the ferro-concrete structures the hardened 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 400mm thickness, (because of selfweight loading considerations over the 4m spans).

The point here is that the building structures of a nuclear plant require to maintain complete containment during an aircraft crash because even relatively small penetrations will permit the inflow of aviation fuel with the almost certain fire aftermath which would, in itself heighten the release and dispersal of any radioactive materials held within the building structure.

Thus the risk of radioactive release applies not just to the nuclear reactor considered and discounted by EdF, but also to the irradiated fuel ponds and other radioactive waste processing and storage areas. These other sources of potential radioactive release have not at all been considered in the leaked EdF document.

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23 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 = 2.109 and b = 10.106, so that the final penetration thickness into a steel element (ie a building stanchion) is about 200mm.

24 MOD Assessment, Strengthening, Hardening, Repair and Demolition of Existing Structures, Army Code No 71523, MoD 1992 which, for the same missile adopted for Footnote 23 the slab penetration is about 1,100mm.