REVIEW

VULNERABILITY OF FRENCH NUCLEAR POWER PLANTS TO UNMANNED AERIAL VEHICLE (DRONE) INTRUSION AND ATTACK

CLIENT: **GREENPEACE FRANCE**

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EXECUTIVE SUMMARY

Over the period from 14 September 2014 to 16 November (the date of finalising this Review) a total of 31 overflights by *unmanned aerial vehicles* - drones - had taken place at 19 French nuclear installations, 14 of which were nuclear power plant (NPP) sites operated by *Electricité de France* (EdF). The motivation for and purpose of the drone flights remain a mystery. The overflights are unauthorised and blatantly flout the restriction orders for airspace above and around NPPs and, of course, there are very serious nuclear safety and security implications. In view of the mounting public concern EdF, along with the national security and nuclear safety authorities, has not been able to anticipate, detect and deter the drone flights, nor identify and restrain the human perpetrators from continuing with this activity.

It is something of a Cat-and-Mouse game but in this game the drones seemed to have, at least for now, gained the upper hand.

On the basis of this recent flurry of drone overflights, this Review examines the capabilities of aerial drones, particularly the smaller to medium *tri- quad-* and *octocopters* that are readily available in high street hobbyist stores and internet without any requirement for registration, certification and/or licensing. The range of *'plug-and-play'* add-ons available for advanced navigation, control-and-command, manoeuvring actions and flight strategies are assessed, it being concluded that the well-informed hobbyist and amateur is able to custom-build very sophisticated autonomous drones and accompanying android devices.

The fact that many of the recent overflights have been during the hours of darkness, obviously out of sight of any human controller, being extremely difficult to detect by the surveillance equipment at the NPPs and, indeed, by the advanced military systems brought into place at some nuclear installations, all suggest that the aerial drones deployed have been sophisticated and, to some degree, autonomous and stealthlike.

The Review briefly examines the vulnerabilities of the French NPPs giving particular regard to the status of the *l'Autorité de Sûreté Nucléaire* (ASN) ongoing programme of *Complementary Safety Studies* (CSA) improvements and, separately, the requirement for the '*hardened safety core'* (SSC). These pressing nuclear safety requirements were first enerated during the 2011-12 round of *stress tests* invoked by the European Commission's post Fukushima Daiichi directive. Particular regard is given to the CSA tasks at the 41 NPPs prioritised for action and, separately, the Herculean effort required of EdF to have the SSC in place at **all** presently operational NPPs. Both CSA and SSC task programmes are found to have slipped behind, so much so that it is certain, especially for the SSC, that the '*hardened safety core'* programme will not be completed by 2018 as targeted by ASN, being adrift by at least four or more years to 2022 and beyond.

This outcome is most disturbing, particularly the revelation that all of the French NPPs are vulnerable when challenged by external threats and, moreover, the fact that to rectify this weakness all of the NPPs require substantial modification and time (years) to achieve the desired *'hardened safety core'* status. From the CSA and SSC tasks it is quite feasible to identify the weaknesses and vulnerabilities of any specific NPP, particularly in respect to the absence of an alternate heat sink and reliable power pumping in the event of a loss of all on- and off-site electricity power in a station blackout (SBO) situation - all of this is invaluable information giving a would-be adversary the means of how, when and where to strike when planning to act against a French nuclear installation.

The final mission of the Review has been to match drone capabilities to the known vulnerabilities of a hypothetical NNP. The attack scenarios included unauthorised drone access to the spent fuel building; aiding and abetting an insider saboteur; the dropping of a spent fuel flask; dewatering of the spent fuel pool; and engineering a SBO event.

Of course, these scenarios are conjectured: they are nominated as a representative sample and are not therefore a comprehensive representation of all reasonably foreseeable attack scenarios; obviously, each is unrehearsed; intentionally, they are applied to a detailed design of NPP that is not present in France; nor are they proven exemplars but, instead, untried possibilities. Nevertheless, even at the most rudimentary level it is shown that the use aerial drones opens up further opportunity for severe damage events to arise at any one of the presently operational French nuclear power plants.

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NUCLEAR POWER PLANTS – DEFENCE IN DEPTH

It is recognised and accepted that nuclear power plants (NPPs), along with other nuclear facilities, might be considered potential targets for terrorist attack and other modes of malevolent action, including unauthorised behaviour of employee(s).

Many national nuclear safety regulatory bodies, such as the *l'Autorité de Sûreté Nucléaire* (ASN), required operators to review the resilience against such malicious acts following the devastating September 11, 2001, attacks on the United States Pentagon and the World Trade Center buildings. Similar security reviews were completed supplementary to the post-2011 round of European Commission (ENSREG) *Stress Tests* following the Fukushima Daiichi incident in which four light water moderated boiling reactor (BWR) NPPs were severely damaged in the immediate aftermath of the earthquake and tsunami of 11 March 2011.

Although obviously undertaken in earnest, none of the national nuclear safety regulators have published in any great detail the additional measures required to bolster the resilience of NPPs against malevolent acts. In the United Kingdom, for example, whereas the nuclear safety regulator – the *Office for Nuclear Regulation* (ONR) – now acknowledges that although the initiation of a terrorist or sabotage threat may be *'reasonably foreseeable'*, it considers a successful attack that results in a significant off-site radioactive release greater than the safety related *reference* or *design-basis*[see later] accident ***not*** to be reasonably foreseeable.[1]

Much the same anti-terrorism line of defence has and continues to be presented by ASN and *Electricité de France* (EdF), in that any reasonably foreseeable malevolent act would not result in a severity of damage and consequences any greater than that ensuing from the nominated *design-basis accident* (DBA).

However, the rationale underpinning this claim is doubtful because ASN, acting in its civil nuclear safety regulatory role, has no formal jurisdiction over matters of security, this being the responsibility of *Secrétariat Général de la Défense Nationale* (SGDN).[2] Yet, SGDN, itself, has no formal expertise in defining the DBA nor, overall, in matters of nuclear safety since its primary function is the detection of and defence against terrorist attack. In fact, informed analysts[3] have argued that France has no effective deterrent against direct action on NPPs unless, that is, the attack was undertaken by an identifiable state.[4]

Even in the absence of hard information and data, held back on security grounds, critics of the nuclear industry have and continue to question the adequacy of the measures required by NPP operators to defend against such malevolent actions. Some claim that this is because the subsequent remedial measures put in place belatedly recognise the threat, thereby acting reactively and not proactively. Also, it is often just not possible to implement the appropriate modification to the structure or adaptation of an existing system, because these were designed and set down years, if not decades, before the new threat arose or when an existing but latent threat was eventually recognised.[5]

For example, the 9-11 World Trade Centre and Pentagon commercial airliner attacks provoked the subsequent introduction and/or enhancement of overflying restrictions over and around NPPs because these nuclear facilities could also have been attractive targets to such terrorists. In another later example, the emergence of the computer worm *Stuxnet*[6] gave rise to considerable anxiety because its exploitation of weaknesses in the cross linkages present in the centralised control and instrumentation systems, necessitating a further barrier of system isolation to be introduced.

These two examples illustrate the continuing need to adapt and strengthen the *defence-in-depth* of NPPs as new threats emerge because of, on one hand, changes in the *modus operandi* of would-be adversaries and/or, on the other, the development, emergence and availability of new technology.

Because it is restrained by the extant design and construction of the NPP, the nuclear industry typically responds to new threats with the introduction of what it claims to be more resilient physical barriers or cordons defining a series of *'owner controlled'*, *'protected are*a' and *'vital area'* zones – typically, these zones extended radially from nuclear safety critical locations and equipment, comprising physical fences and barriers, supplemented with enhanced security, thereby providing, albeit limited in height, physical demarcation of the NPP site.

The rationale underpinning cordoning is that the intervention of the barrier itself protects the plant and equipment within the protected area, thereby negating the need to afford those *'protected'* items of equipment any further and extraordinary safeguarding measures, that is in an absolute sense the equipment itself is *'unprotected'*. The weakness of this approach is that the barriers, both physical and security derived, are custom matched to a specific threat (a Design Basis Threat – DBT)see later and thus may not be at all resilient against a new and different threat – for example, if a *'protected'* area is isolated by unscalable fence then the *'unprotected'* equipment within is only safeguarded until a new threat or modus operandi is able scale or, perhaps, fly over or tunnel under the fence.

In the latter of the above examples, *Stuxnet*, the intervention was that of an electronic firewall to isolate the central computer from extraneously sourced input, added to which was the simple practical expedient of physically removing and/or disabling of USB and other input ports.

The second line of defence-in-depth measures invoked somewhat notional separation of the NPP from external threats. For aircraft crash this included the establishment of no-fly zones[7] and enhanced security scanning at remote airports, a *catch-all* filter that it was claimed applied to a range of hundreds potential targets extending beyond a relatively few NPPs identified to be at heightened risk.

NPP Defence-in-Depth: The available strategies for safeguarding NPPs against terrorist and other forms of malevolent acts is at a crossroads in France:-

- France, unlike other west nuclear power democracies, has not integrated the responsibilities for assessing the disruption of NPP nuclear safety as a direct result of terrorist and/or other malevolent action, with the radiological consequences of such acts - this places considerable doubt over claim that the most extreme terrorist act would not result in radiological consequences greater than those predicted for the design-basis accident.
- Because of the age and set design of the NPP structures and safety systems, particularly the older 900MWe units, new threats and/or changes in modus operandi can only be countered by the provision and/or augmentation of limited physical barriers and legislation/regulatory prohibitions.

The outcome is that French NPP installations are inflexible and limited in counteracting new adaptable threats and newly conceived and hitherto encountered *modus operandi*.

THE NEW THREAT – THE AUTONOMOUS DRONE

Unmanned vehicles (UVs)[8] have become an increasingly familiar day-to-day technology.

Autonomous robotics have been adapted and deployed for a wide range military and civil commercial applications, using aerial, swimming and submersibles, terrestrial and pipe tracking and earth-boring autonomous drones for a diverse ranges of roles and functions.

Unmanned aerial vehicles (UAVs), commonly referred to as *drones*, have specific applications in the military for surveillance and, increasingly, being armed for engagement in theatres of active conflict. These larger drones, such as the US military *Hornet* and *Predator*, are typically fixed wing, capable of bearing significant payloads over great distances and for long flight durations. Control and navigation of these exclusively military drones is, typically, launch and landing under local control (such at an improvised airfield, deck of ship, etc), being switched to and from a remote control centre that may be thousands of kilometres distance – depending on the impositions of the theatre of operation, route navigation and target acquisition is direct via satellite *Global Positioning System* (GPS) or exclusively by *Terrain Contour Matching* (TERCOM).[9]

The military has also developed a range of smaller aerial drones for a variety of surveillance and combat support roles with subsequent marques becoming smaller, more capable, and less expensive due to both military investment in the UAV industry and rapidly improving technology. In recent years, the technology of these smaller drones has been adopted for civilian and commercial use, particularly in news gathering and sporting event filming, surveying of remote land areas, inspection of inaccessible structures such as oil rigs, delivery of small packages,[10] and the like. Such has been the rapidity of uptake and use of these smaller drones that in many countries there is little domestic legislation in place to control the intrusion of air space and privacy.[11, 12]

The relatively recent availability of the so-called *Quadcopters* and *Octocopters* whereby lift, forward propulsion and 3-D yaw, roll and pitch are controlled and maintained by 4 or 8 horizontally dispersed fixed pitch propellers, provide a small (0.6 to 2m diameter) footprint delivery platform. Unlike fixed wing drones, quad/octocopters (*copter drones*) are able to achieve vertical take-off and landing, along with tight positioning manoeuvres. However, because all lift is via propeller thrust flight duration is limited, although with relatively small payload lifts (~1kg) flight duration times can be increased from typically 15 to 20 minutes to in excess of 1 hour.

Many variants of commercial copter drones are available with a diverse range of *'bolt-on'* or *'plug-and-play'* control, function and navigation options – such drones may be purchased without restriction and/or prior registration and licensing, for example:

4 & 8 BLADED COMMERCIAL QUAD/OCTOCOPTORS

Tare weight 4.4kg – Take-Off weight 11kg – load capacity about 6kg

Power Source - 6S 15000mAh Li battery

Flight Duration – 15 to 60 minutes

Structure – Carbon Fibre – Major Dimension 1 to 2m diameter

Typical Purchase Cost - @ €4,500 to €11,000

Features: GPS location navigation - preprogrammed route and tracking – hover - autonomous return to launch or other specified site – follow-me tracking – first-person-view - multiple input channels - autopilot such as 3DR Pixhawk with 32 bit ARM M4 processor capability

Application: professional filming, surveying of difficult to access buildings and structures, police surveillance, traffic control

Video: http://www.youtube.com/watch?v= j2HmicDUs

Similarly, a range of *'hobby'* copter drones are obtainable for purchase on the Internet and from retail outlets – such drones are available a various levels of control and navigation sophistication, for example:

4 BLADED HOBBY QUADCOPTOR APPENDIX 1 for Manufacturer's Specification

Tare weight 1.2kg – Take-Off weight 1.6kg – load capacity about 0.4kg
Source - 700mAh Li Ion battery
Flight Duration – about 10 to 15 minutes
Hover Accuracy – vertical 0.8m – horizontal 2.5m
Structure – resin reinforced plastic – 0.35m diameter
Typical Purchase Cost - @ €150 to €1,100
Application – hobby activities
Video: http://www.youtube.com/watch?v=ESKl2dza16U

Recently, the military developed micro aerial vehicles (MAVs) have been adapted to the civil commercial marketplace. One role of military MAVs, typically of *tricopter* geometry and ranging in overall size from a few to 10 or so centimetres, is to *'perch and stare'* when deployed in operational theatres. Another operational role for MAVs is to deploy in swarms with each MAV complementing and/or supplementing the actions of others, as shown here in a ball catching role (right).

Video: http://robohub.org/video-watch-flying-robots-cooperate-throw-and-catch-balls/

Many of the active components (motors, controllers, etc) of coptor and other geometry drones are readily available on the internet, as are plans and instructions for their design and assembly – the availability of such components and information has led to a thriving amateur build community resulting in some very high capability amateur drone builds, as shown by the following:

EXAMPLES OF AMATEUR BUILT COPTOR DRONES

1)	Ducted Fan	http://www.youtube.com/watch?v=yQILzdfmXukPower
2)	Heavy Lift	http://www.youtube.com/watch?v=L75ESD9PBOw
3)	High Endurance	http://www.youtube.com/watch?v=BfpfFgRTddc
4)	Fully Autonomous	http://www.youtube.com/watch?v=vxoQaaI3-7A
5)	Manoeuvrability	http://www.youtube.com/watch?v=f3UyZTrODzc

A wide range of types and manufacturer of UAV drones are available at commercial and retail outlets. The recent and rapid development of the highly manoeuvrable copter drones, at affordable purchasing costs, favours this type of drone for both commercial and hobbyist use in the civilian sector.

The basic skeletal and power frameworks of many of the copter drones presently available can be custom modified by a comprehensive range of *'plug-and-play'* control, function and navigation hardware packages. Drones may therefore be custom-tailored to fit within a required functionality envelope with, for example, ability for *'first-person-view'* (ie with the remote handler looking through the *'eyes'* of the drone or via an accompanying drone); the drone journey timing, route and destination might be pre-programmed and GPS waypoints located, thereby freeing the drone of dependence upon its remote handler, enabling it to operate in the dark and/or out of sight of its handler; and it might be equipped with a '*follow-me*' function enabling it to autonomously track and fly alongside a GPS-enabled android device; several drones might be programmed to operate in accompaniment of each other; and so on and so forth.

Similarly, the modular design approach and universal load/function deck of the drone can be adapted to receive a wide range of add-on and independently powered devices, thereby extending the functionality of the drone from, say, primarily that of being a platform for aerial photography and filming, to that of, for example, delivery and placement of loads and packages, the positioning of devices and instrumentation, and so on. Once positioned, these devices and packages might, themselves, assume an autonomous role and await instruction from a remote handler or, indeed, from another android such as an MAV acting in a *perch and stare* mode.

The Autonomous Drone: A variety of types, sizes and capabilities of unmanned aerial vehicles are readily available for commercial purchase, both completely assembled and in kit form. The purchase and ownership of such drones is not subject to any registration, certification and licensing and the security and commercial air space agencies have yet to put in place any practicably enforceable legislation and regulation.

Of the fixed wing, single rotor helicopter, and copter drone geometries, it is the latter tri-, quad-, and octocopter drones that dominate the civil commercial and hobby markets. This is because copter drones have vertical take-off/landing, hovering and tight manoeuvring capabilities and, being mainly of carbon fibre build and electrically powered, the drones are quiet, virtually undetectable by radar, and generate a very small heat signature when in operation – these stealth features, coveted by the military, have along with other advanced and miniaturised technologies fully transferred to the civilian commercial and hobbyist sectors.

THE DRONE OVERFLYING OF FRENCH NPPS AND NUCLEAR FACILITIES

On 29 October 2014, EDF stated that unidentified aerial drones had flown over and around seven of its French nuclear power plants and other nuclear fuel and research and development facilities across France.

The first of these unauthorised intrusions took place at the Saclay nuclear research centre operated by the *Commissariat à l'énergie atomique* (CEA) on 14 September. Then on 5 October drone activity was encountered at Creys-Malville, in the ensuing days followed by similar airspace incursions in Gravelines, Cattenom, Moselle, Le Blayais, Bugey, Chooz and Nogent-sur-Seine south-east of Paris. On at least one instance, on October 19, drones were flown at the same time over several sites hundreds of kilometres apart.

Since 5 October to date, reported aerial drone activity over and about French NPPs has been:

TABLE 1 UNAUTHORISED DRONE OVERFLIGHTS OF FRENCH NUCLEAR FACILITIES UP TO 16 NOVEMBER 2014[13]

FACILITY		OWNER	DATE OF FLIGHT	SOURCE	CONFIRMED	Nº FLIGHTS
Saclay	R&D	CEA	14 Sept	GP		1
Superphenix	FBR	CEA	5 Oct, 3 Nov	GP	confirmed	3
Nogent	NPP	EdF	13, 19 Oct	EdF	EdF	2
Le Blayais	NPP	EdF	13 Oct	EdF	EdF	1
Cattenom	NPP	EdF	14 Oct, 10 Nov	EdF	EdF	2
Chooz	NPP	EdF	19 Oct	EdF	EdF	1
Bugey	NPP	EdF	19, 20, 24 Oct, 6 Nov	EdF	EdF	4
Graveline	NPP	EdF	19 Oct	EdF	EdF	1
Pierrelatte	U Enr	AREVA	29 Oct	GP		1
Golfech	NPP	EdF	30 Oct, 12 Nov	GP		2
Penly	NPP	EdF	30, 31 Oct, 14 Nov	GP	police	3
Flamanville	NPP	EdF	31 Oct	EdF	EdF	1
Fessenheim	NPP	EdF	31 Oct	EdF	EdF	1
Dampierre	NPP	EdF	31 Oct, 2 Nov	GP	police	2
Saint-Laurent	NPP	EdF	31 Oct	GP	police	1
Belleville	NPP	EdF	31 Oct	GP	unconfirmed	1
La Hague	Fuel	AREVA	31 Oct, 14 Nov	AREVA	AREVA	2
St Alban	NPP	EdF	5, 7 Nov	GP	GP confirmed	2
Marcoule	Fuel	AREVA/CEA	6 Nov	media	confirmed	1

As at 16 November 2014, over the period from 14 September, a total of 31 drone overflights had taken place at 19 French nuclear installations, 14 of which were NPP sites operated by EdF. It is believed that each of these flights happened in the early morning or overnight during the hours of darkness.

The French NPP Overflights: Other than official confirmation that overflight intrusions have occurred, very little further information has been made publicly available on the flight path patterns, the duration of the individual flights, altitude, speed etc. Nor is information available on the type and size of the individual drones involved.

However, what is likely is that these drone intrusions comprise, as a whole, a concerted and well organised campaign centred on nuclear facilities and, particularly, focussed on EdF nuclear power plants. Moreover, because the first public reporting by EdF of the overflights was not until 29 October, before which some eleven or more overflight incidents had taken place, these could not have arisen as *'copy cat'* adventures of unrelated, individual remote controllers.

There are two obvious deductions to be drawn from the spate of drone overflights: first, that it was organised and implemented by a single-minded, national group of individuals operating in unison across France and, second, that the authorities have not been able to predict when and where the overflying is to happen and, thus, the security and safeguarding of the NPPs has been seriously compromised.

IMPLICATIONS OF UNAUTHORISED DRONE INTRUSION INTO THE NPP SAFETY REGIME

First, it has to be considered and acknowledged that the perpetrators (whoever they are) of the present drone overflight activities may not have any further malevolent intent.

Even so, the unauthorised drone activity has revealed a serious and apparently systemic weakness in the security and isolation of the French NPP sites. This is that it is possible to access inner and *'protected'* areas within the NPP site with small, low flying drones, relatively undetected during the hours of darkness.

The point in question is now that these particular perpetrators have breached into the *'protected area'* by the use of aerial drones, there is no reason why a similar aerial assault could not now be undertaken by those also intending to assail the existing defence-in-depth barriers with the objective of inflicting severe damage to the NPP.

SHORTFALLS, WEAKNESSES AND NUCLEAR SAFETY RISK AT FRENCH NPPS

In 2012 ASN acknowledged that 41 of the 58 operational French NPPs required some degree of modification to meet the *stress tests* and *baseline safety standards* set by the European Commission (ENSREG) in the wake of the Fukushima Daiichi disaster of 2011 – the weaknesses and shortfalls that could, according to ASN, result in a nuclear safety risk below the *baseline safety standards* are set out in the findings of series of *Complementary Safety Studies* (CSAs).[14,15]

In its CSAs, ASN identified a number of individual NPPs requiring urgent evaluation *'installations et sites prioritaires à traiter en 2011'*.[14,15] **APPENDIX 2** lists 41 NPPs gleaned from the ASN CSA reports, Each which requires some element of modification to satisfy the specific nuclear safety shortfalls identified by the European Commission *stress tests* – a small representative sample of these is as follows:

TABLE 2 SAMPLE OF NPPS PRESENTLY WITH INTOLERABLE LEVELS OF NUCLEAR SAFETY RISK – PRIORITY NPPS

NPP SITE	NPPS (TOTAL)	NPP YEAR	EARTHQUAKE	FLOODING	SPENT FUEL POND	ULTIMATE HEAT SINK	RADIOACTIVE RELEASE	STATION BLACKOUT SBO
FESSENHEIM	2 (2)	1977	flood containment damage loss of ultimate heat sink requires seismic analysis of dykes, etc protecting against flood seismic reinforcement required	cooling canal embankment damage nuclear island below flood level below CMS flood level assessment required of standing water level following embankment failure	spent fuel flask drop	assessment of consequences of Grand Canal d'Alsace embankment failure required Heat sink 'clogging' review awaited heat sink higher than NPP platform	local hydrogeology favours groundwater contamination	Grand Canal d'Alsace embankment failure could result in total station blackout reactor basement reinforcement required
BUGEY	2 (4)	1978	flood containment damage loss of ultimate heat sink requires seismic analysis of dykes, etc protecting against flood low SSE rating (0.1g) seismic reinforcement required	cooling canal embankment damage nuclear island below flood level below CMS flood level	spent fuel flask drop	heat sink higher than NPP platform	local hydrogeology favours groundwater contamination	containment pressure electrical backup
TRICASTIN	2 (4)	1980	flood containment damage loss of ultimate heat sink Extensive evaluation of embankment structures required particularly with regard to internal erosion and liquefaction	cooling canal embankment damage nuclear island below flood level		heat sink higher than NPP platform	knock-on effect of Tricastin AREVA facilities to the be assessed	

Also, as part of its assessment of the NPP operator's CSA response, ASN instructed *L'Institut de Radioprotection et de Sûreté Nucléaire* (IRSN) to independently evaluate the operator's CSA programme.[16] IRSN identified that, in addition to the current nuclear safety provisions and CSAs, a new concept of a '*hardened safety core* of *structures, systems and components*' (SSCs) should be urgently put in place – these SSCs are in addition (where warranted) to the existing safety systems and management procedures. This, IRSN argued, would render the NPPs sufficiently robust and reliable to cope with all considered extreme external hazard scenarios necessary to maintain control of reactivity, heat removal and containment of radioactive materials, applied to both the in-core reactor fuel load and the spent fuel storage ponds.

Correspondingly, ASN required EdF to formulate the measures necessary to achieve the "*hardened safety core*" (SSCs) of NPP features by 30 June 2012 – these are individually identified in the ASN National Plan[18] of 2012 although the programme for practicable implementation of the SSCs in support of this at each affected NPP has yet to be fully resolved.[17,18,21] A central requirement of the '*hardened safety core*' is the provision of an alternate heat sink for the site blackout (SBO) casesee later for **all** presently operational NPPs but, for this, EdF is being allowed until the close of 2018 to table and practicably implement its proposals.[19]

The programme of physically upgrading all of the presently operating French NPPs with an alternate heat sink (together with failsafe emergency electrical power for pumping, emergency response) is likely to demand significant resources once that EdF's proposals have been approved,[20] taking several years to complete, certainly beyond 2022,[21] during which the risk of failure under extreme external hazards will remain heightened.

> **Outstanding Nuclear Safety Issues at French NPPs:** Following Fukushima ASN set EdF a number of CSA and SSC tasks that are detailed in the ASN National Plan of 2012.
>
> Viewed overall, the SSC *'hardened safety core'* requirement placed a Herculean task on EdF, requiring that it identify and scheme design all of the structural components, safety systems, etc., by the revised dates of June and December 2014 and 2015 and, following approval by ASN, to have the *'hardened safety core'* installed and commissioned by the close of 2018 in all of the presently operational NPPs. However, little information is available on the progress of the SSCs, together with the CSA tasks, some of which were prioritised as very urgent, although there is one intriguing snippet from EdF suggesting that the *'hardened safety core'* at each of the present operating NPPs will not be practicably installed until well past 2022.
>
> A most disturbing outcome of the post Fukushima Daiichi *stress tests* is the revelation that all of the French NPPs are vulnerable when challenged by external threats and, moreover, the fact that to rectify this weakness all of the NPPs require substantial modification and time (years) to achieve the desired *'hardened safety core'* status – all of this is invaluable information to a would-be adversary planning to act against a French nuclear installation.

POTENTIAL NUCLEAR SAFETY INCIDENT SCENARIOS INVOLVING AERIAL DRONE INTRUSION

The following series of postulated incident scenarios involving violation of the NPP *'protected'* area(s) by aerial drones – the scenarios cited here are played out for a nominal 1,000MW_e single reactor NPP of mid-1980s design vintage, being a Westinghouse 4-loop SNUPPS[22] not that dissimilar to the AREVA P4 units.[23]

The nuclear safety case for this Westinghouse SNUPPS plant is drawn from probabilistic risk assessment of the acceptable likelihood or frequency (ie say a chance of 1 in 1 million years) of *'reasonably foreseeable'* accidents that, put simply, requires all *'credible'* accidents not to result in intolerable radiological consequences. The acceptable plant response in curtailing the radiological consequences to a tolerable level is the *'design-basis'* of the plant and its safety systems.[24]

This probabilistic design approach, which equally applies to French NPPs and, particularly, ASN's regulatory framework, is rooted in the rationale that accidents are by their very nature *accidental*, random and unmotivated events. This rationale contrasts with the reality that underpins and motivates malicious actions, that is where the adversary *intentionally* and intelligently seeks out and exploits the vulnerabilities of the plant and its protective systems.

Outside the probabilistic design-basis rationale, malicious acts have to be assessed on a non-probabilistic *Design Basis Threat* (DBT) basis, defined and shared jointly by ASN and, it is assumed, SGDN. The response to the French DBT (post 9/11) was originally defined by IRSN as a series of *force-on-force* exercises, these being relatively small scale *Level 1* and *2* events compared to the *Level 3* EPEES exercises that are to test the post accident/incident response mainly in the public domain.[25] Although virtually nothing is published in the public domain, it is doubtful that the current DBTs adopted for French NPPs includes an element accounting for aerial drone attack.

As presented here, the Westinghouse SNUPPS scenarios have not been completely thought-through; obviously, each is unrehearsed; and, importantly, nor should they be considered as proven exemplars but, instead, untried possibilities. Essentially:

Drone Accessibility: Each scenario briefly explores and expands on the accessibility to the NPP site that the coptor type of drone makes possible – this ability to penetrate the NPP site and its *'protected'* areas has been irrefutably demonstrated by the recent unauthorised overflying of NPP sites.

Vulnerabilities of the NPP: Once access is established, particular vulnerabilities of the NPP and its supporting systems are identified – equipment and plant within hitherto inaccessible *'protected'* areas becomes vulnerable and rendered *'unprotected'* by the drone intrusion. A fundamental vulnerability of all operating French NPPs is the unavailability of an alternate heat sink, particularly during SBO events during which both the reactor core fuel and/or the spent fuel in the ponds is at risk.

Drone-NPP Interaction: The drone has to address the task and interact with the NPP at the point(s) of vulnerability, this being matched in complexity, duration and physical exertion to the ability of the drone(s) to deliver some form of physical and/or electronic interaction with the NPP – the commercial and military use of drones has shown adaptability of even the smaller MAV drones to successfully undertake and complete complex tasks.

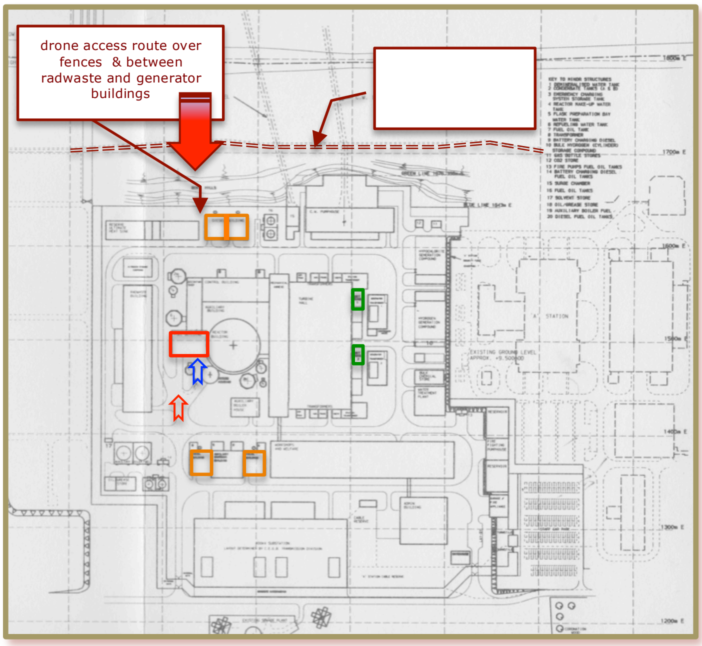
Planning and Implementation: The would-be terrorist (or saboteur) has time to plan, improvise and perfect the attack well ahead of its implementation - such preparation time will enable the drones to be customised with add-ons, such as manipulators and grabs; armed with shaped explosive charges; and an armoury of radio-jamming and other diversion technologies developed for drone deployment – it should be noted that perpetrators of the 9/11 attacks practised and rehearsed theirs skills at pilot training schools for a year or more ahead of the attacks on the World Trade Centre, Pentagon, and the unknown target destination of UA Flight 93 that failed in its mission, crashing near Stonycreek Township, Pennsylvania.

Drone Intrusion and Attack Scenarios

a) NPP Site Access

Entry to the NNP main site from seaside beach at about 6m altitude over double chainlink fence and sterile land corridor, then at lower level through passageway formed between radioactive waste and emergency generator buildings.

Remote handler positioned on beach in line of sight of the entry pathway. Alternatively, remote handler mingles with other beach users during daylight hours to navigate MAV drone into site thereby establishing an entry path during daylight hours, registers and records path waypoints for transfer to larger drone for a remote, pre-programmed entry path during the hours of darkness. Alternatively, for the second entry, the MAV drone could act as an android in *'follow me'* mode taking the larger drone with it.



Plan 1 - Site Access Route

b) Aiding and Abetting an Insider Saboteur[26]

Items useful to an insider are smuggled into the NPP site via a load carrying copter drone adapted to transport a cargo box or similar. The drone adopts the established entry route of Plan 1 (above) making its way to a suitably hidden stash location, say on a roof, tucked into equipment or similar, where the load is released for collection at a later time by the would-be insider saboteur – the drone or drones may make several delivery trips.

The larger (1 to 2m diameter) quad/optocoptor drones typically have a payload capacity of between 6 to 10kg. This capacity is sufficient for a variety of load lifts, for example a small calibre, light machine gun such as the Heckler & Koch M27 weighs around 3.6kg empty and fires a 4g bullet projectile, with a 20 round magazine weight of about 0.7kg.

Other deliveries might include batches of explosive, such as the RDX based C4 plastic explosive at a density of about [redacted]g/cm usually available in [redacted]kg block sizes, together with the requisite [redacted] or [redacted] detonators with detonating cords; canisters of toxic gas, such as the organophosphate nerve agent [redacted]; and so on.

c) Spent Fuel – Drop Flask

Following a decay period of 3 to 5 years, irradiated (spent) fuel is transferred from the cooling pond in the spent fuel building (shown □ in Plan 1 above).

The intensely radioactive fuel transfer includes loading the fuel assemblies into a flask submerged in the spent fuel pond. The flask is loaded with up to 6 to 10 tonnes of fuel in the flask fill bay (shown in RH cross-section deeper into the building), sealed, purged and then hoisted out of the bay where it is surface decontaminated. When the flask is dry, it is then moved forward over the dispatch

REDACTED

Plan 2 - Spent Fuel Building Dispatch Bay

bay (LH section) where it is lowered onto a low-loader vehicle for dispatch to a railhead for the onward journey to a reprocessing or chemical separation facility – in France this is the AREVA (nee COGEMA) plant at Cap la Hague.

During the flask handling operations in both the flask loading and dispatch bays there is risk of the flask dropping – at a number of NPPs the free-fall height exceeds the certified flask impact certification height[27] and so there is an attendant risk of flask failure and a significant radioactive release from the flask contents. At the Bugey and Fessenheim NPPs specific excessive height, flask drop scenarios were identified for remedial action – see **TABLE 1**.[28]

Referring to PLAN 2, a MAV is sent onto the NPP site to *'perch and stare'* at the dispatch bay low-loader vehicle door of the fuel store (PLAN 1 - ⇧). Then, when the [redacted].

It might be possible for the MAV to *'perch-and-stare'* inside the fuel pond building, thus providing the remote human controller visual update of the hoisted position of the flask waiting dispatch, at which time the cable cutting drone commences its approach to the fuel building.

d) **SPENT FUEL BUILDING – SPENT FUEL POOL WATER DRAIN DOWN (SF POOL DEWATERING)**

Spent (irradiated) fuel is periodically transferred from the reactor pressure vessel into the spent fuel storage pond where remains for a period of 3 to 5 years during which the short-lived radioactivity naturally decays. Since spent fuel in the NPP pond continues to generate heat (by virtue of radioactive decay alone) the pond requires continuous and long-term cooling which, if lost or disrupted, can result in boiling and water loss over relatively short times from a few hours to a day or more.[29] Thereafter, should the fuel uncover, the zirconium alloy fuel cladding is likely to exothermically oxidise with liberation of free hydrogen and consequential high risk of deflagration and/or explosion.[30]

Although, detailed accounts of the spent fuel inventories for each NPP are not published,[31] at any one time the radioactive inventory of the spent fuel pond is very significant and, in terms of the longer-lived radionuclides such as Caesium-137, the fuel pond inventory can be greater than that of the NPP's operating nuclear reactor.[32] Continuing containment of the fuel pond water level and temperature is therefore essential.

It is now acknowledged[33] that the spent fuel storage ponds present a weakness in the overall nuclear safety case, so much so that concern has been expressed about the lack of resilience of the spent fuel ponds, particularly in respect of the ponds of the earlier P900 NPPs that require strengthening to improve resilience against external threats, including terrorist attack. At each of the operating French NPPs the spent fuel pond and associated cooling systems feature in the SSC *'Hardened Safety Core'* requirements.

There are a number of opportunities for severe disruption and possible radioactive release within and from the spent fuel pond building (□ PLAN 1).

Because the pond structure comprises a thick, reinforced concrete tank, breaching the walls would be a challenge for the limited size of the (explosive) load carried by a drone (at best about 10 to 15kg). However, there is opportunity to damage and disrupt the pond cooling system which would also result in some pond water loss – for a NPP plant that was undertaking a reactor pressure vessel non-destructive examination (say, at a 5-10 year life extension review) with all of the reactor fuel core transferred into the pond, the pond boil down time could be a low as 6[34] or 8 hours.[29]

A drone attack could therefore focus on the auxiliary equipment servicing the spent fuel pond, for example a two-drone assault on the lower level, pond water cooling room. The first drone blasts an entry into the building [PLAN 1 - ⇧] via a shaped charge, and with the second drone laying [redacted]> <[redacted] Another option, is to stage a drone attack on the roof mounted [redacted] believed feature on certain of the earlier French NPPs.

REDACTED

PLAN 3 - SPENT FUEL BUILDING COOLING ROOM

In or around 2002, IRSN considered[35] a number of fault conditions leading to the accidental drainage of the spent fuel pond of a $900MW_e$ series NPP acknowledged *"the weaknesses of the containment of the fuel storage building"* coupled with the observation that *"there is no physical separation of both cooling channels of the PTR [pond cooling system – heat exchangers and pumps] system. Indeed, both pumps of this system are in the same room"* adding that an *"internal hazard – fire or flooding. . . – may result in a total loss of cooling of the spent fuel pond"* - this lack of redundancy and diversity in the pond heat exchanger pumps is reflected in the Westinghouse SNUPPS plant assumed for the conjectural scenario above - it is not known if modifications were subsequently implemented to eliminate or at least mitigate potentially very severe radiological consequences of a pond dewatering event – if not then the French $900MW_e$ series NPPs may remain susceptible to the pond dewatering scenarios above and below.

Again referring to the earlier $900MW_e$ plants, it as long been acknowledged that the higher level outer containment of the spent fuel pond building is somewhat minimal, being little more than that of a commercial warehouse of the times. Breaching through the roof by deploying a series of explosive cutting charges could permit a larger diameter, and hence greater load carrying capacity, octocoptor drone into the building. Once inside, and bearing a larger explosive load, the drone action possibilities could include applying [redacted] into the ponds and water filled flask bays; similarly, shaped charges could be positioned to dislodge and/or breach the [redacted], and the [redacted] (PLOT 4) and thus provoke dewatering of the main pond; and, it should also be possible to rig a [redacted] thereby damaging and displacing the spent fuel assemblies under storage and, possibly, breaching the pond walls.

REDACTED

PLAN 4 - SPENT FUEL BUILDING LOWER & MID DECKS

To supplement such attempts to dewater the main spent fuel pond, a separate drone might target the [redacted], this being only lightly protected and located outside the nuclear island.

It is a relatively straightforward calculation to determine the quantity of C4 equivalent explosive, in cased, shaped charge geometry for both surface mounted and surface stand-off, sufficient to fracture and/or penetrate the [redacted] of the pond building, [redacted],

[redacted], and the [redacted] – these sensitive detailed design and specification aspects are withheld from this Review.

e) **LOSS OF BOTH ON- AND OFF-SITE POWER – TOTAL NPP BLACKOUT - SBO**

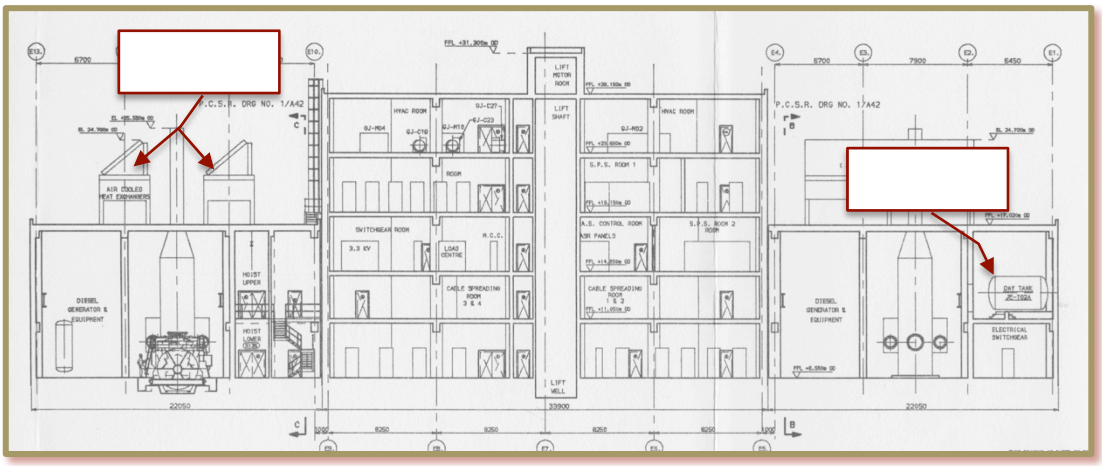
Total station blackout (SBO), a situation where the NPP sustains a complete loss of electrical power with both off-site (LOOP)[36] and on-site power (emergency generator power) isolated. Although in such an event the reactor will trip and shut down, the in-core fuel continues to generate heat and requires cooling for several days following shut down – essential electrical services, including reactor in-core fuel cooling, require about 8% of the maximum power output (MPO) of the plant when operating normally, with this demand rapidly reducing and steadying at about 1% MPO at about one and one-half hours following the reactor trip.

At Fukushima Daiichi in March 2011, the three operational reactors immediately tripped and shut down when the earthquake was sensed. At the same time a LOOP situation occurred because the earthquake also disrupted the regional electricity distribution grid breaking off-site power links to the Fukushima NPP. However, as planned for, the on-site emergency generators automatically started and maintained adequate cooling the reactor fuel cores. Then, about 40 minutes later, the earthquake generated tsunami came ashore swamping the Fukushima site and putting the emergency generator sets out of action. Denied any forced cooling, about one hour later the fuel core of each of the previously operating reactors entered irreversible meltdown and all three plants suffered catastrophic damage as a result of the hydrogen liberated by a steam-zirconium reaction,[30] the consequence of which has been very significant (and ongoing) radiological releases to the atmospheric, terrestrial and marine environments.

Achieving SBO requires a multiple drone onslaught of both on- and off-site facilities. Separately, the four on-site emergency-generators building (□ PLAN 1) and the connection to off-site grid supplies (□ PLAN 1) have to be isolated. For the Westinghouse SNUPPS plant adopted here the grid connections are on-site but, more typically, these are usually located just off-site, such as at the Fessenheim NPP where the two[37] grid connections are [redacted] the [redacted].

Fessenheim NPP Off-Site Grid Connections

Disrupting the two off-site grid connections could be achieved with two or more sacrificial drones acting independently to deliver and place [redacted]. Alternatively, two sets of MAV, each operating in coordination, could selectively place [redacted] to short-circuit and burn out the overhead power conductors.[38]



PLAN 5 EMERGENCY DIESEL GENERATOR SETS (SOME ACTION LOCATIONS REDACTED)

For the Westinghouse SNUPPS NPP there are four emergency generators, dispersed in two pairs at opposite extremes of the NPP site (□ PLAN 1). Each generator set has a number of vulnerable features that, if damaged, would result in overheating and halt operation of the generators – these include the roof mounted generator engine cooling system and, just within each generator building, the diesel fuel day tank and its small lift pump. Aerial access [redacted] and therefore exposed to a direct [redacted] and, although the [redacted] the generator enclosure building, this comprises [redacted], non-structural [redacted] that could be readily breached with a small shaped explosive charge.

With off- and on-site electricity feeds isolated in these ways, the crippled NPP would be wholly dependent upon its non-powered emergency cooling systems that, incidentally, were the final line of defence that failed at Fukushima Daiichi in March, 2011.

The CSA assessments identified specific issues, sufficient to warrant the ASN National Plan,[18] with certain and all of the operating French NPPs, including:

> FESSENHEIM: THIS NPP is acknowledged to be at risk of a total station blackout (**TABLE 1**) if some natural external event triggered an embankment failure[39] on the Grand Canal d'Alsace running alongside the NPP and which serves the turbine steam circuit condenser cooling intakes. Embankment failure could result in total station blackout. In this respect, it would not be particularly challenging to connive a scheme (not necessarily drone assisted) whereby the embankment of this and a number of nuclear islands of other NPPs (see **APPENDIX** 2) could be flooded – such inundation might disable the emergency generators and render the relatively lightly protected spent fuel buildings and pond cooling and water level replenishment system inoperative. A similar serious flooding incident actually developed at Blayais NPP in December 1999 when the seawall was overwhelmed, following which three operational nuclear reactor plants had to revert to emergency cooling procedures.[40]
>
> TRICASTIN: As at Fessenheim, the heat sink serving this NPP is higher than the NPP site level and at risk of disruptive inundation.
>
> ALL OPERATING NPPS: The importance of the maintaining on-site emergency generator electricity supplies is because all of the NPPs will be required to establish a viable alternate heat sink – at a number of NPP sites the SEA (demineralized plant water) supplies are considered sufficient for this but these need to be upgraded to ASN's *'Hardened Safety Core'* standard.
>
> This dependency upon maintaining cooling water supplies is because none of the presently operating French NPPs have access to an alternate heat sink serving both the reactor primary circuit and the spent fuel pond.[41] ASN's *'Hardened Safety Core'* requirement stipulates that pumping from an alternative heat sink be maintained in the event of a SBO to safeguard against fuel melt in both the reactor core and spent fuel pond. Maintaining pumping from an alternative heat sink requires an extraordinary level of safeguarded emergency electricity supply when all other on- and off-site power supplies (including the existing standby emergency generator sets) have failed – this extremely demanding requirement has to be determined (although not actually installed and commissioned) by at least the close of December 2018.[42]

Until the alternate heat sinks and stand-alone pumping schemes are established French NPPs remain vulnerable to fuel melt (reactor core and spent fuel pond) scenarios during SBO situations.

Drone Intrusion Attack Scenarios: The example scenarios presented here suggest that opportunities exist if access to *'protected'* areas is gained – the spate of drone flights over French NPPs clearly demonstrate that unchallenged and unauthorised access has taken place at least at 26 occasions over 17 nuclear installations, 14 of which were EdF operational NPPs.

Access to *'protected'* areas of the NPP site opens up new opportunities for new types of threat. Detecting and apprehending aerial drones entering, hovering, going about tasks and/or in *'perch'* and *'sleep'* modes is challenging in the visual, acoustic and electronic signal cluttered industrial environment of an operational NPP. Moreover, if the current rate of technology transfer from the military continues apace soon, if not already, commercial and hobbyist drones are likely to acquire further stealth features to counter the most advanced military detection and jamming techniques.

The coupling of advanced, autonomous drones to the existing vulnerabilities of NPPs is and will continue to be a challenge indeed.

PostScript: No doubt, upon receipt of this Review, the operators, its nuclear safety regulator and those responsible for security of the NPPs will opine, giving reasons for this, that and the other, why the each of the example scenarios will be countered by its soundness of design, regulatory prowess and security vigilance – that said, one might postulate that the architects, engineers, builders, air traffic controllers, and others in Homeland Security would have reasoned with much the same conviction before knowledge that the 9/11 events were about to happen.

Another expected nuclear industry response to this Review will be the claim that French NPPs are the best defended industrial facilities of the entire French energy infrastructure. This may be true but it provides little reassurance because just being better is not the same as being good enough – such a false sense of security is, perhaps, one of the biggest obstacles to achieving real security and resilience against malicious acts.

This exercise has shown that, clearly, opportunities exist to exploit the known vulnerabilities of French nuclear power points, all via the readily available aerial drone technology.

APPENDIX 1

TYPICAL HOBBY QUADCOPTER MANUFACTURE'S SPECIFICATION

DJI PHANTOM FC40 QUADCOPTER W/2.4 GHZ WIFI CAMERA

General Features	• With new 5.8G Remote Control and Receiver. • Featherweight 2.4G Wi-Fi Camera With 720p/30fps HD Video • User Friendly Smartphone App For First Person View (FPV) • 10x Digital Zoom Function While In FPV • Low Latency Live Preview • Remote Control Mobile Phone Capture • Capture Images & Record Video While Flying • In-phone Album Synchronization			
Basic Parameters	Operating Temperature	Power Consumption	Take-off Weight	Hovering Accuracy (GPS Mode)
	-10°C ~ 50°C	3.12W	<1200g	Vertical: ± 0.8m Horizontal: ± 2.5m
	Max Yaw Angular Velocity	Max Tilt Angle	Max Ascent / Descent Speed	Max Flight Velocity
	200°/s	35°	±6m/s	10m/s
	Diagonal distance (motor center to motor center)	Phantom Prop Guard		
	350mm	Weight(Single):18.7g Size(Single): Angle(155.0°) Radius(112.32mm) Whole Size with Four Prop Guards: 575.5mm		
ESC Sound Introduction	Ready	throttle stick is not at bottom	Input signal abnormal	Input voltage abnormal
	♪1234567	BBBBBB…	B——–B——–B…	BB—BB—BB—BB…
Charger & Battery Parameters	Charger AC Input	Charge Current	Current Drain for Balancing	Power
	100-240V	1A/2A/3A	200mA	20W
	Battery Type			
	LiPo			
Transmitter	Working Frequency	Communication Distance（open area）	Receiver Sensitivity（1%PER）	Transmitter Power
	5.8GHz ISM	CE: 300m; FCC: 500m	-93dBm	CE: 25mw; FCC: 125mw
	Working Current /Voltage	Battery		
	80 mA@6V	4 AA Batteries		
FC40 Camera	Image Sensor	Lens	FOV	Focal Range
	HD 720p/30fps	Aperture F2.2	100 Degree Wide Angle	25cm-infinity
	Wireless	Wireless Mode	Mobile With-Fi Video Size	Battery
	IEEE 802.11 b/g Compliance	Direct Mode	WQVGA	Built-in 700 mAh Li-on Battery

APPENDIX 2

SHORTFALLS IN RESILIENCE AGAINST EXTREME EXTERNAL EVENTS AT THE ASN PRIORITY NPPS[43]

NPP SITE	Nº NPPS PRIORITISED (TOTAL UNITS)	OLDEST NPP YEAR	EARTHQUAKE	FLOODING	SPENT FUEL POND	ULTIMATE HEAT SINK	RADIOACTIVE RELEASE	STATION BLACKOUT SBO
BELLEVILLE	2 (2)	1987	✓ low SSE rating (0.1g)	✓ no account of Strickler coefficient – elevated water flow levels ✓ below CMS flood level				
BLAYAIS	2 (4)	1981	✓ dam burst	✓ previous flood incident (1999) ✓ elevated hatch thresholds required				
BUGEY	2 (4)	1978	✓ flood containment damage loss of ultimate heat sink ✓ requires seismic analysis of dykes, etc protecting against flood ✓ low SSE rating (0.1g) ✓ seismic reinforcement required	✓ cooling canal embankment damage nuclear island below flood level ✓ below CMS flood level	✓ spent fuel flask drop	✓ heat sink higher than NPP platform	✓ local hydrogeology favours groundwater contamination	✓ containment pressure electrical backup
CATTENOM	4 (4)	1986		✓ below CMS flood level				
CHINON	2 (4)	1982		✓ below CMS flood level				

CHOOZ	2 (2)	1996		✓ flood operating rules not applied					✓ lightening strike protection
CIVAUX	2 (2)	1997	✓ seismic qualification under review	✓ cooling canal embankment damage nuclear island below flood level		✓ safety case justified only for single NPP on site	✓ local hydrogeology favours groundwater contamination	
CRUAS	2 (4)	1983		✓ cooling canal embankment damage nuclear island below flood level ✓ thousand year flood peripheral protection issues ✓ flood operating rules not applied and isolation procedures not in place	✓ below CMS flood level	✓ Heat sink ‘clogging’ review awaited		
DAMPIERRE	2 (4)	1980	✓ low SSE rating (0.1g)	✓ flood operating rules not applied	✓ below CMS flood level			
FESSENHEIM	2 (2)	1977	✓ flood containment damage loss of ultimate heat sink ✓ requires seismic analysis of dykes, etc protecting against flood ✓ seismic reinforcement required	✓ cooling canal embankment damage nuclear island below flood level ✓ below CMS flood level ✓ assessment required of standing water level following embankment failure	✓ spent fuel flask drop	✓ assessment of consequences of Grand Canal d’Alsace embankment failure required ✓ Heat sink ‘clogging’ review awaited ✓ heat sink higher than NPP platform	✓ local hydrogeology favours groundwater contamination	✓ Grand Canal d’Alsace embankment failure could result in total station blackout ✓ reactor basement reinforcement required
FLAMANVILLE	3† (2)	1985	✓ make-up SEA ponds transfer must be ‘hard cored’ and seismic qualified			✓EPR total loss of heat sinks study required ✓ make-up SEA ponds must be ‘hard cored’		✓EPR 2-hour battery backup requires extending
GOLFECH	2	1990						

Gravelines	3 (6)	1980	✓ lack of reactor cavity robustness	✓ below CMS flood level ✓ elevated hatch thresholds required ✓ flood operating rules not applied and isolation procedures not in place		✓ intake channel retaining wall stability under assessment	✓ rupture etc of oil pipeline crossing site requires justification	
Nogent	2 (2)	1987		✓ cooling canal embankment damage nuclear island below flood level ✓ flood operating rules not applied and isolation procedures not in place				
Paluel	3 (4)	1984	✓ make-up transfer water must be 'hard cored' and seismic qualified			✓ make-up SEA ponds must be 'hard cored'		
Penly	2 (2)	1990	✓ make-up SEA ponds transfer must be 'hard cored' and seismic qualified			✓ make-up SEA ponds must be 'hard cored'		✓ lightening strike protection
St Alban	2 (2)	1981		✓ cooling canal embankment damage nuclear island below flood level ✓ below CMS flood level ✓ thousand year flood peripheral protection issues ✓ maximum river flood scenario requires evaluation of embankment structures				

S^T LAURENT	1 (2)	1981							
TRICASTIN	2 (4)	1980	✓ flood containment damage loss of ultimate heat sink ✓ Extensive evaluation of embankment structures required particularly with regard to internal erosion and liquefaction	✓ cooling canal embankment damage nuclear island below flood level		✓ heat sink higher than NPP platform	✓ knock-on effect of Tricastin AREVA facilities to the be assessed	

† Includes EPR under construction.

References and Notes

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1 Office for Nuclear Regulation, *the Technical Assessment of REPPIR Submissions and the Determination of Detailed Emergency Planning Zones*, A34 December 2013 - http://www.onr.org.uk/operational/tech_asst_guides/ns-tast-gd-082.pdf

2 ASN does not itself define the type, modus operandi, and the 'reasonably foreseeability' of malicious threats although the mitigation measures against such acts can be subject to ASN requirements. The threats to be considered when examining malicious acts are defined by the Government via SGDSN – see ASN, *'Report on the State of Nuclear Safety and Radiation Protection in France in 2013'* - http://www.asn.fr/annual_report/2013gb/files/assets/common/downloads/publication.pdf

3 Bruno Tertrais, *'La dissuasion nucléaire française dans l'ère du post-11 septembr*e', Les Cahiers de Mars, No.178, 3ème trimestre, 2003 – in other words, potential state adversaries might consider that they could circumvent a French military response, perhaps including use of the nuclear deterrent, by employing an apparently stateless terrorist group.

4 However, there must be a level of terrorist attack at could provoke a nuclear response: London, Madrid, or something like 11 September – the limit is impossible to fix precisely and the risk in wanting to be too precise is that of putting the State in situations in which it looks weak – Yostim, David *"France's New Nuclear (Deterrent) Doctrine"*, International Affairs 82, 4 (2006).

5 Large, John H, *Decommissioning Nuclear Facilities – Openings for the Terrorist Threat*, September 2006.

6 *Stuxnet* is a standalone malware computer program that replicates itself in order to spread to other computers believed to have been effective in damaging the Iranian uranium enrichment facility at Natanz and at the then commissioning Bushehr NPP in or around 2010.

7 In France, the no-fly restriction excludes commercial and private aircraft traffic operating below an altitude of 1,000m in a 5km diameter zone centred on the NPP site – see Large & Associates, *'Vulnerability of French Nuclear Power Plants to Aircraft Crash*', R3205-A1, April 2012.

8 Because of the recent flurry of drone flights over and around French NPPs, is Review concentrates on aerial unmanned vehicles at the neglect of other developing and established forms of robotic/autonomous vehicles and delivery systems. In 2011 4 individuals were accused of planning to deploy a scale model car, packed with explosives, to pass under a security gate at the Territorial Army Centre in Luton – http://www.telegraph.co.uk/news/uknews/terrorism-in- e-uk/9237329/Men-appear-in-court-charged-with -plotting-to-attack-Territorial-Army-with -model-car.html

9 TERCOM enables the drone complete autonomy and when engaged renders the drone navigation effectively unjammable, although TERCOM-like navigation systems are not openly available on the civil commercial marketplace.

10 Deutsche Post DHL AG recently announced its intention to establish a routine delivery service of small pharmaceutical packages by copter drone from the port of Norddeich to the island of Juist, about 12km, the drone flying autonomously on a preprogrammed route. Similar package delivery development trials have also been undertaken separately by Amazon and Google.

11 For example, in the United States the Federal Aviation Administration (FAA) first au orised the use of unmanned aerial drones in 1990 but en under very stringent control conditions. More recently in 2012 the FAA introduced *'Special Rules for Certain Unmanned Aircraft Systems'* to permit licensed operation of drones in low-risk, controlled environments. In June 2014 the FAA enacted a requirement at all other use, including recreational use of airspace, generally limits drones to a ceiling of 400ft (~120m) and operation in a manner at does not endanger the safety of the national airspace system. In addition to controls over UAV traffic there are a number of *Active Prohibited Areas* (for example, over the Amarillo Pantex nuclear assembly plant in Texas) that apply to all air traffic (manned and unmanned).

12 In France all traffic is prohibited above the City of Paris, with exceptions include military aircraft and civil airplanes flying no lower an 2,000 meters. Authorised organisations are either given permission by the *Ministère de la Défense*, for military aircraft, or by the Préfecture de Police de Paris and the *Direction Générale de l'Aviation Civile* for civil flights.

13 Table 1 draws upon a variety of sources and is not presented here as authoritative although, that said, the reported incidents is dominated by 'official' EdF statements. Of course, it may be that a number of additional unauthorised drone flights have occurred but have not been detected and, if so, the EdF reported incidents must therefore be assumed to be reliable in *de minimis.*

14 *Présentation des évaluations complémentaires de la sûreté des installations nucléaires au regard de l'accident de Fukushima*, ASN 9 May 2011.

15 Appendix II to Nuclear Safety Authority Opinion N° 2012-Av-0139 of 3rd January 2012 - *Provisions to Improve the Robustness of the Facilities to Extreme Situations*, ASN – see Nuclear Safety Authority (ASN) opinion N° 2012-AV-0139 of 3rd 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, ASN 3 January 201

16 *Post-Fukushima Complementary Safety Assessments: Behaviour of French nuclear facilities in the event of extreme situations and relevance of the proposed improvements*, Report No 679, IRSN, February 2012.

17 Large & Associates, *'Vulnerability of French Nuclear Power Plants to Aircraft Crash'*, Addendum *'Identifying Specific Nuclear Power Plants that should be Shut Down on Risk and Nuclear Safety Grounds'*, R3205-A3 November 2011 - http://www.largeassociates.com/LA%20reports%20&%20papers/3205%20French%20NPP%20Vulnerability/R3205-A3.pdf

18 ASN's National Plan, *'National Action Plan of the French Nuclear Safety Authority'*, December 2012, as amended - http://www.asn.fr/publications/2012/national-plan-ASN-12-2012/index.html#/I/zoomed

19 There is some ambiguity about the timescales for the *hardened safety core* to be put in place: For example, the ECS-19.II SSC task of providing additional electrical power supplies (for the alternate heat source pumps) the requirement is that the installation should "*As early as possible, given the constraints of fleet-wide deployment, and in any case before 31 December 2018, the licensee should install – for each reactor on the site – an additional electrical power supply capable of supplying the systems and components of the hardened safety core . . .* "[18] compared to EdF's position in 2014 that the hardened safety core will not be in place and commissioned until at least post 2022.[21]

20 In fact there seems to have been some slippage in EdF's response to the timescales for the *Hardened Safety Core* installation originally specified in the 2012 National Plan with, now, EdF required to respond with its proposals in June 2014 and later by June and December 2015 – see *'Resolution 2014-DC-0403 of 21th January 2014 instructing Electricité de France - Société Anonyme (EDF-SA) to comply with additional prescriptions applicable to the Flamanville (Manche) NPP further to the examination of the file presented by the licensee in compliance with prescription (ECS-1) of ASN resolution 2012-DC-0283 of 26th June 2012'*, ASN, January 2014 - file:///Users/largeassociates/Downloads/ASN+Resolution+2014-DC-0403.pdf

21 Debes M, *'EDF PWR Fleet Overview, Post Fukushima Safety Improvements, Practical Implementation and Challenges'*, Slide 15, MNTK Int Conf, Moscow, May 2014 - http://mntk.rosenergoatom.ru/mediafiles/u/files/2014/Sections/4%20eng/4_Debes_EdF.pdf

22 SNUPPS – Standardised Nuclear Unit Power Plant System.

23 Intentionally, the scenarios are not applied exactly to a named, specific and existing French NPP so as not to provide succour to any would-be adversary.

24 Like conventional electricity generating plants, NPPs raise steam to drive electricity generating turbo-alternator sets. However, unlike conventional plants NPPs must ensure that sufficient heat is removed from the reactor fuel core at all times, even when the plant is not generating electricity. For this the plant has both regular and a diverse array of emergency core cooling systems and, should these fail and the nuclear fuel overheat and melt, the nuclear elements of the plant, referred to as the *'nuclear island'*, are enclosed within a series of containments designed to withstand the energy released during certain credible or *'design-basis'* accidents.

25 Virtually nothing is available on the French DBT in the public domain other than the somewhat sketchy narrative Aurelle J, Nannini A, '*Exercises in the Field of Security'*, IRSN, 2005 - http://193.174.114.174/files/pe_405_24_1_seminar4_03_2005.pdf

26 For a definition and discussion on various terrorist roles, including *'passive'* and *'active insiders'* see Large J H, *'The Implications of 11 September for the Nuclear Industry'*, Royal United Services Institute, HSR Monitor, February 2003.

27 ASN adopts the International Atomic Energy Agency *'Regulations for the Safe Transport of Radioactive Materials'*, TS-R-1 requiring irradiated fuel to be transported in Type B flasks that, amongst other things, are required to withstand a free fall drop onto a hard target of 9m.

28 For Bugey and Fessenheim NPPsm, ASN required EdF to report on the '*ECS-21: Additional Measures to Prevent or Mitigate the Consequences of a Fuel Transport Package Falling in the Fuel Building'* by December 2013, although nothing of this seems to have been placed in the public domain – see the *ASN National Plan.*[18]

29 During a refueling outage, the higher levels of residual power of the fuel stored, a total loss of pond cooling could lead to boiling in 8 to 16 hours – see Gilloteau L, '*Safety of the Fuel Storage in French Nuclear Power Plants 900 MWe*', ISRN, undated - http://www.eurosafe-forum.org/files/pe_119_24_1_seminaire_1_1.pdf

30 Large J H, '*Incidents, Developing Situation And Possible Eventual Outcome at the Fukushima Dai-Ichi Nuclear Power Plants*', R3195, April 2011, footnote 5, p11 - https://www.greenpeace.de/sites/www.greenpeace.de/files/Large_Report_R3196-A1_10_April_2011-3_0.pdf

31 A total of about 4,010 tonnes of spent fuel (mostly uranium oxide and about 10% of mixed oxide) is held in the ponds at the NPPs across France (latest data available for 2010) so, on average, each NPP has about 200 tonnes, although this may be collectively held in the ponds of several individual power plants sharing that site – see Synthesis Report 2012, *'National Inventory of Radioactive Materials and Waste'*, Andra, 2012, p49

32 Typically, a 1 GWe PWR core contains about 80t of fuel undergoing irradiation. Each 18 to 24 months about one third of the core fuel is discharged into the spent fuel pool so a pool with 15 year storage capacity will hold about 400t of spent fuel. The caesium-1367 fission product radionuclide gives a good gauge of the total radioactive inventory of the pond - the Cs-137 inventory at reactor shutdown is about 0.1 MCi/tU with a burn-up of 50,000 MWt-day/tU so, with some natural radioactive decay over the period, the pool with 400t spent fuel would contain about 33MCi (1000E+15 Bq) of Cs-137.

33 In a recent interview M Chevet of ASN, stated that with "*drones flying over nuclear plants for over a month, the spent fuel pools should be bunkered"* but note the context of this quotation is unconfirmed, as is the translation to English - http://www.lesechos.fr/industrie-services/energie-environnement/0203929250455-pierre-franck-chevet-surete-nucleaire-nous-serons-obliges-de-faire-des-choix-1063149.php

34 There are a number of studies on the boil down time for spent fuel ponds, the authoritative US Nuclear Regulatory Commission study gives a boil down time (to uncovering the fuel) of 8 hours for a pond into which has been transferred the complete PWR core (~100t) 5 days after reactor shutdown – see US Nuclear Regulatory Commission, Briefing *'On Spent Fuel Pool Study'*, Public Meeting, November 14, 1996; www.nrc.gov/reading-rm/doc-collections/commission/tr/1996/19961114a.html

35 Gilloteau L, '*Safety of the Fuel Storage in French Nuclear Power Plants 900 MWe*', ISRN, undated c2002 - http://www.eurosafe-forum.org/files/pe_119_24_1_seminaire_1_1.pdf

36 Off-site power received from the grid distribution power lines feeding into the NPP site, referred to as *Loss Of Offsite Power* (LOOP).

37 There might be a third off-site grid connection at Fessenheim feeding directly into the NPP from the weir of *Grand Canal d'Alsace* north of the site.

38 [redacted]

39 ASN required EdF to report on the '*ECS-11: Robustness of the Fessenheim and Tricastin Embankments'* by December 2013, although nothing of this seems to have been placed in the public domain – see the *ASN National Plan.*[18]

40 Fraguiet E, '*Lessons Learned from the 1999 Blayais Flood: Overview of EDF Flood Risk Management Plan'*, US NRC, March 2010 - http://www.nrc.gov/public-involve/conference-symposia/ric/past/2010/slides/th35defraguierepv.pdf

41 ASN required EdF to report on the *'ECS-16J: Emergency Water Supply Resources',* before 30 June 2013 although nothing of this seems to have been placed in the public domain – see the *ASN National Plan.*[18]

42 ASN required EdF to report on the *'ECS-18.II: Additional Electrical Power Supply Means',* before the close of 2018 although nothing on the progress of this requirement seems to have been placed in the public domain – see the *ASN National Plan.*[18]

43 All of the operating NPPs are identified as *Priority Sites* by ASN TABLE 2 and APPENDIX 2, but not all NPPs on each site are considered to be rated as *Priority*.