ASSESSMENTS OF THE RADIOLOGICAL CONSEQUENCES OF RELEASES FROM EXISTING AND PROPOSED EPR/PWR NUCLEAR POWER PLANTS IN FRANCE

REF N^{O} R3150-3

Client: **GREENPEACE FRANCE**

1ST ISSUE	REVISION NO	APPROVED	CURRENT ISSUE DATE
10 NOVEMBER 2006	R3150-3-34		13 OCTOBER 2013

REVISION DATE	PAGE	REVISION
17 MARCH 2007	p3 Table p47 Table B	Tabulated entry for Early Deaths under Fessenheim – MEAN value should read 26 and not 258 – reason transcription error in rounding data

Risks and Hazards of the proposed and Existing EPR/PWR NPPs in France

Summary

France is advancing its plan to construct a pressurised water reactor (PWR) at Flamanville in the Manche on the site of the existing nuclear power station. The new plant, a Generation III European Pressurised Reactor (EPR), has been approved by the Authorité de Sûreté Nucléaire (ASN) and is to be built by the nuclear group Areva and operated by Electricité de France (EdF).

In preparing the way for this development at Flamanville, EdF has published its claims that the EPR design is failsafe and that its operation, even if subject to the most severe accident or terrorist attack, will not result in intolerable consequences for the local communities, France and the region as a whole.

This assessment rejects EdF's claims.

Using European Community Standard modelling software (COSYMA), this assessment compares the proposed Flamanville EPR to the radiological consequences of a severe radioactive release arising from a containment-bypass or containment failure at each of a number of existing NPPs in France, including Tricastin, Nogent-sur-Seine and Fessenheim.. Because France has in place a programme to utilise reactor-grade plutonium fuel (MOX) in certain of its existing NPPs and specifically in the EPR development at Flamanville, the impact of a radioactive release of MOX is examined in comparison with a low enriched uranium (LEU) fuelled NPP. The assessment includes account of the type of nuclear fuel, both LEU and MOX that is currently in use in French NPPs, and it projects the higher radiological consequences should the Generation III European Pressurised Reactor (EPR) proposed at Flamanville be subject to a severely damaging incident

In presenting its nuclear safety case to the public, EdF declare that any untoward event that could credibly occur to the EPR and the existing NPPs located throughout France would not result in unacceptable radiological consequences to members of the public. EdF claims that all reasonably foreseeable accidents and external hazards will not jeopardise the fundamental nuclear safety of the plant, so much so that there are no foreseeable circumstances under which the radiological containment structures of the nuclear island will be breached. Indeed, with the severely damaging incidents '*practically eliminated'*, so EdF argues, the resilience of the plant to accidents and external hazards is sufficient to safeguard against terrorist and malicious acts, including the crashing of a fully fuelled commercial airliner on the nuclear island.

However, the history of technological development is littered with examples of unforeseen failures of hi-tech systems with, for example, with the *Challenger* and *Columbia* shuttle failures reverting NASA's one-in-a-million design criterion to a chance of just 1:57; the *World Trade Center* towers designed to withstand a Boeing 707 crash were to be defeated by the advance in aircraft design over the years; and, of course, the unsinkable ship *Titanic* sank on its maiden voyage. The axiomatic fact is that all engineered systems are at risk of catastrophic failure and that, moreover, it may not be possible at the time of design to foresee all possible causes and mechanism that could initiate and cascade through to failure: an iceberg so far South, a detached piece of polystyrene insulation damaging a ceramic tile, and suicidal terrorism successfully pitting one technology against another. Moreover even those events that might be reasonably foreseen, not all are entirely predictable in terms of frequency or chance of occurrence and, of course, acts of terrorism are totally beyond prediction by *a priori* and probabilistic analysis upon which the NPP nuclear safety case so heavily relies.

There is nothing exceptional about nuclear power plant technology that excludes NPPs from the risk and actuality of catastrophic failure so, on this basis alone, the EdF-Areva conjecture that it is possible to design, build and operate a failsafe and terrorist proof NPP is not accepted.

This assessment examines the radiological consequences following a catastrophic failure at each of a number of NPPs. The potential mechanisms leading to and through the failure are not examined in great detail, other than to muse that such an event, should it occur would probably centre about human failings or some form of terrorist act, suffice that the event involves an operational nuclear reactor and that the containment building is breached. The assessment examines the severity of the radiological impact in terms of amounts of the radioactive fission products (the release fractions) that could expel from the reactor fuel core, with these deduced from those adopted for a number of nuclear industry consequence analyses and from factual information on the actual release at Chernobyl. The immediate, interim and longer term aftermaths of the incident are modelled and analysed using the European Community standard software COSYMA to provide a probabilistic based projection of the individual risks, extent of land area and population numbers requiring countermeasure actions, and the early and late radiological health consequences for the specific locations of NPPs at Flamanville, Tricastin, Nogent and Fessenheim. The trajectory of the radioactive release plume and the footprint of radioactive fall-out are also projected at each location using satellite archived meteorological data (NOAA) to graphically illustrate the tracts of land and communities at risk.

France has in place a programme to utilise reactor-grade plutonium fuel (MOX) in certain of its existing NPPs and specifically in the Generation III NPP EPR development at Flamanville. MOX cores have greater quantities of plutonium and other actinides than LEU cores so the amount of radioactivity potentially available for release will differ and the health impact, particularly because of the increased plutonium content, will be greater for a radioactive release from a MOX-fuelled reactor. The assessment of MOX fuel releases includes account of the so called *reactor-grade* plutonium used in the French MOX programme and, in outline, an explanation of the greater risk of malfunction that the introduction of MOX fuelled reactor cores brings about.

The EPR targets to attain much higher levels of LEU fuel irradiation (burn-up) than hitherto achieved in commercial PWR power generation. Higher fuel burn-up not only increases the quantity of fission products available for release, and hence a greater potential radiological impact, but it introduces uncertainty over the amount of radioactivity released from the individual fuel pellets and pins in a reactor core degrade or melt down. Recent research programmes have shown a significant increase in release fractions for both LEU and MOX fuels at higher levels of burn-up so, in this respect, the release fractions assumed for this analysis may result in an under-assessment of both the LEU and, particularly, MOX fuel cases.

The results of this assessment are disturbing.

Presented in terms of probability fractile (but see Table B in Appendix I for full results and range of NPPs assessed):

		NUMBER OF HEALTH EFFECTS FRACTILE		
NPP SITE	HEALTH EFFECT/COUNTERMEASURES	MAXIMUM	MEAN	50th
Flamanville EPR 100% LEU core Target 65GWed/tU Fuel Burn-Up	EARLY Death	381	81	42
	LATE Fatal Cancer	26,430	6,212	5,623
	Thyroid Cancer DEATHS	1,454	309	263
	LAND Area (ideally) Evacuated km^2	16,930	7,214	6,475
	Area (ideally) Iodine Prophylaxis km^2	1,541	361	257
	NUMBERS Persons (ideally) evacuated	1,246,000	313,00	239,900
	Persons (ideally) I-131 Prophylaxis	68,050	14,570	11,750
FLAMANVILLE EXISTING 1330MWe PWR 100% LEU core	EARLY Death	179	41	23
	LATE Fatal Cancer	15,020	3,748	3,311
	Thyroid Cancer DEATHS	824	184	158
	LAND Area (ideally) Evacuated km^2	13,320	4,796	4,365
	Area (ideally) Iodine Prophylaxis km^2	1,445	318	2,512
	NUMBERS Persons (ideally) evacuated	725,300	176,800	151,400
	Persons (ideally) sheltered	869,500	125,800	35,480
	Persons (ideally) I-131 Prophylaxis	65,380	12,990	10,470
FLAMANVILLE EPR 100% MOX core	EARLY Death	650	147	85
	LATE Fatal Cancer	60,760	8,055	7,586
	Thyroid Cancer DEATHS	1,307	161	110
	LAND Area (ideally) Evacuated km^2	44,810	13,300	11,750
	Area (ideally) Iodine Prophylaxis km^2	7,3214	2,360	2,138
	NUMBERS Persons (ideally) evacuated	3,319,000	662,200	549,500
	Persons (ideally) I-131 Prophylaxis	376,000	69,260	33,110
FLAMANVILLE EPR 30% MOX core Thyroid Prophylaxis limited to 10km	EARLY Death	322	67	34
	LATE Fatal Cancer	29,260	6,295	5,754
	Thyroid Cancer DEATHS	984	212	186
	Thyroid Cancer Incidence	9,630	2,116	1,862
	LAND Area (ideally) Evacuated km^2	36,540	11,660	10,000
	Area (enforced) Iodine Prophylaxis km^2	314	78	63
	NUMBERS Persons (ideally) evacuated	3,246,000	567,600	537,000
	Persons (enf'd) I-131 Prophylaxis	13,070	3,228	2,570
Tricastin EXISTING 915 MWe PWR 100% LEU core	EARLY Death	28	6	2
	LATE Fatal Cancer	11,890	3,234	3,020
	Thyroid Cancer DEATHS	530	165	166
	LAND Area (ideally) Evacuated km^2	6,320	2,261	1,995
	Area (ideally) Iodine Prophylaxis km^2	1,281	275	209
	NUMBERS Persons (ideally) evacuated	712,000	181,600	123,000
	Persons (ideally) I-131 Prophylaxis	100,900	18,610	15,490
Tricastin EXISTING 915MWe PWR 30% MOX core Higher Release Fraction for Group 7 Radionuclides	EARLY Death	123	22	11
	LATE Fatal Cancer	29,330	10,290	10,470
	Thyroid Cancer DEATHS	753	240	246
	LAND Area (ideally) Evacuated km^2	23,990	8,704	8,318
	Area (ideally) Iodine Prophylaxis km^2	3,142	72	60
	NUMBERS Persons (ideally) evacuated	2,341,000	652,600	602,600
	Persons (ideally) I-131 Prophylaxis	25,290	2,258	2,042
Nogent sur Seine EXISTING 1310MWe PWR 100% LEU core	EARLY Death	434	41	15
	LATE Fatal Cancer	109,900	11,510	4,898
	Thyroid Cancer DEATHS	4,670	354	257
	LAND Area (ideally) Evacuated km^2	13,530	4,841	4,365
	Area (ideally) Iodine Prophylaxis km^2	1,445	320	251
	NUMBERS Persons (ideally) evacuated	6,386,000	424,000	263,000
	Persons (ideally) I-131 Prophylaxis	88,530	22,000	17,380
Fessenheim EXISTING 880MWe PWR 100% LEU core	EARLY Death	194	26	10
	LATE Fatal Cancer	36,010	10,340	8,913
	Thyroid Cancer DEATHS	2,599	492	479
	LAND Area (ideally) Evacuated km^2	6,188	2,206	1,950
	Area (ideally) Iodine Prophylaxis km^2	1,268	273	200
	NUMBERS Persons (ideally) evacuated	2,960,000	563,300	331,100
	Persons (ideally) I-131 Prophylaxis	502,900	90,180	31,150

Using precisely the same modelling and analysis methods, this compares to the worst case incident proposed by EdF for the EPR at Flamanville:

Flamanville EPR 100% LEU High Burn-Up Target & EDF Release Fractions English Version x10^2	EARLY Death	0	0	0
	LATE Fatal Cancer	11	4	4
	Thyroid Cancer DEATHS	1	0	0
	LAND Area (ideally) Evacuated km^2	123	57	50
	Area (ideally) Iodine Prophylaxis km^2	12	10	10
	NUMBERS Persons (ideally) evacuated	2,952	2,458	2,239
	Persons (ideally) I-131 Prophylaxis	630	560	562

The striking difference between the two sets of results for the Flamanville EPR (ie blocks coloured ■ in the main table) results from EdF's assertion that all seriously damaging incidents, including terrorist acts, can either be *'practically eliminated'* or contained within the absolutely failsafe secondary containment of the EPR. This claim, which is not at all substantiated by information and data available in the public domain, is not accepted for this assessment which adopts the pragmatic approach that accidents can happen and that NPPs are vulnerable to both unforeseen accidents and external events, including extreme acts of terrorism.

Moreover, as the output size of successive generations of NPPs increase, so does the amount of fuel held in the reactor core, and as the utilisation of this fuel is increased by greater irradiation, or *burn-up*, the radiological impact of a radioactive release also increases. However, the public tolerance to radioactivity, the acceptable radiological health impact, sensibly remains constant or, indeed, may reduce in line with changes of public perception and tolerability of radiation specifically and health harm generally. To satisfy this covenant, the potential for radioactive release from each successively larger generation of NPPs has to be more effectively contained or, where this is not at all practicable, the type of fault condition or incident has to be eliminated. For its latest and largest NPP, the 1,600MW$_e$, high burn-up fuelled Flamanville EPR, EdF claim that the radiological impact of an accident will be no greater than that for the existing 880MWe, modest burn-up NPP at Fessenheim. EdF's claims for the EPR in this respect are not at all convincing nor, indeed, have these been factually demonstrated, proven and tested in a commercially-sized NPP.

Another unproven conjecture is forwarded by EdF on the resilience of the EPR design against acts of terrorism, with the claim that whatever the nature of any well planned and implemented terrorist attack, the radiological consequences would be no worse than those arising from the nominated and tolerable *design basis* accident. Even if applicable to the EPR, which is extremely doubtful, this new fangled resilience would not apply to the earlier, pre-9/11 NPPs at Nogent, Fessenheim, Tricastin and Flamanville.

Second and should there be a radioactive release, this assessment confirms that there is marked radiological penalty accompanying the use of *reactor-grade* MOX in the existing NPPS and for the EPR NPPs planned for Flamanville. For example, at Flamanville the (statistically mean) projected early deaths following exposure increase by one-quarter over the LEU fuelled reactor for a 30% MOX core load, and by about threefold for a 100% MOX fuelled reactor core. For those individuals caught within the overhead plume and fall-out regions downwind, the greater plutonium content of a MOX fuelled release results in an increase of the contribution of the inhaled dose pathway from about 80% for an LEU core to 96% for the first few hours of exposure. This particular finding emphasises the crucial importance of implementing countermeasures to mitigate public dose but, that said, the reduction afforded by sheltering only has an hour or so of worth because the building space itself fills with contaminated air. Since it is not practicably possibly to provide respiratory protection to the numbers of population likely to be at risk, a speedy evacuation is the only practicable dose reduction option available.

In fact, the numbers of public requiring countermeasure action can be very large depending of the rural/urban mix downwind of the NPP. At Flamanville the analysis projects that for a 100% LEU fuelled EPR operating at current levels of fuel irradiation (burn-up) a (statistically mean) area of about 5,600km^2 entailing about 230,000 individuals would require evacuation tailing off over the first week following the release. If the EPR is fuelled with MOX the land area requiring evacuation expands to about 13,500km^2 involving about 660,000 evacuees. For the existing NPP at Nogent sur Seine the land tract qualifying for evacuation, although smaller at about 4,800km^2 but of greater urban settlement could require upwards of 424,000 evacuees and at Fessenheim, because of its greater population density in France, together with the populations of the neighbouring states of Germany and Switzerland, upwards 560,000 individuals would require evacuation on the basis of the intervention levels of dose adopted by the French (100mSv at 7 days and not, for example, at the lower German intervention levels)).

The COSYMA modelling arrives at these numerical projections because it slavishly adheres to its instructions which are in accord with the French emergency planning regime and its prescribed levels of dose that trigger specific countermeasure actions but, clearly, confronted with such a onerous evacuation requirement in a real situation, the emergency response would have to be modified (ie increasing the tolerated dose before evacuation) to stave off ensuring chaos that would accompany a collapse of state organised public control. In this and other respects, the COSYMA analyses reported here are not intended to provide precise forecasts of the radioactive releases and consequences at the exampled nuclear power plants. This is because not only is a much greater detailed input required to define the near field data, population density and meteorological conditions, for each locality and how the population would react, particularly if left uninformed, lacking essential information and direction on what to do and when best to do it. That said, the results do provide reliable indicators of the trends and indices of the probability and magnitude of the health impact a radioactive release, accidental or otherwise, from any of the nuclear power plants examined.

MOX fuelling increases the resources needed to be held in reserve if effective post-release countermeasures are to be implemented. For example, the projected EPR at Flamanville when fuelled with a 30% MOX core (the present level achievable in France) will have to provide for a doubling of the land area requiring evacuation than for the EPR fuelled with LEU to the present fuel burn-up levels (12,000 over 6,000km^2).

Administration of prophylactic measures (stable iodine or iodide tablets) would also present similar demands on the emergency services, although there is no significant different between LEU and MOX fuelled cores. For both fuel cores, if the present French emergency reference trigger or intervention levels for prophylaxis are maintained, downwind of Nogent sur Seine, for example, the (statistically mean) numbers involved would reach upwards of 22,000 individuals based on the trigger thyroid dose of 100mSv. However, if the World Health Organisation (WHO) intervention dose of 10mSv for the critical group composed neonates, children and nursing mothers were to be adopted then the qualifying catchment area would be much more widespread and the numbers making up these critical groups very much larger.

Another disturbing result is that the analysis shows that the societal cost varies considerably. This societal cost is expressed as the health detriment in man-Sv arising from the collective dose over the populations downwind of each of the NPPs assessed. For example, the NPP at Fessenheim, although of much smaller capacity at 880MW$_e$ than the proposed 1,600MW$_e$ EPR at Flamanville and analysed here for a 100% LEU core, has the greatest radiological impact over 10 to 100km downwind – this is because of the high population densities of the region, particularly in the nearby adjacent states of Germany and Switzerland. Nogent sur Seine also generates a significant collective dose detriment, at about twice that of each of the Tricastin and Flamanville (EPR) NPPs when fuelled with LEU and, generally, the introduction of MOX fuel about doubles the collective detriment over the equivalent uranium fuelled reactor.

Also, the Nogent NPP is located about 90km East of Paris so there is risk, although in relatively rare atmospheric conditions, that the suburbs if not the centre of Paris would require sheltering and, perhaps, evacuation countermeasures implemented. The societal cost of any nuclear incident and radioactive release is very high but an incident that drew in the capital of France, however slight and short term the radiological consequences might, would have catastrophic consequences that could blight the City, in tourism, prestige and commerce, for many years into the future.

Equally disturbing is the response of the French nuclear industry to change: On one hand, its proposed EPR reactor at Flamanville will be larger than any of the existing French reactors and it will irradiate its LEU fuel cores to levels hitherto untested at a commercial scale, and it is to fuel these reactors with reactor-grade MOX to higher core proportions than presently permitted – all of these changes will render the available radioactive source term and the potential radiological consequences in the public domain larger. The threat to nuclear safety has also changed since 9/11 2001 with the emergence of a form of international terrorism that has no regard for self-sacrifice, and which will adapt and use high technology with brutal disregard for public safety and life. On the other hand, the French nuclear industry continues to claim that its reactor designs are somehow exempt from severely damaging accidents and will withstand the most intelligently contrived terrorist attack and, accordingly, its planning, preparation and implementation of the emergency response to a significant radioactive release, as shown by this assessment, is not at all matched to the potential consequences.

Put simply, because the amount and/or radiotoxicity of the reactor fuel core increases with each new NPP generation, the gravity of the maximum tolerable incident or radioactive release over its predecessor must be correspondingly smaller. This requires each successive NPP generation to have a greater resilience to accidents and external events, thus confounding the claim that each generation of NPPs is *'as safe* *as can be'*. Put another way, since several of the safety features of the EPR cannot be practicably back-fitted to the existing NPPs, a rationale interpretation is that if the EPR is *'safe'* then the existing NPPs are *'unsafe'* in comparison.

Overall, my conclusion is that the risk of a severely damaging accident to any of France's highly hazardous nuclear power plants should not be dismissed on probabilistic grounds alone because, as our technological history shows, it is beyond the wit of mankind to forecast all possible types of incidents and the chance of when these might occur. This is doubly certain for malicious acts, including terrorism, which should be considered to be inevitabilities Accordingly, I am of the opinion that EdF should present its case for the continuing operation of its NPPs, including its venture to construct a series of EPRs, with greater caution and diligence, particularly in that it should make publicly available full analyses of the radiological consequences of severely damaging incidents to its NPPs rather than, as it does now, opportunely dismiss such possibilities to have been *all but practically eliminated.*

JOHN H LARGE
LARGE & ASSOCIATES
CONSULTING ENGINEERS, LONDON

RISKS AND HAZARDS OF THE PROPOSED AND EXISTING EPR/PWR NPPS IN FRANCE

BACKGROUND

France is advancing its plan to construct a pressurised water reactor (PWR) at Flamanville in the Manche on the site of the existing nuclear power station. The new plant, a Generation III European Pressurised Reactor (EPR), has been approved by the Authorité de Sûreté Nucléaire (ASN) and is to be built by the nuclear group Areva and operated by Electricité de France (EdF).

This assessment examines the potential environmental and health issues arising from the existing nuclear power plants (NPPs) at Flamanville and projects the potential impact of the proposed EPR on that site. Similar assessments have been undertaken for the existing plants at Tricastin, Nogent-sur-Seine and Fessenheim. Because France has in place a programme to utilise reactor-grade plutonium fuel (MOX) in certain of its existing NPPs and specifically in the EPR development at Flamanville, the impact of a radioactive release of MOX is examined in comparison with a low enriched uranium (LEU) fuelled NPP.

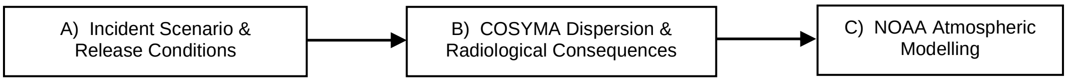
In summary, the NPP sites and reactor fuel cases considered are:

TABLE 1 – SUMMARY OF CASES AND NPP SITES ASSESSED

CASE	NPP SITE	REACTOR	FUEL	FUEL BURN-UP
FLLEU1	Flamanville	1,600MWe EPR	100% LEU	Yr 3 52.0GWd/t
FLLEU1C	Flamanville	1,600MWe EPR	100% LEU	Yr 3 52.0GWd/t
FLLEU2	Flamanville	1,600MWe EPR	100% LEU	Yr 3 65.0GWd/t
FLLEU1a	Flamanville	1,330MWe PWR	100% LEU	Yr 3 35.0GWd/t
FLEdFLEU	Flamanville	1,600MWe EPR	100% LEU	Yr 3 52.0GWd/t
FLMOX1	Flamanville	1,600MWe EPR	30% MOX	Yr 3 34.5GWd/t
FLMOX2	Flamanville	1,600MWe EPR	100% MOX	Yr 3 34.5GWd/t
TRLEU1	Tricastin	915MWe PWR	100% LEU	Yr 3 35.0GWd/t
TRMOX2	Tricastin	915MWe PWR	30% MOX	Yr 3 34.5GWd/t
NsSLEU1	Nogent sur Seine	1,310MWe PWR	100% LEU	Yr 3 35.0GWd/t
FLEU1	Fessenheim	880MWe PWR	100% LEU	Yr 3 35.0GWd/t

MODELS AND ASSUMPTIONS

The basis of the analytical approach adopted for this assessment combines three elements:



INCIDENT SCENARIOS & RELEASE CONDITIONS

This assessment relates to a hypothesised radioactive release from a malfunctioning and/or damage nuclear reactor that has operated continuously immediately prior to the initiating event that results in the release. Thus incidents arising during the refuelling of the reactor (when the primary containment envelope is open) and those that might disrupt the spent fuel in storage in the fuel pond (and beyond the secondary containment) [1] are not considered in this assessment.

FUEL CORE RADIOACTIVE INVENTORY

For the uranium-fuelled scenarios, the three-zone core is assumed to be fuelled with 2.2 to 4% LEU fuel for which the core radioactive inventory is derived. The inventory is for a reactor that has been operating continuously at full power for the year up to the incident and is taken at the end (maximum) of the three-year refuelling cycle, including for one-year feed, once- and twice-burned fuel with an overall, core-averaged irradiation (burn-up) of 35MWd/tU. For the EPR scenarios the irradiation level for a core fuelled solely LEU is set at 52MWd/t and for a (reactor grade plutonium) MOX fuelled core at 30 and 100% fuel load and at 34.5MWd/t. For the MOX element, reactor grade plutonium[2] at a RG-Pu content of 8.3%.

The LEU and LEU/MOX core source term comprise 60 radionuclides arranged in the 7 groups of TABLE 1 which are energetically released to atmosphere during 3 phases following a 1 hour period over which the reactor has been effectively shut down and the release confined to within the nuclear island containment. The inventory excludes activation products such as Co-58/60 and the contribution of the control rods,[3] including isotopes of silver.

The model core inventory adopted for the analysis is listed in APPENDIX II[4] – this source term is used as the basis for all of the source terms appropriately extrapolated to suit the particular NPP under assessment. Although extrapolation in this way is not entirely accurate it provides, nevertheless, a reasonable estimate of the range of reactor core inventories adopted for this assessment.

ACCEPTABLE RISKS AND TOLERABLE CONSEQUENCES – PUBLIC[5] & SOCIETAL LIMITS

The design and operation of nuclear plants centres around achieving an acceptable level of risk to the plant's nuclear safety and, like the aerospace industry, failure levels in practice are very low. The nuclear industry and its regulators generally claim that not only is the risk of failure *acceptably* low but that the consequences of failure are *tolerable*, so much so that this composite (*Acceptable Risk and Tolerable Consequences*)[6] forms the basis of both design and operational nuclear safety case regimes of NPPs. This probabilistic risk approach, the basis of which is probabilistic risk analysis (PRA), provides one leg of how the nuclear safety case for a NPP design is determined.

Even though the general approach is to minimise the risk of occurrence of faults, nevertheless, faults may still occur so a NPP must be tolerant of and/or resilient against a range of sometimes unspecified fault conditions originating from internal (engineered component failure, human error, etc) and external (seismic, flooding, etc) events. Thus, the *Design Basis* is that a NPP should be able to cope with or withstand a wide range of faults without unacceptable radiological consequences by virtue of what is claimed to be the plant's inherent characteristics or safety measures.

The design basis is the second strand deployed to determine the robustness of the nuclear safety case being undertaken by *design basis analysis* (DBA) in assessing the fault tolerance of the NPP. DBA endeavours to determine the effectiveness of the plant's safety measures and the limits to safe operation when subject to all reasonably foreseeable or *credible* faults. DBA is a deterministic approach with the risk not being quantified, instead the adequacy of the design and the suitability and sufficiency of the deterministically defined safety measures are defined in terms of margins of strength, robustness, safety, etc..

Both PRA and DBA are applied against performance (resilience) targets and legal limits sometimes referred to as *Basic Safety Objectives* (BSO) and *Basic Safety Limits* (BSL). For example, the targets for the effective dose received by any person located off-site during a design basis fault sequence might be expressed as a deterministically-defined dose based on a probability of occurrence basis. For this the BSL might stipulate that the target dose of, say, 1mSv should not occur at a frequency greater than 1 in a 1000 per reactor year of operation, 10mSv at a 1 in 10,000, and so on with the objective or BSO to achieve, say, a dose of 0.01mSv[7] per annum. Similarly, BSL and BSO targets might be defined in terms of the individual risk to any off-site person with, for example, the target dose of 1 to 10mSv not occurring at a BSL of 1 in 100 and with the objective of reaching a BSO of 1 in 1000 per reactor year of operation.[8]

In other words, a NPP is considered acceptably safe if its operation presents a risk of unplanned radiation dose exposure that is acceptable to *individual* members of the public. The acceptability or tolerability of the individual is defined by the maintenance of prescribed limits relating the degree of exposure and the frequency at which this is predicted to occur.

It is not practicably possible to include all *credible* faults in the DB analysis the full range of identified faults, so confidence of the adequacy or comprehensiveness of the DBA is taken on the basis of the overly-conservative approach presumed to be an integral element of the design approach to hazardous facilities such as NPPs. Albeit that the design of nuclear plants endeavours to take account of all foreseeable incidents, it is acknowledged that there remains the possibility of an incident occurring that is beyond the design basis. Generally, two other classes of incident are not included in the DBA, these *beyond design basis* events are severely damaging incidents and terrorist or other malicious acts.

Terrorist acts are usually assessed as *external* hazards with the overriding assumption that the worst outcome of any malicious action would not result greater damage and, hence, radiological consequences more severe than any one of the *credible* faults identified in the DBA. For the EPR design this relies upon unsubstantiated presumption that the system design and safety provisions *'helps limit the consequences of an act of malice . . . to ensure that the installation returns to the safe state'*[9] suggesting that however severe the attack and the extent of the damage sustained by the plant (and indeed if the plant post-incident countermeasures are also subject to interference during a terrorist action), the radiological consequences of any terrorist act will not go beyond those assumed for the reference accident.

Generally, very severely damaging faults and incidents are assessed on a best-estimate basis which applies to incidents that are considered to be very infrequent where it may not be considered practicable (ie cost effective) to include design provision against the outcome. Severe incidents are usually defined as those fault sequences that lead either to consequences exceeding the highest radiological doses (ie the maximum BSL), or to a substantial unintended relocation of radioactive material within the facility placing a demand on the integrity of the remaining physical barriers. A *substantial* quantity of radioactive material is usually defined to be the nature and amount which, if released, could result in unacceptable *societal* risk.

Obviously, in severe incidents involving substantial quantity of radioactive release doses to members of the public increase. As dose increases above 1000mSv then deterministic health effects including the possibility of prompt death become more important, if not dominant, so that the effects are likely to apply wider than to a particular individual, giving rise to significant off-site consequences. This is because with increasing levels of dose a greater number of individuals will suffer in both short and longer terms, so much so that in this eventuality the consequences might also have to be considered in societal terms.

BSL and BSO targets and objectives can also be applied to societal risk and are taken from an incident situation where immediate or eventual 100 or more fatalities are expected to occur,[10] even though the greater number of such fatalities would arise as a result of low dose to very large populations leading to stochastic deaths.[11] BSL and BSO societal values determining acceptable rates of incidents resulting fatalities of 100 or more are 1.10^{-5} and 1.10^{-7} per annum respectively.[12]

In summary: Ultimately the operation of a NPP has to be acceptable to the public. This requirement applies to the normal, day-to-day operational in terms of the discharges to the environment, accidents and external events that might result an abnormal discharge of radioactivity. The public acceptability envelope also applies to terrorism and other malicious acts.

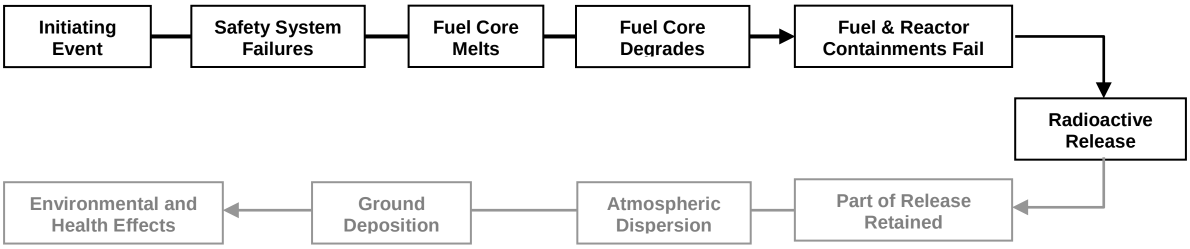
For accidents and external events, the nuclear industry and its regulatory bodies adopt a probabilistic approach in setting the odds of what they consider will be an acceptable level of risk to both individual members of public and society as a whole. Essentially, if the engineered safety systems and plant design are sufficiently robust then the risk is rendered adequately remote or, where it cannot be, the damage to the plant and its systems are contained as to control the consequences to an acceptable level. For this, the NPP is required to contain the radiological consequences of all reasonably foreseeable incidents in proportion to the reckoned frequency of occurrence up to a level where the consequences would be societally unacceptable, a point beyond which the event is ranked as a very severe.

The public acceptability requirement also applies to the NPP's resilience to withstand terrorist and other malicious acts, although for this the probabilistic approach is not entirely appropriate.[13] This because malevolent actions, particularly perpetrated by international terrorism are intentional, intelligent acts that seek out and exploit the vulnerabilities of the system – this is entirely different from the accidental and external hazard situations identified for the DBA. In fact, the to-be operator of the Flamanville EPR, 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'*[14] and that the radiological consequences of any terrorist act will not go beyond those assumed for the reference design accident (ie a consequence manageable DBA event). In other words, so far as terrorist acts relate, 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.

PWR DEGRADED CORE INCIDENT

For this assessment the assumption is that the individual NPPs considered will be subject to a severely damaging incident, either as the result of an accident, external event or a terrorist act. Furthermore, it is assumed that the nature of the incident results in the *degraded reactor core* with some or all of the fuel in the reactor core becoming molten.[15]

This sequence, from initiating fault event to the failure of the plant containments, comprises the following idealized elements



For the present generation of PWR NPPs the engineering and systems design aims to achieve a level of reliability whereby a challenging initiating event or fault will not seriously challenge the plant more frequently than 10^{-4} per year of reactor operation.[16] The failure of the plant and its safety systems to such a challenge that would lead to a core melt and loss of the containments is reckoned not to exceed a probability of order 10^{-4} per year of reactor operation, so the overall risk of a serious radioactive release occurring is taken by the nuclear industry to be somewhere between the order 10^{-7} to 10^{-8} per year[17] of total frequency for all containment threatening fault conditions.[18]

EUROPEAN PRESSURISED REACTOR – EPR

In the EPR system, the primary circuit loop configuration and detailed design of the main components are very similar to existing PWR units,[19] being based on an established separation and containment,[20] particularly 4-way redundancy and diversity approaches,[21] although some levels of redundancy have been reduced over the design base German plants.[22]

Both EdF and Areva claim that the key and central feature of the EPR design is the extended deployment of passive safety systems that are enacted only by 'natural' forces, such as gravity, natural circulation, compressed gas, etc.. For example, the valves and diverters deployed to align certain of the passive safety systems are 'failsafe', requiring power to stay closed for normal operation but which will open automatically upon loss of power (or vice versa). The fuel building and reactor containment[23] introduce elements of enhanced structural design to resist explosion overpressure wave and aircraft crash, and the containment dome includes a perimeter annulus extraction system to supplement cooling in the event of primary circuit failure. The principal means of safeguarding the nuclear island against malevolent acts (ie aircraft crash, placement of explosive devices, explosive packed vehicles, etc) seems to be that of segregation, with a series of safeguard buildings clustered around the most sensitive parts of the plant (reactor, spent fuel, emergency diesel, and seawater intake buildings), although no details of this are available.

However, all that said, the EPR containment design does not seem to differ significantly in structure and layout to the N4 at Chooz[21] which are pre-9/11 in both security rationale, resilience against terrorist and, specifically, deliberate crashing of a commercial aircraft onto the nuclear island. In complex engineered systems, particularly hazardous plants where safety is central to the engineering design and development process, fundamental changes take time. So it has been with the development of the EPR deriving, as it does, from the presently operating French N4 and German Konvoi PWR plants that are, themselves, derivatives of earlier designs of the PWR power plants operating worldwide. As a rule of thumb, implementing a significant change to a generic reactor type takes about ten years with, invariably, the need to change being triggered by some previous event that has either directly affected nuclear plants, such as a serious accident, or indirectly by a trend, possibly such as global warming, or an untoward socio-political faction such as international terrorism.

In other words, it takes time to modify complex hazardous plants and, with nuclear power plants being no exception to this, there has not been sufficient time since 9/11 to implement the fundamental and significant physical changes required to *'terrorist proof'* the EPR.[24]

A novel feature of the reactor containment building is the introduction of a refractory-lined reactor pit from which is intended that molten fuel debris (corium) can be diverted, passively cooled over the long term, managed and eventually recovered; there is also a facility to recombine any hydrogen generated by the zircaloy clad reaction with steam during and in the aftermath of a fuel core melt; and the location of the emergency core cooling water supplies are stored within the main reactor containment building. In the immediate aftermath of a severe core melt and failure of the reactor pressure vessel, the design intends to provide for 12 hours of passive cooling of the containment enclosure, following which enforced cooling of the containment must be evoked. This corium feature together with the claimed structural resilience of the containment buildings and shells, provokes the claim that the severe RRC faults have been *'practically eliminated'*.[25]

The EPR safety design endeavours to tackle shortfalls in the human-machine interaction, such as those that contributing to the Three Mile Island meltdown in 1978, by providing an over-arching array of interactive safeguarding components, autonomous systems and passive design features that do not require, or so it is claimed, human intervention during the early and often crucial stages of the incident progression. The design claims to address the need for effective containment for severely damaging reactor incidents, such as Chernobyl in 1986, by endeavouring to structure the management of events beyond the normal performance envelope with, for example, the installation of quite complex containment structures and with post-incident management of a melted fuel core to thwart the size and impact of radioactive release.

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 of 2001 acts of terrorism that highlighted the need for the engineered design of hazardous plants to take greater account of and to be resistant against malevolent acts. In this respect the anti-terrorism features will comprise, one has to assume because details have been withheld by EdF, mainly means (both physical barriers, etc and by intelligence gathering) by which ill-intended approach to the plant is restricted by security cordon and by the robustness of the plant generally to withstand physical intrusion (by explosive device, crashing aircraft, truck bomb, etc). The second anti-terrorism line of defence is the claim that any reasonably foreseeable malevolent act would not result in severity of damage and consequences of the nominated design basis accidents.

EPR SAFETY ISSUES

MOX Fuel: The use of MOX fuel in a reactor system, the PWR that has been exclusively developed for LEU fuelling introduces a number of challenges on the nuclear safety case for both operation and in the aftermath of any incident that could result in a radioactive release.

These challenges relate to:

- Mainly due to higher capture and fission cross sections of Pu-239 the absorption of neutrons in MOX fuel is nearly twice that of an LEU fuelled reactor. As a result, MOX fuel generates a lower thermal neutron flux and, accompanying this higher thermal absorption, there occurs a substantial diminution in boron, xenon, and control rod worth all of which serve to dampen the rate of fission reaction in the core.
- To maintain either a partial or full MOX fuelled core at a negative moderator coefficient at all operating conditions, enrichment and of increase the number of control rods is required to compensate for the loss of control rod worth (neutron absorption). This is challenging for existing LEU reactors and designs, such as the EPR, that are intended for this dual fuelling role and, for this, the EPR may have to strike a compromise by instead increasing the boric acid control of the primary circuit water.
- The reactivity loss of MOX fuel is lower than its equivalent LEU fuel, particularly because French MOX fuel comprises *reactor-grade* plutonium with its high content and continuing formation of the fissile Pu-241 isotope. This requires a higher inclusion of in-core absorption without exceeding the upper limit of soluble boron (usually about 2000ppm) in the primary coolant by the physical presence of other absorbers, either attached to the fuel assemblies or in the form of a coating to the MOX fuel pins.[26]
- In a partially MOX fuelled core, the flux gradient between LEU fuel assemblies and MOX fuel assemblies requires the MOX fuel assemblies to incorporate low plutonium concentration zones of fuel pins around the periphery of the assembly. This *intra-assembly* zoning is to shield the MOX fuel from the damaging higher neutron flux emitted by the surrounding LEU assemblies but effective management of the LEU flux is difficult throughout the burn-up cycle and will be unique for each operational reactor.
- Fission gas release from MOX fuel at elevated burn-ups (greater than 40 GWD/t) is higher than that for LEU fuel. Compensation for higher fission gas release is by increasing the plenum chamber volume in each fuel pin and by limiting the burn-up limits on the MOX fuel assemblies. Nevertheless, MOX fuel

pins operate at a higher internal gas pressure which may be the cause of the higher shell release rates reported by EdF.

- The radionuclide inventory of spent MOX fuel results in a slightly lower immediate shut down decay heat than that for its LEU equivalent, although in the longer term during fuel pond storage and thereafter, the decay heat is significantly greater than LEU to the extent that special management provisions are required during post reactor core cooling.[27] The lower immediate post shut down decay heat of a MOX fuelled core could contribute to over-cooling the reactor pressure vessel (RPV) whilst the primary circuit is still at pressure, thereby introducing the risk of embrittlement failure of older RPVs (such as at Tricastin NPP operational 1980-81).[28]

Overall, the use of MOX fuel reduces the neutron absorption which results in a more demands on the management and control of the reactivity; there results a decrease of shut down margin; and, generally, the transient response times for partial and full MOX cores are shorter and, it is argued, and less responsive to operator intervention with the outcome that a MOX fuel reactor has a lower nuclear safety threshold than its equivalent LEU fuelled counterpart.[29]

The outline findings of previous analysis of the performance of MOX fuelled reactors when subject to i) a control rod ejection and ii) a primary circuit pipe failure have been published,[30] although the detailed analysis is not available. Even so, the outline analysis demonstrates that considerable modification to the physical design and operating-safety management regimes is required for a MOX fuelled reactor, although there is little in the EdF consultation document to show that the EPR design has been or is capable of specific adaptation to MOX fuelling.

Radioactive Release Incident Scenarios: For the assessments undertaken here it is generally assumed that, either by accident or by intentional act, the reactor plant is somehow rendered unstable, a sizeable part or all of the fuel melts, and that this leads to a failure or bypassing of the secondary containment, giving rise to a substantial radioactive release.

The assumption is that the events leading to the radioactive release will be sufficiently energetic to reduce the fuel to a particulate/aerosol state (ie degrade the fuel core to meltdown), breach all levels of containment (reactor primary circuit and secondary enclosures), and expel some part of the fuel core (ie the release fraction). The severity of the incident is set by the magnitude of the release fractions chosen, generally, the nature of the events leading to the release by the range of release fractions across the radionuclide groupings and the extent of the presence of volatile radionuclides (I, Cs, etc) and the reduction of less volatile radio-elements (La, Am, Pu, Cm etc) to respirably-sized particles.

Generally, the release incidents are modelled for an operational reactor with an assumed one hour delay preceding a phased, three hour radioactive release to the atmosphere. Each phase of release is driven by a simultaneous release of energy that lofts the release plume carrying fractions of the fuel core inventory:

TABLE 2 – RADIOACTIVE RELEASE SCENARIOS AND LOCATIONS

CASE	NPP SITE	REACTOR	FUEL	PROBABILITY[31] yr^{-1}	COMMENTS
FLLEU1	Flamanville	1,600MWe EPR	100% LEU	$2.4\ 10^{-9}$	Existing burn-up
FLLEU1C	Flamanville	1,600MWe EPR	100% LEU	$2.4\ 10^{-9}$	No early countermeasures
FLLEU2	Flamanville	1,600MWe EPR	100% LEU	$2.4\ 10^{-9}$	Target 65GWd/tU burn-up
FLLEU1A	Flamanville	1,330MWe PWR	100% LEU	$2.4\ 10^{-9}$	Existing 1,330 NPP
FLEdFLEU	Flamanville	1,600MWe EPR	100% LEU	$2.4\ 10^{-9}$	existing burn-up – EdF release
FLMOX1	Flamanville	1,600MWe EPR	30% MOX	$2.4\ 10^{-9}$	30% MOX fuel core
FLMOX2	Flamanville	1,600MWe EPR	100% MOX	$2.4\ 10^{-9}$	100% MOX fuel core
TRLEU1	Tricastin	915MWe PWR	100% LEU	$2.4\ 10^{-9}$	100% LEU core
TRLEU2	Tricastin	915MWe PWR	30% MOX	$2.4\ 10^{-9}$	30% MOX core
TRLEU2A	Tricastin	915MWe PWR	30% MOX	$2.4\ 10^{-9}$	30% MOX core
NsSLEU1	Nogent sur Seine	1,310MWe PWR	100% LEU	$2.4\ 10^{-9}$	100% LEU core
FLEU1	Fessenheim	880MWe PWR	100% LEU	$2.4\ 10^{-9}$	100% LEU core

Severely damaging incident scenarios that bypass the reactor containment buildings are reckoned to be highly improbable, being generally referred as *'beyond-design-basis'* accidents. These are *accidental* events of such low probability of occurrence that measures to specifically counter their incidence and/or mitigate the consequences are not considered to be justified. Today, against the 9-11 background of unconstrained terrorism, it is no longer sufficient to rely upon *a priori* probabilistic reasoning when the real threat may a determined and intelligent terrorist attack that seeks out the vulnerabilities of the plant and its safety systems.[32]

The French nuclear safety regulatory system sets design targets for the overall *risk* of a reactor fuel core meltdown in the form of subsets of internal and external initiating events (or *Plant Category Conditions* – PCCs) which, considered collectively, set a frequency of occurrence of about $<10^{-6}$ per year of reactor operation with all other events not formally identified occurring at a frequency of less than 3.10^{-6} per year. For the EPR, as well as limiting the number and severity of initiating events greater emphasis has been placed on reducing the risk of certain categories by identifying the sequence into manageable groups or *Risk Reduction Categories* (RRCs) with the EPR designer Areva going so far as to claim that certain RRCs (*RRC-B*) can be *'practically eliminated'*.[33]

On the tolerability of radiological consequences there is the overall limit of 0.3mSv per year that applies to the NPPs normal operation and which covers the less severe PCCs. For the higher categories of plant condition, PCC3 and PCC4, countermeasures may be invoked before or in the aftermath of a radioactive release to limit the public dose, including enforced sheltering, evacuation and the distribution and uptake of stable iodine prophylaxis. The applicable limits and controls for the radiological protection of individual members of public in the vicinity of the NPP are as follows:[34]

TABLE 3A RADIATION EXPOSURE LIMITS – INDIVIDUAL DOSE

CATEGORY	PUBLIC DOSE LIMIT	COMMENTS – EFFECTIVE BSLS
PCC1 PCC2	0.3 mSv effective	incidents that occur during normal operation. 1 in 100 incidents or once per year of plant operation
PCC3	10 mSv effective	1 in 10,000 incidents or once per 100 years of plant operation
PCC4	100 mSv thyroid	1 in 1,000,000
RRC-B	10mSv/month 1,000mSv	The aftermath of a RRC-B but *practically eliminated* incident

As previously noted, the postulated severity of the RRC-B incident tabulated above is at the point where the societal BSL/O would be considered relevant because at 1000mSv projected dose the consequences are most likely to apply to more than a single or few individuals.

The dose bands of TABLE 3A can be related in an approximate fashion to off-site actions and countermeasures which would be expected in the immediate, interim and longer term aftermath of the release incident.

TABLE 3B DOSE MITIGATION AND COUNTERMEASURES

EDF INCIDENT CLASS	DOSE BAND mSv	ACTION/COUNTERMEASURE
PCC1 PCC2	0.1 - 1	• additional off-site radiation and contamination surveys; • possibility of advice being given to restrict the use of foodstuffs produced close to the site;
PCC3	1 – 10	• increased off-site surveys; restrictions on the use of foodstuffs likely to be implemented; • sheltering or issue of stable iodine may be considered in areas very close to the site;
PCC4	10 - 100	• restrictions on foodstuffs likely to be implemented many kilometres from the site; • sheltering or issue of stable iodine likely to be implemented; • evacuation may be considered in areas immediately adjacent to the site;
RRC-B	100 - 1000	• restrictions on foodstuffs likely to be extensive; • sheltering or issue of stable iodine likely to be implemented to several

		kilometres from the site; • evacuation of nearby population likely to be implemented; • relocation of communities, short, interim and longer terms.

In assigning the radiological consequences the *effective*[35] dose is considered (short term) at 7 days for an individual located in the immediate vicinity (at 500m) of the NPP site at the time of the release and the *thyroid*[36] dose is evaluated for a 1-year child. The longer term or lifetime dose is projected over 50 years[37] at a hypothetical point 2km distance from the NPP site.

For the assessments undertaken here, for NPPs fuelled with both LEU and MOX cores, the assumption is that the incident resulting in the radioactive release falls within the severity of the *RRC-A* and *B* incidents but includes the possibility of a high-pressure core degrade which cannot be *practically eliminated* as claimed by EdF.

EdF's claim is that high pressure core degrade situations can be transformed to a low pressure degrade by manual depressurisation of the reactor primary circuit. Under the EdF scheme manual depressurisation is to be achieved by operation of an additional relief valve over the three existing relief valves, with the manual valve opening being taken when high temperature is measured in the primary circuit. The weakness here is that the speed at which the operators would have to reach and implement a decision to depressurise the reactor, especially in light of knowledge that this act in itself could result in a complete loss, via the almost inevitable low pressure meltdown of the core, of the RPV and the heavy contamination of the containment building. In past reactor accidents the opportunity for such decision making and action has been no more than a few seconds[38] for which operator intervention has been sometimes confused and ineffective.

If it is practicable to transform the high pressure event to a low pressure meltdown (ie by reducing the RPV and primary circuit pressure down from >200b (bar) to below 20b) then, according to EdF, the post meltdown management of the molten fuel core, (*corium*) is such that the secondary containment or building enclosure will not fail via i) burning through the raft foundation slab; ii) overpressure of the building enclosure; and iii) unacceptable leakage rates from the enclosure. To substantiate this claim, the EPR design has to virtually eliminate all high pressure RPV and primary circuit failure modes, including a) hydrogen formation and detonation; b) molten fuel-water steam explosions and demonstrate that the corium catching and stabilising facility located under the RPV system will entirely passively operate effectively under extremely harsh conditions.

Incident Assumed for this Assessment: According to EdF, *'accident situations with core meltdown which would result in large premature discharges must be "practicably eliminated" via practical provisions which allow them to be returned to the residual risk range . . . when these situations cannot be considered as physically impossible, design provisions are made to physically exclude them',*[45] although there is very little in the publicly accessible EdF documentation to demonstrate this claim in detail or in its generality.

Moreover, EdF seems to give little regard to human intervention, either from the NPP operator or from an individual or group with malevolent intent, which could either bypass the safety system or lead the reactor and its associated systems into a sequence of failure. For the hypothetical incident adopted for this assessment it is assumed that operator intervention and error result in EdF's category *RRC-A* severity of incident and the subsequent radioactive release, all arising from the coupling abnormal events into an unforeseen sequence:[39]

TIME seconds	**SEQUENCE EVENT**
0	The assumption is that the reactor is operating at full power when the operators take inappropriate action following what seems to have been a straightforward reactor trip triggered by, say, the loss of steamside feedwater to the steam generators.
30	Unknowingly, the operators then follow established plant procedures to restart the reactor being unaware that the plant is in fact suffering from an unanalysed (not prescribed) event such as, say a small loss of coolant incident via the RPV circuit pressuriser system. As the incident develops with the operator intervention having no effect, at about 30 seconds into the incident, the reactor alarms transmit to the control room at a rate of over 100 per minute.
480	Too many of the alarm messages are of a diversionary nature and delay the operators present moving to a correct analysis of the situation and inability be able to isolate the fault conditions then developing apace.

555	In the highly stressed environment, the operators trigger the high pressure injection pumps not knowing that this would result in a loss of the pressuriser bubble and injection of unboranated water into the core. When, at about 75 seconds. The condenser hotwell high level alarm sounds with an impending loss of condenser vacuum, the operators become preoccupied in considering the option of initiating a steam dump to atmosphere.
2055	With the operators still believing that events are on course for the reactor restart, at about 25 minutes into the incident increased neutron flux signals, caused by steam voids now forming in the MOX fuel core, prompt concern about recriticality so much so that the operators scram the reactor, turning off the primary pumps in one of the two steam generator loops to provoke flow reversal induced by continued pumping in the other loop.
2415	However, again unbeknown to the operators, the isolated loop has boiled dry, so flow reversal and cooling is unavailable because steam has siphon blocked the 'U' section of the primary circuit to this loop. The remaining loop pumps a two-phase mixture, flow decreases due to increasing voidage causing the pumps to trip followed by boiling in the RPV after about 6 minutes with the water level lowering to uncovered the fuel core.
3315^{+} say 1 hour	Within 15 minutes, the dry space above the core fills with superheated steam leading a zirconium-steam reaction with, within seconds, a hydrogen explosion sufficient to rupture the RPV and eject much of the molten fuel mass, itself leading to a series of molten fuel-water explosions sufficient to breach the reactor building containment.
14,115 say 4 hours	Incident ends, radioactive release commences through damaged secondary containment, continuing steadily for about three hours as water remaining in the containment continues to boil off incurring a series of smaller hydrogen burns and explosions.

It is the potential radioactive release from this severely damaging hypothetical incident that has been adopted for the COSYMA analysis – the time scales assumed are a 1 hour delay from the shut down of the reactor until the commencement of a 3 hour release with $1MW_t$ of thermal energy (per hour) lofting the release from the nuclear island containment.

RADIOACTIVITY RELEASE – RELEASE FRACTIONS

In a degraded core (meltdown) situation, the volatile radionuclides such as iodine and caesium which are not totally soluble in the solid fuel matrix of uranium- or plutonium-dioxide, become sufficiently mobile at the elevated temperatures to move to the surface of what is left of the fuel pellet fragments, and thence into the primary containment of the reactor pressure circuit. Some of the escaping radionuclide compounds are soluble in water and this will help to hold back a proportion of the release, other radionuclides might condense or *'plate-out'* on cooler surfaces and fail to release, so in all there are a number of chemical and physical mechanisms that prevent all of the available radioactive substances in the reactor fuel core (the *source term*) from freely releasing into the environment. This part of the total radioactive inventory of the fuel that is not held back and freely releases to the environment beyond the reactor island containment is referred to as the *'release fraction'*.

Obviously, the size of the release fraction is determined by the nature and severity of the incident and the response of the reactor systems, particularly the containment envelopes of the nuclear island. Also, the actual fraction will be different for the various classes or groupings of radionuclides, with the noble gases releasing much more freely than volatile elements such as caesium. TABLE 4A lists the release fractions assumed for the universally accepted benchmark and very comprehensive study[40] of postulated reactor accidents in the United States showing the release fractions assumed for each of eight groups of radionuclides in a severely damaging core degrade in which the containments are bypassed.

TABLE 4A – EXAMPLE RELEASE FRACTIONS

CASE	SCENARIO & NOTES	RELEASE FRACTION							
		Xe-Kr	**I**	**I/I-Br**	**Cs-Rb**	**Te-Sb**	**Ba-Sr**	**Ru**	**La**
	3 hour release with WASH 1400 release fractions.	$9\ 10^{-1}$	$7\ 10^{-3}$	$7\ 10^{-3}/7\ 10^{-1}$	$5\ 10^{-1}$	$3\ 10^{-1}$	$6\ 10^{-2}$	$2\ 10^{-2}$	$4\ 10^{-3}$

These release fractions given above relate to the state of reactor and fuel technology of the 1970s.

The fault condition modelled for this assessment comprises a hypothetical fault severe enough to degrade or melt the reactor core and breach the primary circuit containment, the holding of the secondary (building) containment for a period of 1 hour, then failure of the containment, thereafter a release of 3 hour duration into the atmosphere over which the rate or temporal distribution of the release for the different radionuclide groups is taken to be:

TABLE 4B – TEMPORAL DISTRIBUTION OF AN IDEALISED RELEASE

	FRACTION OF CORE INVENTORY RELEASE EACH PHASE			
ELEMENT	**0 – 1 h**	**1 - 2 h**	**2 – 3 h**	**3 – 4 h**
Xe – Kr	0	$8.1\ 10^{-1}$	$4.5\ 10^{-2}$	$4.5\ 10^{-2}$
organic I	0	$6.2\ 10^{-3}$	$3.5\ 10^{-4}$	$3.5\ 10^{-4}$
inorganic I-Br	0	$6.3\ 10^{-1}$	$3.5\ 10^{-2}$	$3.5\ 10^{-2}$
Cs – Rb	0	$4.1\ 10^{-1}$	$4.8\ 10^{-2}$	$4.8\ 10^{-2}$
Te – Sb	0	4.510^{-2}	$1.3\ 10^{-1}$	$1.3\ 10^{-1}$
Ba – Sr	0	$5.5\ 10^{-2}$	$2.7\ 10^{-3}$	$2.7\ 10^{-3}$
Ru	0	$7.5\ 10^{-3}$	$6.3\ 10^{-3}$	$6.3\ 10^{-3}$
La	0	$9.2\ 10^{-4}$	$1.5\ 10^{-3}$	$1.5\ 10^{-3}$

The release fraction data OF TABLE 4B was applied to a major consequence study of the UK PWR reactor subsequently commissioned at Sizewell.[41] From the accessible details of the UK Sizewell B PWR nuclear power plant (NPP) safety case, it is clear that by the mid-1980s the Sizewell NPP operator challenged the WASH1400 release fractions as being too high even for extreme in-core incidents identified as FLLEU1 in the unabridged TABLE A (see APPENDIX I), electing instead a range of release fractions for each radionuclide group presented as a probability of occurrence subset.[42] The most probable (p=60) band of release fractions from this subset gives significant reductions over WASH-1400 release fractions, shown emboldened italicised ***thus***:

TABLE 4C – SIZEWELL B MODIFIED RELEASE FRACTIONS OVER WASH-1400

CASE	SCENARIO & NOTES	RELEASE FRACTION						
		Xe-Kr	**I/I-Br**	**Cs-Rb**	**Te-Sb**	**Ba-Sr**	**Ru**	**La**
-	1320MWe Sizewell PWR 3 hour release with modified WASH 1400 release fractions	$9\ 10^{-1}$	$7\ 10^{-3}$/***$1.3\ 10^{-1}$***	***$1.3\ 10^{-1}$***	***7.510^{-2}***	***$1.5\ 10^{-2}$***	***$5\ 10^{-3}$***	***$1\ 10^{-3}$***

However, a more recent 1997 NRC study for the same type of 4-loop Westinghouse PWR design at Sequoyah NPP[43] each of the radionuclide group release fractions taken for a seriously damaging incident does not share the same degree of mitigation assumed earlier for Sizewell:

TABLE 4D – SEQUOYAH RELEASE FRACTIONS

CASE	SCENARIO & NOTES	RELEASE FRACTION						
		Xe-Kr	**I/I-Br**	**Cs-Rb**	**Te-Sb**	**Ba-Sr**	**Ru**	**La**
-	Sequoyah[44] PWR 3 minute puff release modified WASH 1400 release fractions	1	$3.7\ 10^{-1}$	$2.7\ 10^{-1}$	$1.3\ 10^{-1}$	$2.5\ 10^{-2}$	$8\ 10^{-3}$	$1.6\ 10^{-3}$
	Followed by 2 hour downstream release	0	$2.2\ 10^{-1}$	$3.5\ 10^{-1}$	$3.0\ 10^{-1}$	$1.3\ 10^{-1}$	$3\ 10^{-3}$	$1.3\ 10^{-2}$

The recent Sequoyah release analysis indicates an order of magnitude increase of the release of the lanthanum grouping (Group 7) which follows a better understanding of how these radionuclides mobilise at high temperatures. This increased release fraction of the transuranic isotopes could have a significant influence in the release performance of MOX fuels which contain higher actinide content.

Justification of the release fractions adopted for the EPR design is not convincing. In its nuclear safety case assessment for the EPR NPP,[45] EdF claim for the very severe *'accidents'* class RRC-B the melted core debris will be entirely confined by the building containment with only a 0.3% release of its volume per day. This so-called *'disconnection'* source term is expressed in terms of the following release fractions to the environment:

TABLE 4E – EPR RRC-B RELEASE FRACTIONS[46]

CASE	SCENARIO & NOTES	RELEASE FRACTION								
		Xe-Kr	**I**	**I-Br**	**Cs-Rb**	**Te-Sb**	**Ba-Sr**	**Ru**	**La**	**Pu**
-	EPR	$1.5\ 10^{-2}$	$1.5\ 10^{-3}$	$6.1\ 10^{-7}$	$7\ 10^{-8}$	$5.1\ 10^{-8}$	$1.3\ 10^{-8}$	$2.6\ 10^{-9}$	$2.6\ 10^{-9}$	$4.6\ 10^{-10}$
	EPR French Language Version	$1.5\ 10^{+0}$	$1.5\ 10^{-5}$		$7\ 10^{-8}$	$5.1\ 10^{-6}$	$1{,}3\ 10^{-6}$	$2.6\ 10^{-7}$	$2.6\ 10^{-7}$	$4.6\ 10^{-8}$

An absolute baseline for the release fractions, albeit for a different type of reactor the RBMK but like the PWR fuelled with uranium dioxide fuel, are the best estimates for the 1986 Chernobyl accident. TABLE 2F lists a number of estimates of selected radionuclide groups compiled from measurements taken in the region of Chernobyl and from within the sarcophagus.[47]

Table 2f Estimates of Released Radioactivity of Major Nuclides by the Chernobyl Accident[48]

Case	Scenario & Notes	Source	Release Fraction					
			Xe-Kr		I/I-Br	Cs-Rb	Te-Sb	Ba-Sr
-	Chernobyl 1986	USSR 1986	1		0.2	0.13		0.04
		Seo[49] 1988	1		0.7	0.57		0.096
		Manaka[50] 1993	1		0.49	0.31		
		Ukraine[51] 1996	1		0.55	0.30		0.05
		Borovi[52] 2001	1		0.55	0.33		
		UN Forum[53] 2005	1			0.30		0.048

Referring to Figure 1, Appendix II:

Interestingly, the 1975 WASH-1400 🟩 analysis anticipates the severity of the Chernobyl 🟨 release of 1986.

The 1997 release fractions calculated for a degraded core incident at Sequoyah[54] 🟦 places the core release fractions higher than the mitigation claimed for the 1982 Sizewell 🟪 analysis. Thus the reduction in the Sizewell release fractions of the mid-1980s should really only be justified in terms of improvement to the resilience of the containment and in-containment fuel particle abatement technologies (sprays, scrubbing, etc) introduced to the Sizewell generation of PWRs. There is some merit for a reduction of the release fractions because WASH-1400 does not fully account for retention of (radio)activity in the primary circuit, its removal from the containment atmosphere (ie via sprays), and scavenging out during the escape from the containment.[55,56] Even so, the Sequoyah scenario is assumed of sufficient damage severity to have rendered much of the abatement processing within the containment ineffective.

The very small release fractions adopted for the EdF EPR design 🟥 are based on, some would opine, a remarkable degree of confidence in the design capability to suppress a number of severe events that could follow from a loss of coolant accident (LOCA) initiating fault.[57] This approach is a departure from the previous design philosophy wherein it was acknowledged that, although certain severely damaging events could happen, the frequency of occurrence was so low that intolerable consequences, as chance would have it, would never arise.[58]

MOX Fuel

The comparisons of the release fractions so far considered apply to the performance of low enriched uranium (LEU) oxide fuels. However, in France, the use of MOX has been a part of the nuclear strategy since 1987 and presently 22 reactors are licensed to operate with partial MOX loading[59] at the so called *'mono-recycling'* of partially MOX loaded cores (~30% MOX assemblies). The EPR design will advance on this level of MOX utilisation with a target of the reactor core being fuelled with a 100% proportion of mixed oxide fuel (MOX),[60] with this target set to be achieved within a few years from the commissioning of the first EPR NPP at Flamanville in or about 2012-13.

MOX fuel is markedly different to LEU oxide fuel in physical make-up, irradiation products (ie the source term), immediate post incident heat generation, and release fractions when subject to adverse conditions. A typical PWR MOX assembly[61] consists of several types of fuel rods with plutonium content varying from about 6 to 12% weight with the LEU support is made of tail uranium with U-235 concentration of about 0.25wt-%.[62]

There is increasing evidence that under adverse core conditions the higher burn-up fuels degrade to provide greater *'shell'* release rates,[63] this particularly applies to mixed oxide (MOX) fuels. This may be a very significant factor in determining the overall release fractions for the radionuclide groupings of the EPR generation of reactors with fuel burn-up targets in excess of 60GWd/tU and a commitment to MOX fuelling.

TABLE 5 REPORTED SHELL RELEASE RATES FOR LEU & MOX FUELS[64]

	RELEASE RATE FOR LEU FUEL		RELEASE RATE FOR MOX FUEL	
GROUP	**<47GWd/t**	**>47GWd/t**	**<33GWd/t**	**>33GWd/t**
Xe-Kr	0.08	0.25	0.08	0.5
Other Noble Gases	0.02	0.08	0.02	0.15
Br-Ru-I-Cs	0.02	0.08	0.02	0.15

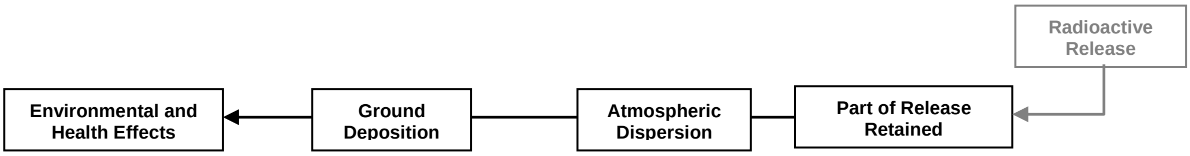
Although the source of Table 5 is not cited, the data presented is most probably linked to the French VERCORS tests carried out from the mid-1990s through to 2002 involving, in all, 28 tests with LEU and MOX fuel materials, replicating severe core conditions[65] but, at its conclusion, the VERCORS programme was reported to be incomplete.[66]

In summary: There continues to remain a great deal of uncertainty about the most appropriate settings of the release fractions for a severely damaging incident. This uncertainty applies overall in matching the release fraction order of magnitude to the incident scenario and, specifically, to fuel types particularly to MOX fuel. The approach by EdF in setting very small release fractions at the containment boundary, via its assertion that the containment enclosures will be sufficiently resilient against all those incident severities that cannot be practically eliminated by design, is somewhat foolhardy, if not cavalier.

The COSYMA model neither allows for probabilistic subsets of release fractions, nor is it possible for different release fractions to be applied to LEU and MOX partitions of the partial-MOX fuelled core, although it is possible to allocate the transuranic radionuclide grouping (Pu-239, Am-241 and Cm-242) with an elevated release fraction. This is particularly important because a MOX fuel core will generate a larger inventory of the transuranics than its equivalent LEU core and, hence, reflect the greater contribution of these long-lived alpha emitters to the consequences of a radioactive release. However, the difficulty here is although the VERCORS test results demonstrate a higher shell (across-the-fuel-cladding) migration for MOX fuels, there is nothing available quantifying the overall release fraction of the transuranic grouping[67] (from fuel through to beyond the secondary containment barrier) other than the fraction adopted for LEU fuelled cores.[68]

However, for the COSYMA analysis of this assessment the release fractions will be limited to a consistent set of the release fraction profiles applied across all of the NPP sites considered, save for the release modelled at the 30% MOX core at Tricastin which also incorporates a separate case with an elevated release fraction for the transuranics (Group 7 nuclides). The Tricastin models illustrate account for the extent, where appropriate, of the MOX fuel incorporated into the reactor core and the higher reported release fractions. The outcome of the assessments illustrates the range of consequences that could develop although, that said, there must remain an element of uncertainty on the derivation and application of the release fractions adopted for these assessments.

A) ATMOSPHERIC RELEASE PARAMETERS



Of the release parameters detailed in Table A, the release duration influences the horizontal dispersion of the atmospheric plume and associated deposition footprint; the release height has a strong impact of the exposure of those individuals near to the point of release; and the energy of the release lofts the aerial plume reducing the exposure over the downwind areas. The release is considered to be in the form of an aerosol of 1μm oxide particles, apart from the noble gases and iodine. The release fractions given in Table A are the proportions of the total fuel core inventory that is released free of the reactor and its containment buildings but excludes any radioactive debris, substances and materials that may be released directly into the local watercourses and/or marine environment.

B) COSYMA & RADIOLOGICAL CONSEQUENCES

The airborne concentrations, dispersion and deposition of the released radioactive materials are evaluated using the European Commission approved code COSYMA.[69] This is a comprehensive software package for evaluating the radiological consequences of radioactive releases in terms of health and other impacts to the public.

The radiological consequences will vary depending upon the prevailing meteorological conditions, particularly the atmospheric stability category (Pasquill) and the wind direction which, combined, determine the rate at which the release is dispersed, its radionuclide deposition and radiation dose (both external and internal from respiratory uptake) the exposed population. The health impact of the exposure is determined in accord with the risk factors recommended by ICRP60[70] and the mitigating countermeasures incorporated into the software.

COSYMA offers two fundamentally different bases of analytical approach to predicting the consequences of a radioactive release, these being *probabilistic* and *deterministic*. Essentially, the *probabilistic* analysis considers a range of meteorological and atmospheric stability conditions and its results are versed in the probability of a range of consequence outcomes, whereas the *deterministic* analysis is contained within a single set of atmospheric stability conditions, usually taken as *Class D Stable*.[71] The results given in this assessment are probabilistic and presented in terms of percentiles drawing on the meteorological, location and population distribution data held on the COSYMA database.[72]

IMPLEMENTATION OF COUNTERMEASURES

It would be unreasonable not to expect some form of mitigation action to be taken in the immediate and during the interim- and longer-term aftermath of any radioactive release incident.

Countermeasure actions considered for the immediate aftermath in France include Evacuation, Sheltering and Iodine Prophylaxis[73] at the following intervention/aversion levels:

TABLE 6 COUNTERMEASURES

COUNTERMEASURE	AVERSION DOSE[74]	DISTANCE & Notes km	COSYMA PARAMETERS ICRP 60
SHELTERING	10 mSv	Not Known	10 mSv
EVACUATION	50 mSv	Not Known	50mSv out to 10km, 100mSv thereafter
IODINE PROPHYLAXIS	100 mSv	10km – as soon as possible	Distribution to 1.8km – WHO 10mSv[75]
RELOCATION/REHOUSING	10 mSv/month or 1,000 mSv	Long term dose considered with decontamination measures	

The COSYMA modelling assumes *dose-based* triggering of sheltering and evacuation countermeasures at the levels given in TABLE 6 with no geometric area based countermeasures in place. Evacuation is assumed to be affective in two distinct dose-level stages (50 and 100mSv) and assumed to be effective whatever the distance from the NPP site. Timings for evacuation and maximum sheltering distance are modelled as follows:

TABLE 6A COUNTERMEASURES DELAYS AND TIMING FROM COMMENCEMENT OF RELEASE

COUNTERMEASURE STAGE	TIME
Initial delay from start of release to commencing evacuation	4 hours
Delay between end of local evacuation out to 2km to start of dose criteria area	2 hours
Time take to drive out of evacuation area	120 minutes
Time between end of evacuation and removal of activity from skin, etc	6 hours
Maximum distance for sheltering	100km
Stable Iodine Distribution	10km
Time taken to distribution stable iodine (average)	4 hours
Maximum stable iodine distribution distance	24km
Relocation	6 days

Although it is possible to model these mitigating actions in the COSYMA software there will be, in a real radiation situation, limits of how effectively the countermeasures might be implemented and, indeed, if the general public will follow the advice and instructions issued by the authorities. For example, in the severely damaging events modelled here the need to organise and evacuate great numbers (see TABLE B *Expectation Value* of ~0.5 million for the NPP at Nogent sur Seine) would not be at all practicable and, moreover, the public might themselves self-evacuate in a disorganised if not chaotic way, possibly unknowingly placing themselves at risk of greater exposure.

The overall outcome of failure to fully implement countermeasures in a real radiation emergency will, effectively, overwrite the somewhat mechanistically derived COSYMA consequence mitigation, thereby increasing the health impact particularly for the interim and longer term predictions.

In this and other respects, the analyses reported here are not intended to provide precise forecasts of the radioactive releases and consequences at the exampled nuclear power plants. This is because much greater detailed input is required to define the near field data, population density and meteorological conditions, for each locality and how the population would react, particularly if left uninformed of essential information and direction on what best to do. However, the results do provide indicators of the trends and indices of the probability and magnitude of the health impact a radioactive release, accidental or otherwise, from any of the nuclear power plants examined.

COSYMA provides a wealth of results and data, including:

- Airborne and Ground Concentrations
- Mitigation (dose reduction) by Early Countermeasures of Sheltering, Evacuation and Iodine prophylaxis
- Short Term Individual Dose for a specified Integration Time Period
- Individual Health Risks of Mortality and Morbidity for Organs and overall Effective Dose
- Early Health Effects of Mortality and Morbidity for Organs and overall Effective Dose
- Late Countermeasures including Decontamination and Relocation
- Long Term individual Risks to Late Effects
- Long Term Individual Organ and Effective Doses
- Long Term Collective Dose
- Late Health Effects

Not all of these outputs have been reproduced in this assessment although such are available if required. COSYMA also includes algorithms determining the economic consequences and the longer term impact of contaminated food ingestion, although these facilities have not been used for this assessment. Also, The selection of the COSYMA results reproduced in the NPP ANNEXES have not been 'smoothed' for presentation, being presented unmodified *'warts and all'*.

C) AIR RESOURCES LABORATORY – NOAA HYSPLIT MODELLING

This on-line atmospheric dispersion modelling facility is deployed to provide a snapshot of the plume dispersion pattern and a deposition footprint.

The trajectories and footprints generated rely upon archive weather data to model the dispersion from geographic point (ie the NPP site) which is superimposed onto a photographic image (Google Earth) as a series of frames that can be used to portray the plume development over time for the particular past time and date chosen. The modelling incorporates the duration of the release, the height of the release and an overall deposition or settling velocity for the modelling of what are, essentially, small parcels of air contained within the trajectory, plotting the trajectory and deposition in four bands of air and ground deposition concentrations.[76]

Subject to these obvious limitations, HYSPLIT modelling of a hypothetical atmospheric release at NPP sites provides a useful insight and illustration of how a radioactive release might be *expected* to generally develop in similar meteorological circumstances at the particular time and date chosen. All of the NOAA trajectories are plotted for a unity rate of release from the NPP site.

RESULTS OF COSYMA ANALYSIS

Before considering the detail results for NPP sites nominated for this assessment the structure of the complex field of COSYMA results provides for an understanding of the important features of the release and its radiological implications.

Exposure Pathways: For example, the relative important of the exposure and uptake pathways contributing to early health effects shows that the total effective (ie whole body equivalent) dose is dominated by *inhalation* during the early stages of the event aftermath. Inhalation contributes about 80% to the overall dose from a reactor fuel core comprised entirely low enriched uranium (LEU), with smaller components of *groundshine* contributing about 15% and *cloudshine* 4%. For a MOX fuelled reactor core the dose impact is of greater magnitude, being dominated by *inhalation* uptake with more than 90% of the effective dose being received via the inhalation pathway. The uptake of alpha emitting nuclides, the transuranics from the plutonium content of the MOX, has a very significant impact on the long term dose commitment over the remaining lifetime of the receptor.

The above contribution from groundshine of gamma (γ) emitting material (contamination), inhalation and the other uptake pathways relates to a 7 day integration period but this will vary according to the period over which the individual receptor is subject to exposure, it is site- and habit-specific and, of course, to the radionuclide content of the release (fuel burn-up, LEU/MOX proportion, etc). For a LEU of relatively low burn-up (35GWd/tU) the proportional contribution from the main uptake paths under stable category (neutral - D) meteorological conditions are:

TABLE 7 EXAMPLE OF % CONTRIBUTION OF MAIN UPTAKE PATHS TO EFFECTIVE DOSE
CATEGORY D, NO RAIN – 100km from NPP

PERIOD	INHALATION αγ	CLOUD βγ	GROUND βγ
7 days	77	1.5	22
30 days	63	1.2	36
>30 days	27	0.5	73

TABLE 7 shows the relative importance of the different uptake pathways with inhalation dominating because, once the overhead plume has passed, resuspension of deposited contamination continues to provide airborne particulate.

The challenge for countermeasures and other dose mitigation actions in the immediate aftermath of a MOX fuelled reactor incident is to provide respiratory protection to members of public or, before the uptake becomes significant, evacuate individuals from the radiological area. However, because of the rapidity of events and the very large numbers of public that could be involved, it may not be at all practicable to provide respiratory protection, or effective evacuation. With typical air-exchange rates for both domestic and commercial buildings, sheltering would not be effective against arresting respiratory uptake after an hour or so.

For a LEU fuelled reactor the dominance of the inhaled uptake path falls off to about 80% (but with a corresponding reduction from the MOX dose level). In the longer term and at further distances from the NPP site, the bulk of the exposure[77] is received via inhalation and deposited shine up to 7 days (~75 and 20% respectively), thereafter up to 30 days (~60 and 35%) and after that and effectively forever, until the activity has significantly decayed, 25 and 70%. This outcome does not account for ingestion of contaminated foodstuffs, etc., but it underscores the importance of evacuation and efficient decontamination of the radiological zones.

The external dose received from deposited γ emitters will also have an influence on early and late effects and, similarly, this is very much determined by the isotopic composition and the distance from the NPP. At 10km from the NPP the deposited activity source of effective dose is:

TABLE 8 % CONTRIBUTION OF EFFECTIVE DOSE FROM DEPOSITED ACTIVITY
CATEGORY D, NO RAIN – 10km from NPP

% TOTAL DOSE FROM DEPOSITED EMITTERS OVER INTEGRATION PERIOD					
1 day	7 day	30 day	1 year	5 year	50 year
7.7	18	29	46	73	99

COSYMA includes facility to model dose uptake via ingestion of local foodstuffs in the longer term but, for this, considerable data is required on the local agriculture and food uptake habits of the critical groups of potential human receptors of radiation exposure. This facility has not been utilised in these assessments on the assumption that effective food controls would be implemented in the areas so affected.

MOX Fuel – Increased Radiological Burden: The introduction of MOX fuel has a number of implications for the patterns and magnitude of the radiological consequences. MOX fuel includes, on a weight-for-weight basis with LEU fuel, a greater proportion of the transuranics (Pu-239, Am-241 and Cm-242) which, being long-lived alpha emitters, will contribute disproportionately to the health consequences, particularly if inhaled. The French use of MOX fuel comprising *reactor-grade* plutonium further heightens the long term contribution of the transuranics to the health consequence. Putting aside the uncertainties over the believed higher release fractions relating to MOX fuels, the general outcome of the COSYMA assessment is that the higher transuranic inventories in MOX loaded cores result in increased health consequences, particularly so in both the early fatalities and the longer term or latent cancer deaths.

TABLE B, APPENDIX I shows this via assessments for the proposed EPR at Flamanville fuelled solely with LEU (Case FLLEU1) by directly comparing to the same reactor partially and fully with MOX (FLMOX1 and FLMOX2). The statistically mean predictions compare on early deaths at 222/322/650 for the LEU, 30% and 100% MOX cores respectively, but with the thyroid cancer incidence (not mortality), being not that significantly different between the 100% LEU and 30% MOX fuel assessments.

Mitigating the Dose by Countermeasures: If the evacuation is delayed past the first day or so, as it might be in a serious and far-reaching release, the external irradiation contribution, even with sheltering, increases to 50 to 70% of the total dose. If the prevailing meteorological conditions include rainfall, then the external dose rises to about 80% and 90% for the two respective evacuation times and illustrates the importance of ground and surface contamination in the second phase of early dose commitment.

Thus the crucial need to evacuate speedily and ahead of the dose commitment which may not, however, be practicable in a rapidly developing release scenario.

The timing of effectively implementing countermeasures is also extremely important in mitigating the dose. For the general isotopic inventory released in these assessments and for neutral meteorological conditions with no significant rainfall, about 5 to 10% of the dose is delivered within the first day of exposure and which is, in effect, unavoidable whatever countermeasures are implemented. About 20% of the total dose is absorbed during the first week, 20 to 30% in the first month, and about 50% over the first year.

For the radioactive release incidents assessed there exists the potential demand to evacuate very large numbers of population according to the land areas affected. The location of the particular NPP under scrutiny is obviously important, particularly in terms of the local population densities and location of urban conurbations under the path of the radioactive plume and, of course, if the NPP is located in the region of an international border (such as Fessenheim) then the authorities of other states will have to be involved in the emergency planning and implementation of countermeasures. In this case, different national standards of trigger or intervention levels may apply possibly adding to the post incident chaos as some populations groups are, say, evacuated whereas others just across a state border are not.

In fact, the numbers of public requiring countermeasure action can be very large depending of the rural/urban mix downwind of the NPP. At Flamanville the analysis projects that for a 100% LEU fuelled EPR a (statistically mean) area of about 7,200km^2 entailing about 176,000 individuals would require evacuation tailing off over the first week following the release. In a number of the *weather sequences* (N^o 12 , 14 & 60 of 107 sequences in total) adopted in the COSYMA model for the Flamanville region, several place the prevailing wind to the North East (NNE) which takes the airborne plume and deposited contamination into the urban population of Cherbourg (about 20km distant for Flamanville), requiring evacuation and short term (7 days) relocation of large numbers of population. Another weather sequence (N^o 10) for Flamanville results in a direct fall-out over the nuclear reprocessing plant at la Hague with a similar evacuation and relocation period of 7 days – if and how the reprocessing activities would close down and maintain safety during and in the radiological aftermath of a serious incident at Flamanville is not at all clear.

For the existing NPP at Nogent sur Seine the land tract qualifying for evacuation, although smaller at about 4,800km^2 but of greater urban settlement could require upwards of 424,000 evacuees. Where there is a need for evacuation events may move so rapidly as to overtake the evacuation criteria, or the task of evacuating so many members of population may be impossible to achieve within the criteria (ie 50mSv effective dose). In either case, failing the dose criteria for evacuation and other dose mitigation countermeasures, will inevitably result in a higher than forecast health consequence simply because fewer people had been removed or had been removed later than scheduled, and or there may be insufficient resources to monitor and decontaminate those arriving at hastily prepared evacuee reception centres.[78]

MOX fuelling increases the resources needed to be held in reserve if effective post-release countermeasures are to be implemented. For example, the projected EPR at Flamanville when fuelled with a 30% MOX core (the present level permissible in France) will have to provide for a doubling of the land area requiring evacuation than for the EPR fuelled with LEU to the present fuel burn-up levels (12,000 over 6,000km^2).

Administration of thyroid prophylactic measures (stable iodine tablets) would also present similar demands on the emergency services, although there is no significant different between LEU and MOX fuelled cores. If the present French emergency reference trigger levels for prophylaxis are maintained downwind of Nogent sur Seine, for example, the (statistically mean) numbers involved would reach upwards of 22,000 individuals based on the trigger thyroid dose of 100mSv. However, if the World Health Organisation (WHO) intervention dose of 10mSv for neonates, children and nursing mothers were to be adopted then the qualifying catchment area for these critical groups would be much more widespread.

Radiological Consequences of a Degraded Core: So that the different NPP sites might be compared in terms of radiological impact the incident modelled, in terms of the same degree of containment damage (or bypass) and release fractions for the appropriate reactor core inventory, on reactor size (MW_e) for a 100% LEU core and, where appropriate, for 30% and 100% MOX cores. Of course, the composition and form of the released radioactivity will determine the nature and severity of the radiological impact and the assessments presented here are, generally, just for one situation which (other than the contrast between LEU and MOX releases) does not illustrate the influence that different types and severity across the range of all potential release situations.

For example, if the content of the ruthenium group (Group 6) increased say by a larger energy and temperature of release there would be as a result a greater irradiation of the lung of receptors. As noted previously, the effective countermeasures in targeting (mitigating) radionuclide-specific consequences early in the incident aftermath is crucial to limit the long term consequences. There would be expected a greater incidence of thyroid deaths in a situation involving a higher energy of release, following a longer period of the reactor heating and the in-core fuel systems breaking up prior to failure or bypassing of the containment.

Individual Risk: It is quite realistic for the COSYMA model to determine the risk to an individual (the *individual risk*) of fatal cancer and early death as a function of distance from the NPP. Like all of the other results of this assessment the analysis is presented in a range of probabilities of outcome but here the discussion relates to the *expectation value* or *statically mean* outcome. COSYMA evaluates and arrives at the individual risk at specific downwind distance but by averaging over all wind directions (taken from the built-in data base).

The individual risks presented in this assessment have been isolated from the risk of the NPP arriving at a radioactive release situation, that is the individual risk is presented is above the risk of the incident itself taking place. For the type of incident modelled, the nuclear industry[31] generally assumes an extremely remote frequency of occurrence of about 1 in one million per reactor year (1.10^{-6}) or even lower at the $2.4.10^{-9}$ per reactor year assumed for the hypothetical fuel core degrade cited in this assessment.

However, the 'COSYMA' risks should not be considered to be entirely unavoidable or, indeed, solely conditional upon some incident triggering the release, because the COSYMA risk includes and accounts for siting, local and regional weather (meteorological), and population distributions. These factors, contributing to the risk and consequences, are quantified by this assessment to be significant with the disparities shown between the various NPPs compared (see *Collective Dose*) suggesting inequalities in the site selection process (ie not an even playing field).

Cancer risks are evaluated as an average value in a population having an age distribution typical of that in the UK so variation would be expected if the age demography downwind of the French NPP sites analysed differed significantly from this. Here, the individual risk is the *mean effective* risk arrived at by summing over the organ risks and, in reality, the risk would vary above and below the mean with age, habit, etc., of the individual, with some individuals at no risk.

The NPP ANNEXES include a selection of detailed results for each NPP assessed with Flamanville and Nogent sur Seine given greater coverage than Fessenheim and Tricastin. Here the detailed results for Flamanville are reviewed, although much the same applies to the other NPPs suitably amended to take account of NPP, its site and regional factors.

GRAPH FR1 (FLAMANVILLE ANNEX) compares *mean* individual risks for early death and long-term mortality for Case FLLEU1 (the current LEU burn-up EPR core at Flamanville) with and without countermeasures. With countermeasures implemented, the individual risk of *early* death rapidly peters out to a risk of about 1 in 200,000 for an average individual located at 20km distant from the NPP; the risk increase to about 1:2,000 at about 8km; and 1:100 at about 2km. The individual risk of long-term mortality is 1:200 at 20km; 1:80 at 8km; and 1:15 at 2km. For the proposed Flamanville EPR fuelled at 30% MOX, GRAPH FR3, the individual risk early *death* is 1 in 140,000 at about 20km distant from the NPP; the risk increases to about 1:1,800 at about 8km; and 1:30 at about 2km and, similarly, the individual risk of long-term mortality is 1:56 at 20km; 1:20 at 8km; and 1:10 at 2km.

Generally, the use of MOX fuel increases both the early and late individual risk as a result of the respiratory uptake of the lanthanum group radionuclides in the immediate aftermath of the incident. Rapid implementation of the evacuation countermeasure, requiring a projection ahead of the dose, results n a marked reduction in both early and long term individual risk. If, as discussed earlier, moderate burn-up MOX fuel releases a greater fraction of its inventory during a core degrade then the consequences will be correspondingly greater. To illustrate this possibility two identical cases have been analysed for Tricastin NPP fuelled with a 30% MOX core but with a greater (doubling) of the release fraction for the lanthanum group of radionuclides (*Group 7*) but with all other groups set at the Sequoyah NPP levels. This comparison is highlighted in TABLE B (cases TRMOX2 and TRMOX2A) and gives, generally, an increase of about 50% over for the higher release lanthanum group for the Tricastin site specific factors.

COSYMA Modelling: The COSYMA modelling arrives at the numerical result with slavish adherence to its instructions setting countermeasure intervention levels (both geometric and dose) as prescribed by the French emergency planning regime. The prescribed countermeasures are introduced in a mechanistic fashion and, although there is some degree of flexibility in setting the level and nature of the intervention, it is difficult to foresee and model the outcome of sometimes chaotic human behaviour. The effect of countermeasures can be gauged by comparing Cases FLLEU1 and FLLEU1D of TABLE B where, for the latter, the early stage countermeasures beyond 2km have been disengaged showing a statistically mean doubling of early deaths (51 to 119).

Of course, it is expected that the local and then state authorities will implement countermeasures but in the chaotic aftermath of a major nuclear incident the situation is unlikely to go to plan: For example, the number of individuals requiring evacuation may outstrip resources; there may arise lengthy delays in transferring evacuees from the contaminated area because of traffic jams on roads arising from disorganised self-evacuation by large numbers of public; there may be delays in decontaminating evacuees; stocks of prophylactic tablets may be insufficient; and so and so on. Once committed to a site specific assessment COSYMA cannot change the countermeasure prescripts if it encounters an unrealistic countermeasure task, as with the large numbers requiring evacuation at Nogent sur Seine, so it carries on regardless generally, by this adherence, reducing the radiological consequences by assuming the countermeasures will be implement seamlessly and effectively.

In the models adopted for this assessment, the challenges encountered in effectively implementing countermeasures have been, albeit somewhat crudely, incorporated by introducing a 4 hour delay in commencing the evacuation countermeasure and a 6 hour delay in decontaminating evacuees.[79] Overall, it is believed that this is reasonable ‘adjustment’ in account of the significant numbers of evacuees involved, although it may result in a disproportionate skewing of the early death and morbidity rates particularly, as discussed above, for the MOX fuel release incidents. That said, the very large numbers (>500,000) requiring evacuation downwind of some NPP sites (eg Fessenheim) would stretch emergency planning resources and there may be introduced particular bottlenecks and difficulties where the radioactive release drifts across another state (again Fessenheim into Germany and Switzerland).

Another important aspect of the COSYMA modelling is misrepresentative. This is the modelling assumption is that the reduction of dose rate over the interim and longer terms is due to mainly as a result of radioactive decay and the migration of contaminants downwards from the soil surface. On the assumptions integral to its analysis, COSYMA assumes a decline of about one order of magnitude over a period of the first five to ten years following the incident, thereafter the decline is much slower with few tens of years passing to achieve a second order of magnitude reduction. However, these prescriptive rates of activity decline due to migration into the soil have been found to be very more complex with, indeed, an apparent resurgence of dose exposure from certain radionuclides during the second decade following the release at Chernobyl.[47]

Importance of the Release Fractions: The release fractions adopted for the assessment have been consistently applied across all of the LEU and MOX fuel cores and, essentially, comprise the fractions used in the latest, publicly available study (1997) for the Sequoya PWR NPP in the United States. This set of release fractions do not take into account, on one hand, the claimed improvement in the containment design of the EPR or, on the other hand, the recent evidence that higher burn-up and, particularly, MOX based fuels are susceptible to significantly higher rates of *shell* release. Of course, the containment mitigation based on the EdF claim that the severe containment breach and bypass incidents are *'all but practically eliminated'*, even if applicable to the EPR in all conceivable and credible incidents, which is doubtful, would not apply to the earlier NPPs at Nogent, Fessenheim, Tricastin and Flamanville.

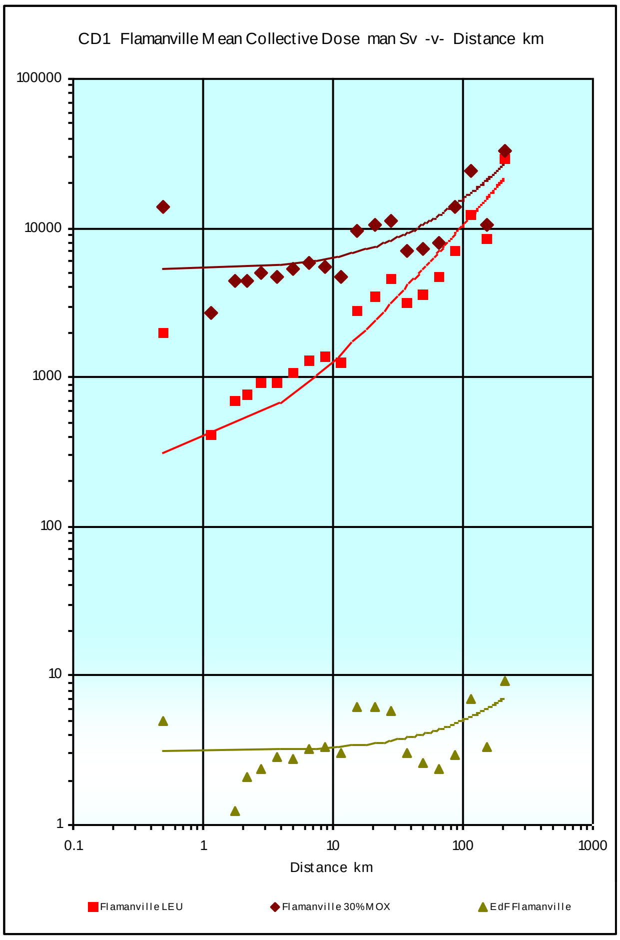
One other controlling feature to the assessment is that the radioactive release emanates from a single reactor at the NPP site. This might be appropriate for accidents applying to an individual reactor system, but there is risk that all reactors on a single site might be subject to common mode failure from some external hazard (ie earthquake) and, of course, it is not beyond the realms of imagination that a terrorist act might encompass all reactors on a NPP site (ie both of the World Trade Centre towers) or, indeed, take action against several NPPs simultaneously (ie World Trade Center, Pentagon, and one other unknown target).

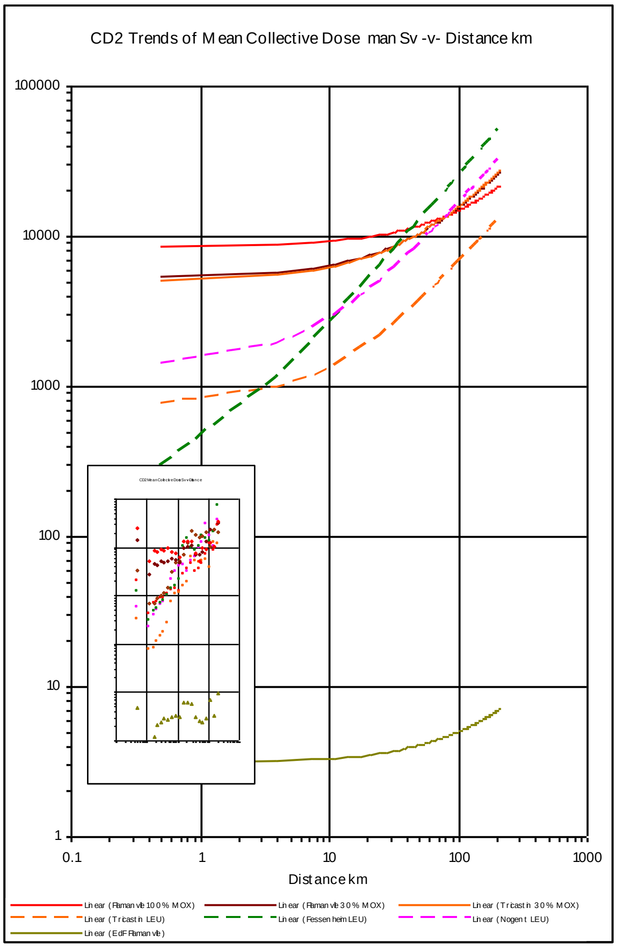
In assessing the radiological impact the form of the individual radionuclides has bearing on the outcome. The radio-iodine fission product (I-131) is particularly sensitive in this respect. Apart from a small component in organic form, for this assessment the iodine is assumed to be released in elemental form as an aerosol. In certain incident situations it could be that the iodine is present as caesium iodide in a particulate which will influence its behaviour in the release processes, via the containment removal processes taking place in the dwell period prior to the release from the containment (here assumed to be 1 hour). There are also implications for the efficacy of iodine dispersion and eventual deposition in the environment beyond the NPP containment because the elemental aerosol form might be assumed to have a faster deposition velocity than the particulate form (10^{-2} compared with 10^{-3}m/s respectively).[80] Applying the extremis of these factors results in a range typically doubling the thyroid cancer incidence, with the analysis adopted here providing results at about the mid-point of this range.

Agricultural and Ingestion of Contaminated Foodstuffs: Insufficient data is available to model the contribution from the ingestion of foodstuffs gathered from the contaminated areas in both the short and longer terms. A reasonable assumption is that strict food controls would be applied during the early and interim stages of the aftermath with, thereafter, what controls could be applied would limit the contribution from this uptake path to 5 to 10%, although there is strong evidence from Chernobyl that controlling the agricultural product uptake path in the longer term is difficult.[47]

ASSESSMENTS OF THE RADIOLOGICAL CONSEQUENCES OF RELEASES FROM PROPOSED EPR/PWR NUCLEAR POWER PLANTS IN FRANCE

COLLECTIVE DOSE ANNEX





COLLECTIVE DOSE

The *Collective Dose* is the sum of the individual doses received in a given period by a specified population to a source of radiation.

Collective dose is generally used for expressing the societal impact of the aggregate radiation exposures in units of man-sievert (man-Sv). In this assessment the individual doses are those projected by COSYMA to have been exposed to the radioactive release downwind of each of the NPPs, which is the source of the radiation. Here the collective dose is the statistically mean or *expectation value* of the whole body or effective dose received over a period of 50 years following the incident.

GRAPH CD1 compares the collective dose data points for the Flamanville EPR fuelled with 30% MOX ♦, fuelled with LEU ■ and fuelled with LEU for the EdF release fractions of TABLE 4E ▲. The sets of data points are linearly rationalised into the single line trends superimposed on the data sets.

For the Flamanville EPR, the potential impact of MOX over LEU shows the greater impact of MOX fuelling out to 20 to 30km downwind from the NPP. This increased impact is also reflected the increased early and long term individual risk of GRAPHS FR4 and FR3 respectively.

Similarly, Graph CD2 is a composition of all of the NPPs and fuelling options included in this assessment. The plotted data shown on the inset graph below, have been linearly rationalised with the solid lines representing the MOX fuelled NPPs and the dashed lines.

This comparison shows the societal impact of the Fessenheim NPP operating in the more densely populated areas of mid-eastern France nearby the borders with Switzerland and Germany, the populations of which are included in the COSYMA projection.

The very high collective dose impact to the populations within the immediate vicinity of the NPPs (typically out to 1 to 2km) are indicated on the inset version of GRAPH 2CD.

ASSESSMENTS OF THE RADIOLOGICAL CONSEQUENCES OF RELEASES FROM PROPOSED EPR/PWR NUCLEAR POWER PLANTS IN FRANCE

FLAMANVILLE ANNEX

FLAMANVILLE

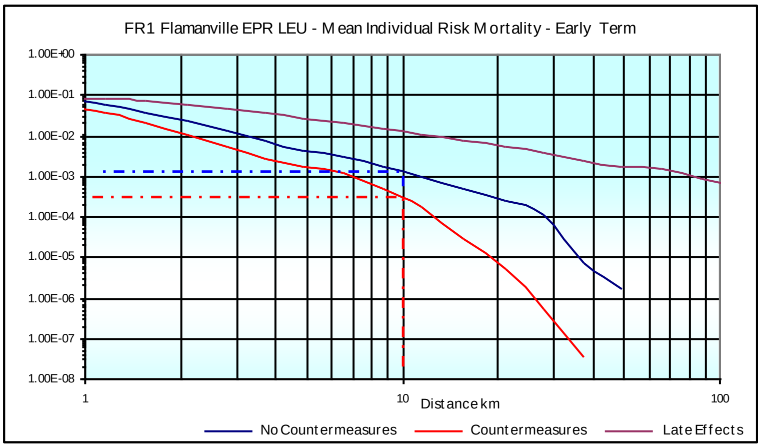
CASE	NPP SITE	REACTOR	FUEL	COMMENTS
FLLEU1	Flamanville	1,600MWe EPR	100% LEU	**EPR** 100% LEU core Existing Fuel Burn-Up Target
FLLEU1D	Flamanville	1,600MWe EPR	100% LEU	**EPR** 100% LEU core Existing Fuel Burn-Up Target as for FLLEU1 but no short term countermeasures modelled to show the dose mitigation lost when early countermeasures are removed
FLLEU2	Flamanville	1,600MWe EPR	100% LEU	Target 65GWd/tU burn-up, compares directly with Case FLLEU1 but with target fuel burn-up being achieved, although no account is given to possible increased release fractions from higher burn-up fuel.
FLLEU1A	Flamanville	1,330MWe PWR	100% LEU	EXISTING 1330MWe PWR 100% LEU core considers failure of one of the existing PWR units at Flamanville
FLEdFLEU	Flamanville	1,600MWe EPR	100% LEU	This is the *worst-case* incident identified by EdF in the public consultation documentation, presumably at the 65GWed/tU target fuel burn-up, compares directly with Case FLLEU2
FLMOX1	Flamanville	1,600MWe EPR	30% MOX	30% MOX fuel core, illustrates the MOX induced increased early consequences with Case FLEPRU1 with current MOX burn-up target being achieved but no account given to possible increased release fractions of MOX fuel
FLMOX2	Flamanville	1,600MWe EPR	100% MOX	100% MOX fuel core, illustrates the MOX induced increased early consequences with Case FLEPRU1 with current MOX burn-up target being achieved but no account given to possible increased release fractions of MOX fuel

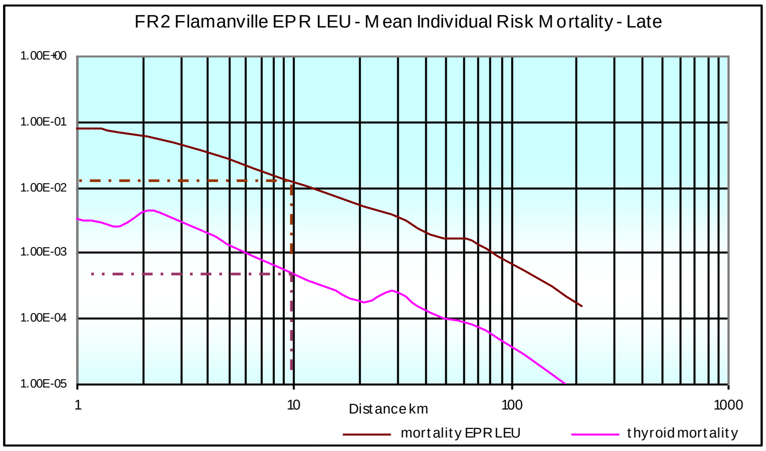
COSYMA RESULTS FOR FLAMANVILLE

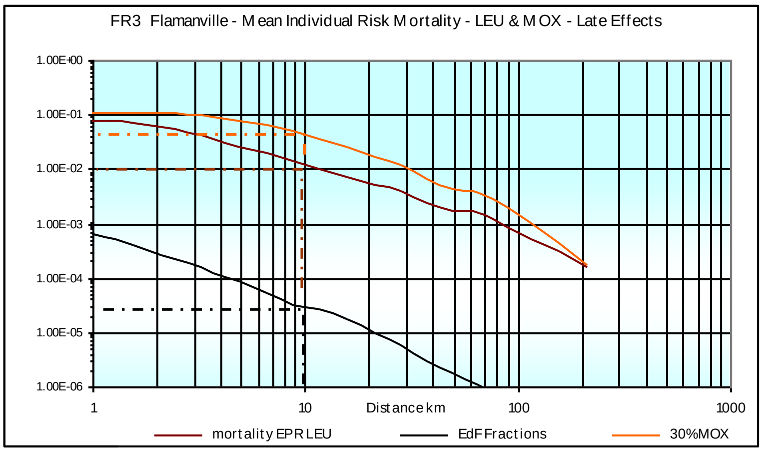
MEAN INDIVIDUAL RISKS

GRAPHS FR1 to FR4 relate the statistical mean (*Expectation Value*) of any individual located at any distance out to 210km downwind of the NPP site and who has been subject to the prescribed countermeasure implemented at that particular locality – note both horizontal and vertical scales change from graph to graph and that GRAPHS FD1 to FD3 use a linear distance (x-axis) scale whereas all other graphs use a logarithmic distance scale.

The individual risk is expressed for both the *short* (weeks) and *longer* (50 years) terms.







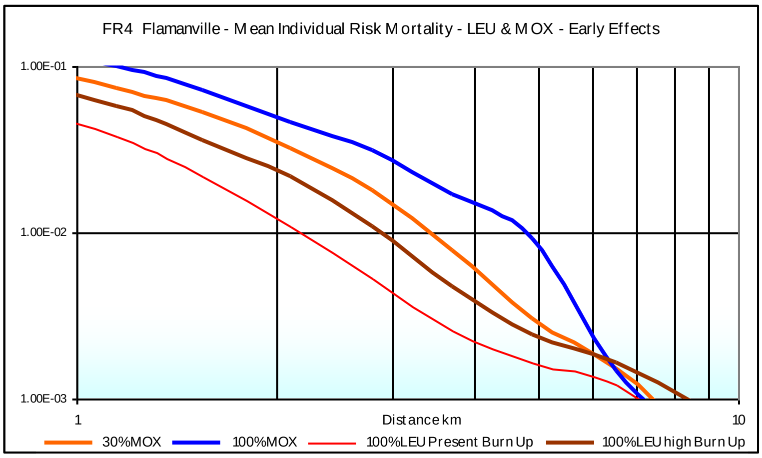
Countermeasure Mitigation: Not withstanding the somewhat mechanistic approach adopted by COSYMA in following through countermeasures, GRAPH FR1 illustrates the influence of not undertaking early countermeasures such as sheltering and evacuation in the short term except, that is, evacuation within the immediate vicinity of the NPP.

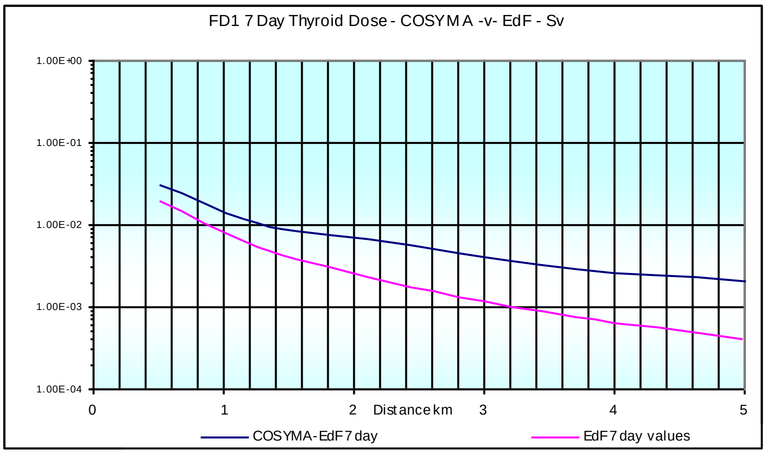
For example, an individual located at 10km of the proposed Flamanville EPR fuelled with LEU, who had complied with effective countermeasures would run a lesser risk, at about 3.10^{-4} (1 in 3,333) compared to a situation where countermeasures had not been implemented at about $1.5.10^{-3}$ (1:666) of short term mortality.

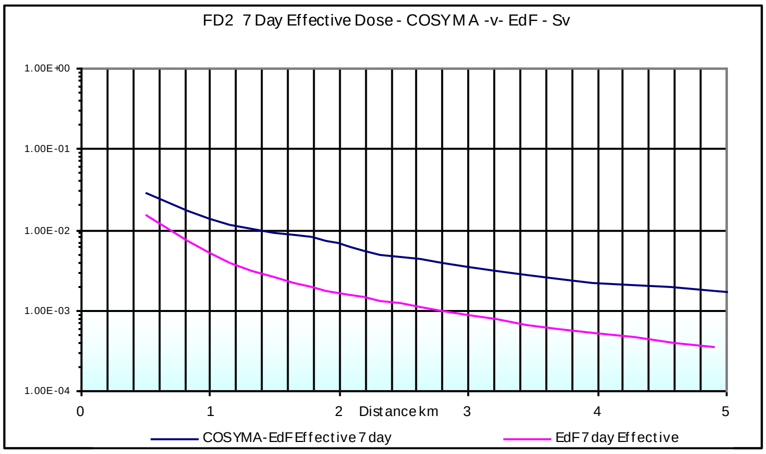
Late Effects: GRAPH FR2 shows the long term individual risk of mortality from all organ exposures (effective or whole body) for the LEU fuelled EPR with countermeasures, together with the individual risk for fatal thyroid cancer with the respective risks being about 1:2,250 and 1:100 at 10km.

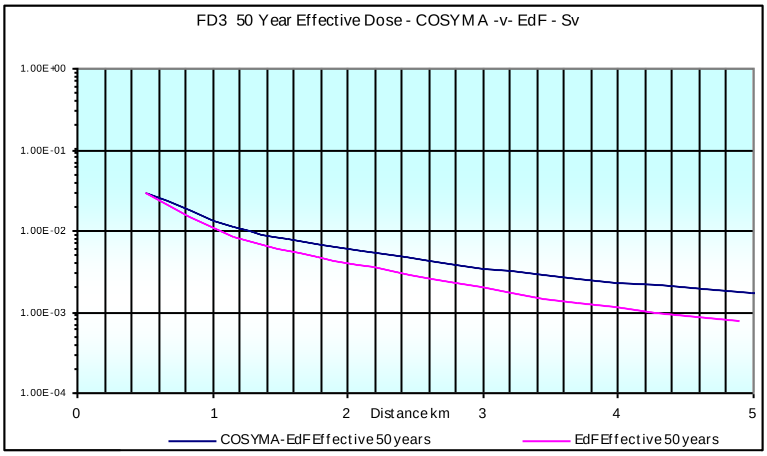
The thyroid risk extends to about 50km at which point the risk is 1:10,000 which may or may not be deemed an acceptable level of risk for members of the public – if not, then prophylactic measures would have to be extended out to and beyond this point. This assessment of risk is based upon the average age of the population segment and excludes special consideration of thyroid critical groups, particularly neonates, nursing mothers and adolescents.

EdF Release Fractions: GRAPH FR3 shows the individual risk of late effects for the EPR fuelled with LEU for i) the maximum credible accident nominated by EdF (the EdF release fractions of TABLE 4E) compared to core degrade situation adopted for this assessment applied to the EPR with the Sequoyah (TABLE 4D) release fractions.









MOX: Graph FR3 also shows the late effects individual risk of the EPR fuelled with 30% MOX, also at TABLE 4D release fractions.

At 10km the individual risk of late mortality are about 1:30,000, 1:100 and 1:20 for the EdF and Sequoyah release fractions respectively..

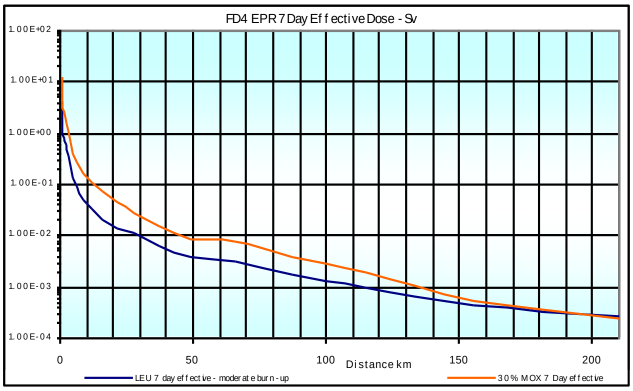
LEU -v- MOX: GRAPH FR4 compares the early effects individual risk for the different fuelling options for the EPR, that is with a 100% LEU fuel core irradiated to present burn-up levels, a LEU core at the target 65GWd/tU burn-up, and for 100% and 30% MOX fuelling. The increased radiological impact of the higher concentrations of actinides, including isotopes of plutonium, americium and curium, of the MOX fuel cores is marked in the near field area.

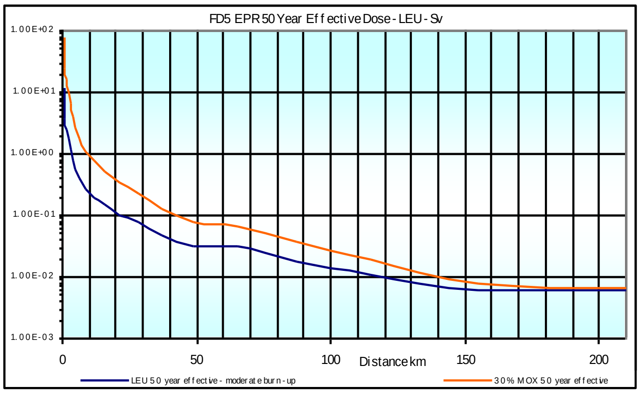
MEAN INDIVIDUAL RADIATION DOSE

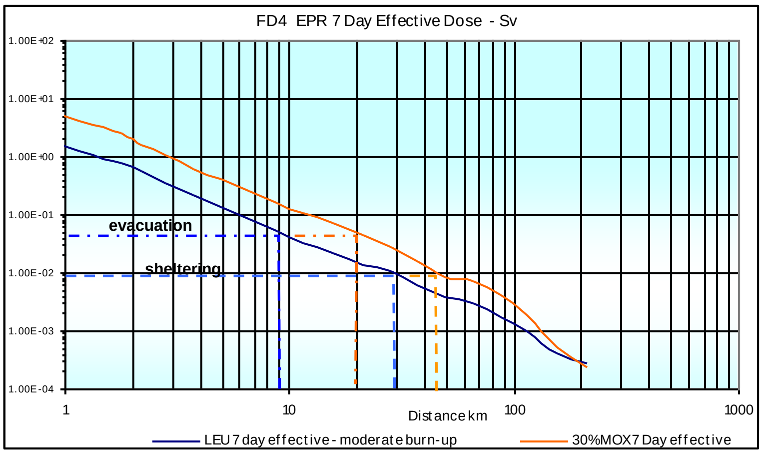
GRAPH FD1 compares early individual thyroid dose as projected by COSYMA for the EdF release fractions and, similarly, the same comparison is made by GRAPHS FD2 and FD3 for the early (7 day) and late (50 year) integration periods. The reasonably good match between the COSYMA analysis and the EdF projection (from Figures D-V.1c, d, e & f[81] of the EdF Safety Case consultation document) generally serve to endorse the COSYMA modelling with the differences between the results most probably arising from small differences in, for example, the source term, the accident scenario details, assumptions on the abatement of radio-iodine, etc.

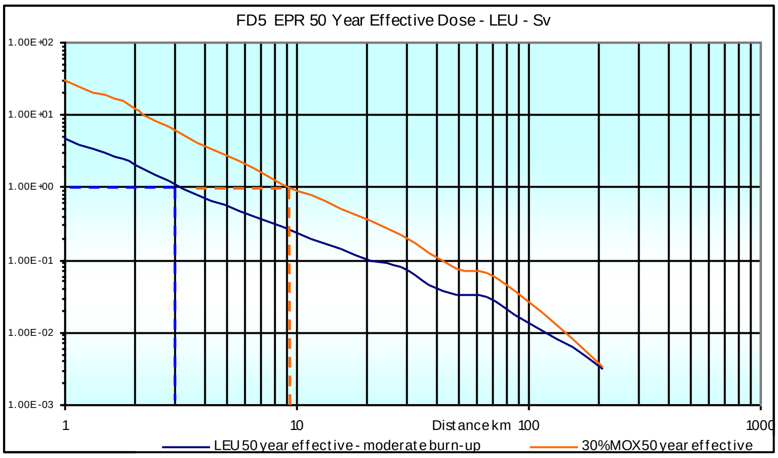
EdF claims to arrive at what might be considered to be very low release fractions by the use of abatement technologies within the containment building and, particularly, by assuming that in all credible accidents (and terrorist acts) that the building containments will not be breached or bypassed. The only means of escape are leakage at a rate of 0.3% per day with high efficiency filters serving to retain 99.9% of aerosols including particulate iodine. The magnitude and nature of the radionuclide groups released from the primary into the secondary containment range from *Category 2* (PCC2) to *Category 4* (PCC4) incidents and which result in a range of dose exposures to an adult stationed 2km for the NPP site between $6.1.10^{-4}$ to $6.8.10^{-6}$Sv effective 50 year dose.

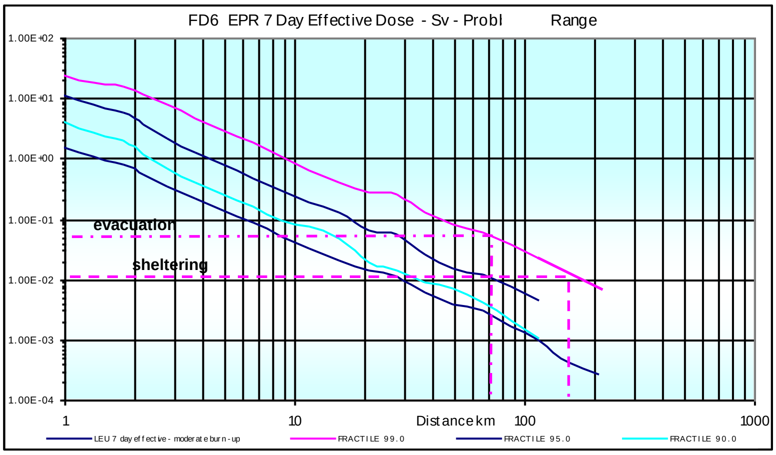
The dose following a serious incident at *RRC-B* level is shown by GRAPHS FD1 to FD3 with the so called EdF *disconnection* release fractions given by the EdF Table V.1.2.4.2.2. All of that











noted, the must be considerable uncertainty that in a severely damaging reactor incident (ie primary circuit completely breached and fuel completely melted) the filtration systems and volumetric leak rates would be maintained.

GRAPHS FD4 and FD5 are reproduced above with a linear distance scale (horizontal axis) and to the left with a logarithmic distance axis.

The effective dose for the first 7 days following the release is given by GRAPH FD4.

The French authorities have a sheltering dose limit of 10mSv accumulated dose and an aversion limit of 50mSv for evacuation countermeasures. If these trigger action levels were imposed then for the 100% LEU and 30% MOX fuelled cores respectively, evacuation would be required out to 9km and 20km and, similarly, sheltering would be required 30km and 45km respectively These evacuation and sheltering distances are for the statistically mean or *expectation value*.

GRAPH FD6 (below) shows the extent by which these evacuation and sheltering distances could extend for a LEU fuel core as a result of arrange of meteorological conditions, in the extreme case with sheltering out to 150km and evacuation 70km or thereabouts. On the basis of probability, this 99th fractile would occur once every 100 incidents.

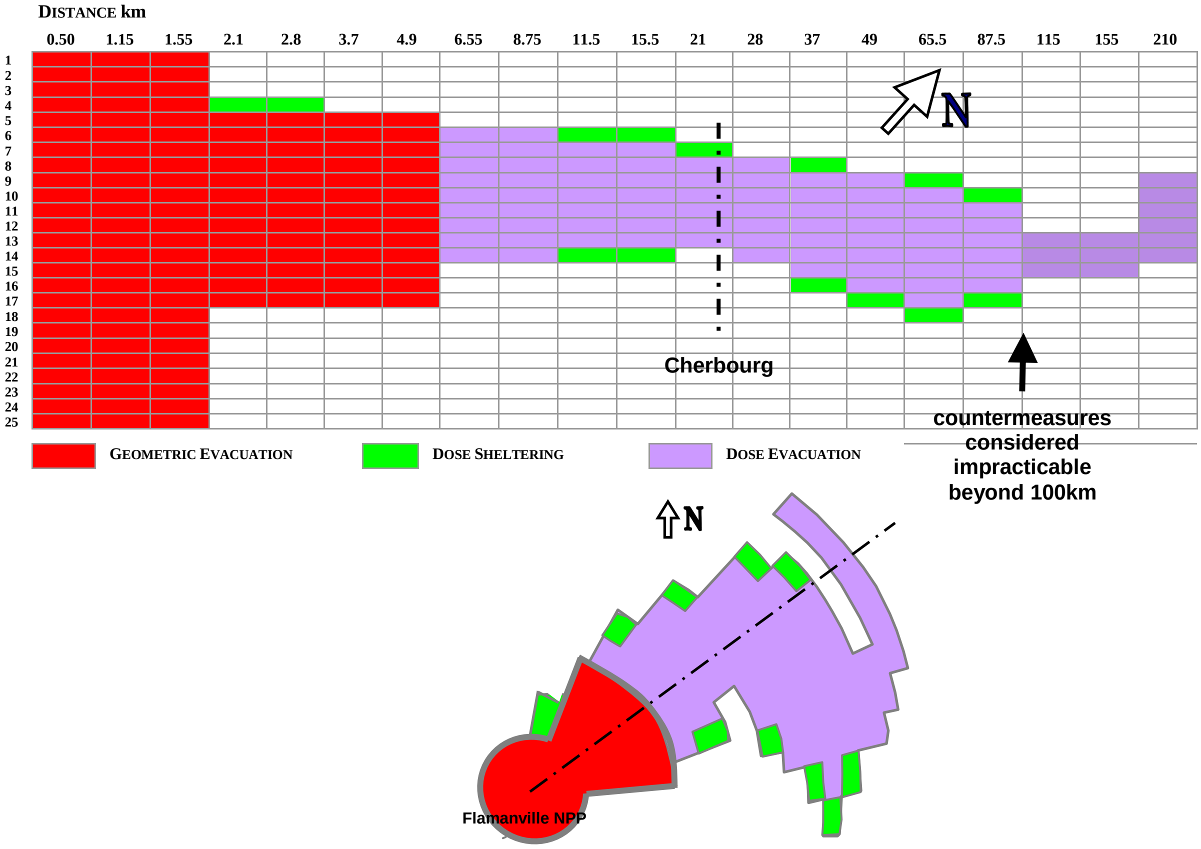
GRAPH FD5 shows the 50 year dose with the French relocation dose limit of 1Sv for the statistically mean LEU and 30% MOX fuel cores. This gives relocation distances of 3km and 9.5km respectively.

As illustrated by the trends of GRAPH FD6, the prevailing meteorological conditions, both wind direction and dispersion efficacy, would also determined the actual requirement for sheltering and evacuation in the aftermath of the radioactive release incident. The 99th fractile (not shown), extends the permanent relocation requirement out to 40km$^+$ and 90km for LEU and 30%MOX cores respectively.

STABLE IODINE, SHELTERING & EVACUATION

Stable iodine prophylaxis, sheltering and evacuation countermeasures are determined by COSYMA in accord with the implementation values for the particular counteraction. These have been specified in accord with the French requirements of Tables 6 and 7 with realistic times introduced for delays in implementing actions, issuing of stable iodine tablets, evacuation drive out times, etc.. Evacuation on a geometric basis is assumed for 1.5km radius entirely around the NPP, extending out in a keyhole pattern to 5km downwind of the plant

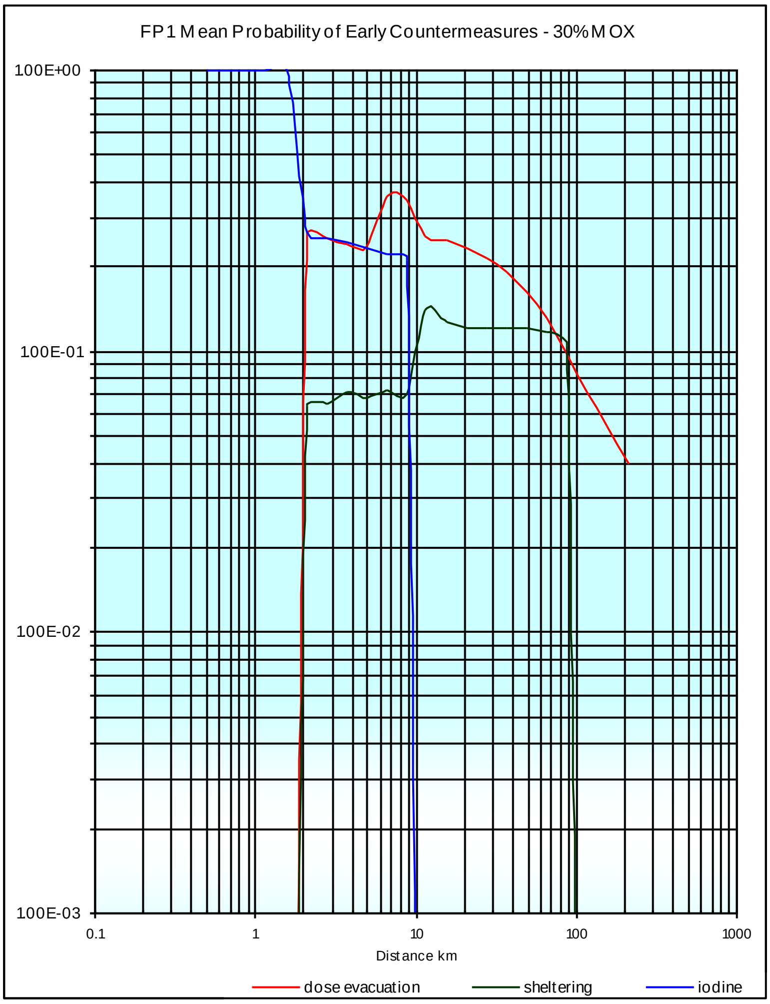
The COSYMA model evaluates the radioactive release dispersion, together with the countermeasures, through a total of 107 individual weather sequences drawn from its database for the specific NPP location, applying these over 72, 5^o radial segments. For example, for *Weather Sequence 12* the prevailing wind direction is towards compass point 50^o (NE) – the resulting sheltering and evacuation countermeasures footprint, shown here in geometrical blocks (note the compressed and non-linear scale of distance:



ILLUSTRATIVE SKETCH OF COUNTERMEASURES FOOTPRINT
SCALE OF RADIAL DISTANCES COMPRESSED – 30% MOX *WEATHER SEQUENCE 12*

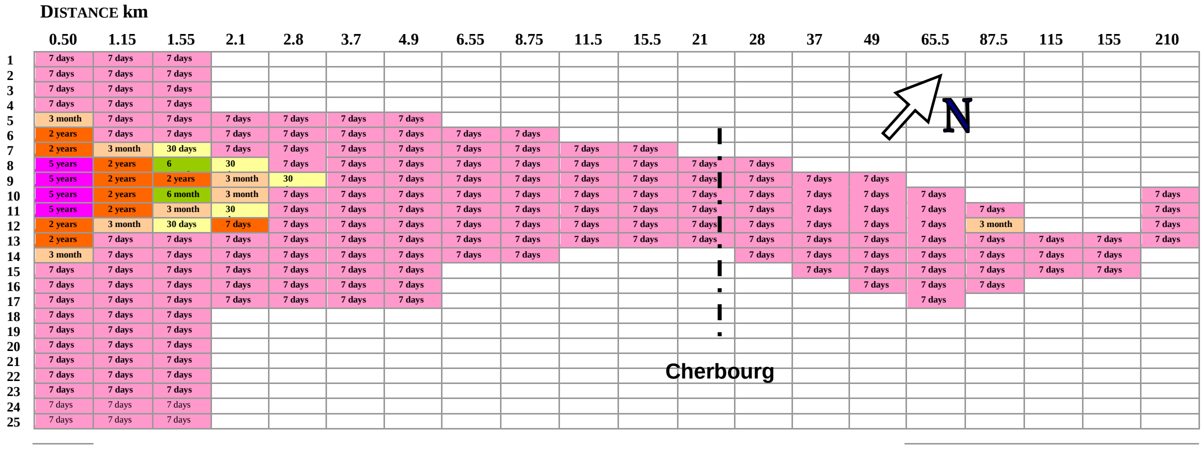
The mean probability of each of these countermeasures being necessary, including stable iodine prophylaxis, is set against distance in Graph FP1 which is for the 30% MOX fuel core.

From Graph FP1 the probability that stable iodine prophylaxis will have to be implemented at, say, 3km from the Flamanville NPP is about 1:4 and at 9km about 1:5. The probability that evacuation of the area beyond the automatic evacuation zone (keyhole) at, say, 15km is 1:4, at 30km about 1:5, and at 100km about 1:15. The sheltering requirement, which applies to both radial areas around as well as areas extended beyond the evacuation zone, ranges from 1:10 at 10km, 1:8 at 50km, and so on. Examples of the number of individuals and land areas subject to these countermeasures are given in Table B of Appendix I.



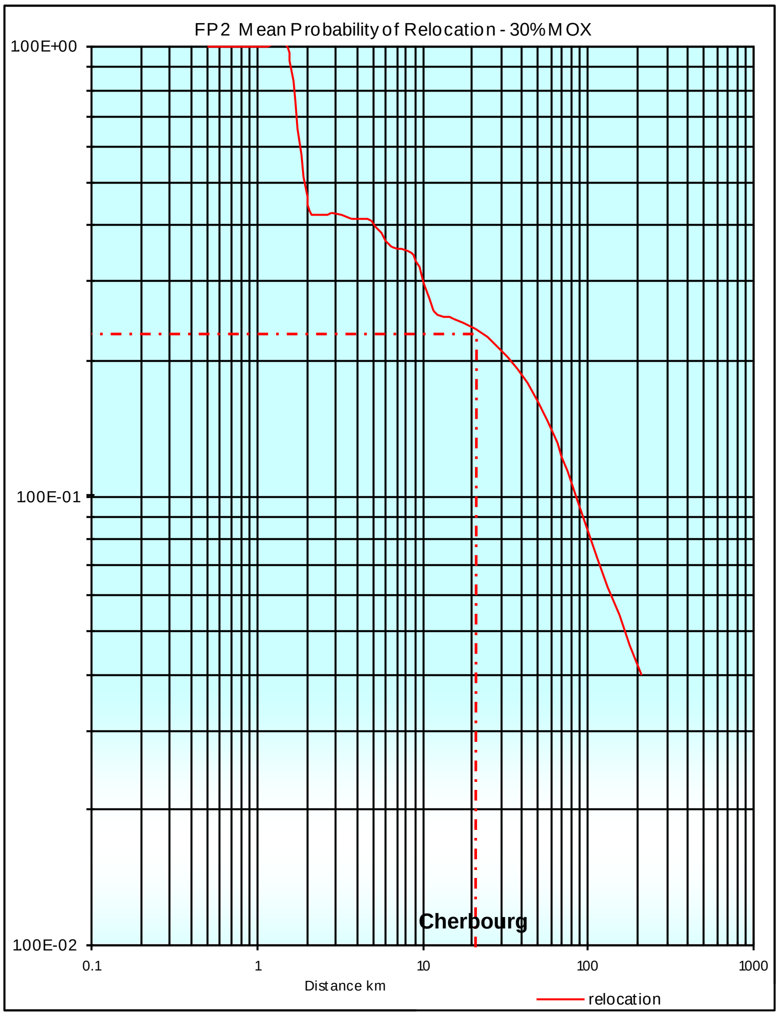
DECONTAMINATION & RELOCATION

Relocation is also presented in area blocks in terms of the period over which residential (permanent occupancy) is barred. For the 30% MOX *Weather Sequence 12* and based on the French relocation limit of 1Sv, the relocation distribution, set out in area blocks of the length of time that relocation out of the area would be required, is:



DISTANCE km

	0.50	1.15	1.55	2.1	2.8	3.7	4.9	6.55	8.75	11.5	15.5	21	28	37	49	65.5	87.5	115	155	210
1	7 days	7 days	7 days																	
2	7 days	7 days	7 days																	
3	7 days	7 days	7 days																	
4	7 days	7 days	7 days																	
5	3 month	7 days	7 days	7 days	7 days	7 days	7 days													
6	2 years	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days											
7	2 years	3 month	30 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days									
8	5 years	2 years	6	30	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days							
9	5 years	2 years	2 years	3 month	30	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days					
10	5 years	2 years	6 month	3 month	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days				7 days
11	5 years	2 years	3 month	30	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days			7 days
12	2 years	3 month	30 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	3 month			7 days
13	2 years	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days
14	3 month	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days				7 days	7 days	7 days	7 days	7 days	7 days	7 days	
15	7 days	7 days	7 days	7 days	7 days	7 days	7 days							7 days	7 days	7 days	7 days	7 days	7 days	
16	7 days	7 days	7 days	7 days	7 days	7 days	7 days								7 days	7 days	7 days			
17	7 days	7 days	7 days	7 days	7 days	7 days	7 days									7 days				
18	7 days	7 days	7 days																	
19	7 days	7 days	7 days																	
20	7 days	7 days	7 days																	
21	7 days	7 days	7 days																	
22	7 days	7 days	7 days																	
23	7 days	7 days	7 days																	
24	7 days	7 days	7 days																	
25	7 days	7 days	7 days																	



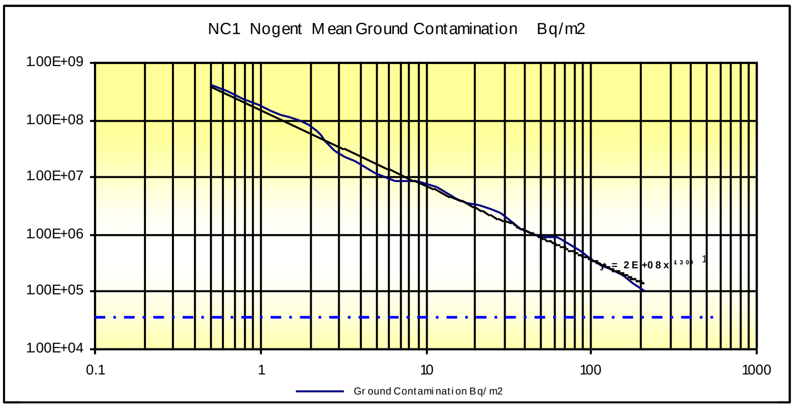
GRAPH FP2 shows the mean probability that individuals will have to be relocated from areas downwind of the NPP. At a distance of, say, 5km the chance of relocation becoming necessary is about 1:2, at 10km about 1:3, at 30km about 1:4, and at 100km about 1:14.

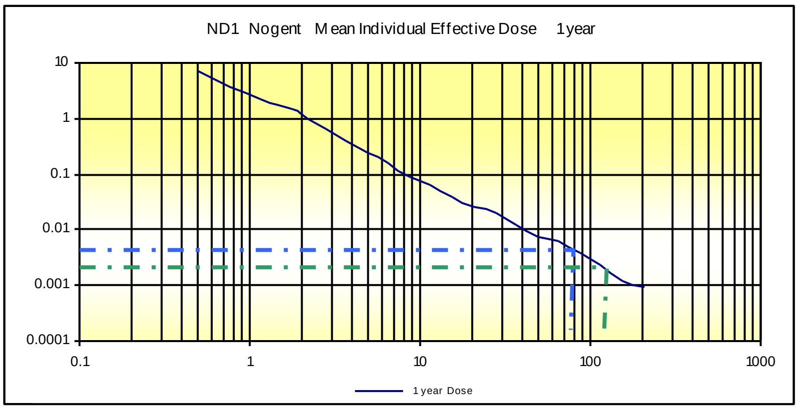
This mean probability applies across the range of weather sequences so for the 30% MOX block area example, *Weather Sequences 12,* there would arise a 1 in 4 chance that relocation would have to be implemented. Examples of the number of individuals and land areas subject to relocation are given in TABLE B of APPENDIX I.

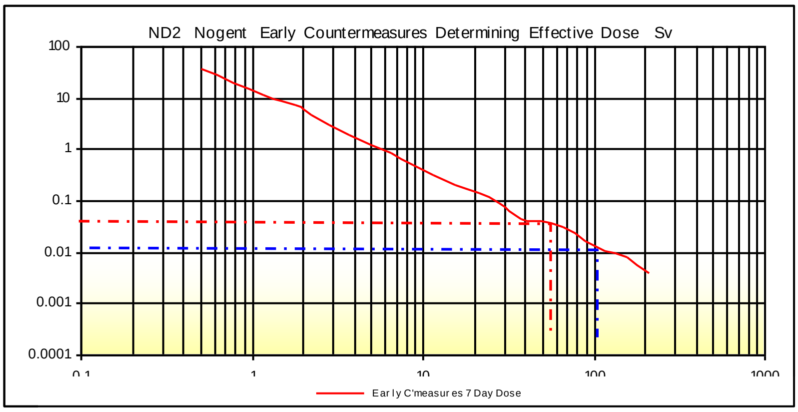
ASSESSMENTS OF THE RADIOLOGICAL CONSEQUENCES OF RELEASES FROM PROPOSED EPR/PWR NUCLEAR POWER PLANTS IN FRANCE

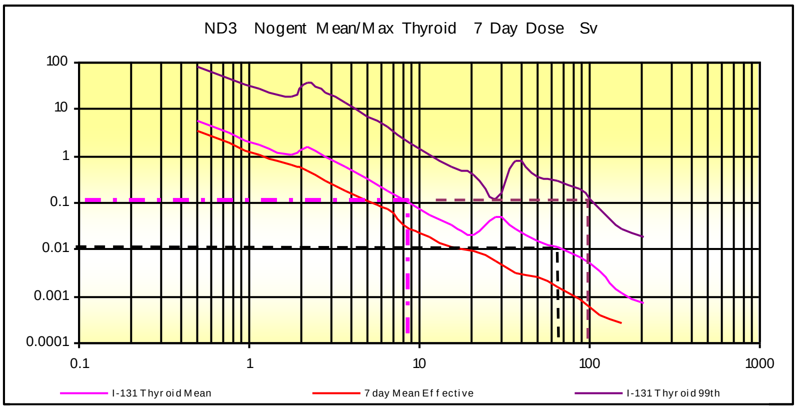
NOGENT SUR SEINE ANNEX

TABLE B REF	REACTOR, FUEL & CONDITIONS	COMMENTS
NSLEU1	**EXISTING** 1,310MWe PWR 100% LEU core	Shows large scale evacuation required because of increased population density of region









GROUND CONTAMINATION

GRAPH NC1 Mean ground contamination for Cs-137 in the shadow of the plume downwind of Nogent NPP – the *Weather Sequences* (1 to 107) provide the formation of the contamination footprint.

The dashed line shows the present UK level of surface contamination required for notification[82] and decontamination at 4E+04Bq/m^2 although if this is considered impracticable then a 3mSv per annum individual dose limit is adopted in lieu of full decontamination.

1 YEAR INDIVIDUAL EFFECTIVE DOSE

Graph ND1 shows the mean effective dose received by an individual remaining at any position for the whole of the first year downwind (centre plume) of Nogent sur Seine NPP.

The UK dose exposure limit of 5mSv annual exposure for the area to be deemed and Emergency Planning Zone in which countermeasures should be in place is shown by the blue dashed line extending out to about 80km, thereby and depending on the wind direction prevailing on the immediate aftermath of the incident, requiring the South-East suburbs of Paris and the South suburbs of Rheims to provide for pre-prepared emergency countermeasures (as defined by UK statute). The green dashed line at 3mSv per annum exposure, is the UK limit at which a contaminated zone is declared.

EARLY COUNTERMEASURES TRIGGER

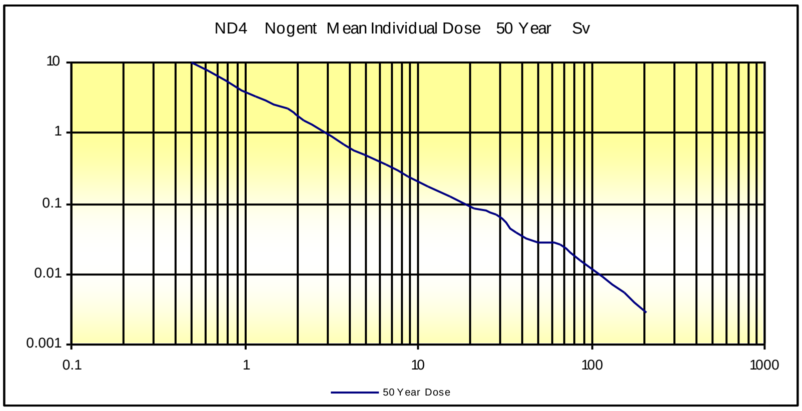
GRAPH ND2 illustrates the basis of implementing sheltering and evacuation countermeasures to avert the mean 7 day exposure showing sheltering out to about 100km and evacuation out to 60km.

I-131 PROPHYLAXIS COUNTERMEASURE

GRAPH ND3 shows the ideal stable iodate (thyroid prophylaxis) distribution based on the implementation dose projection of 100mSv for Mean and Maximum projected 7 day thyroid dose with the prophylaxis measure required out to 8km and 100km respectively – to issue stable iodide over an area extending 100km for the NPP would be impracticable. If the WHO 10mSv guideline for critical groups is applied then prophylaxis would be required out to about 80km for the mean projected dose.

LONG TERM INDIVIDUAL DOSE

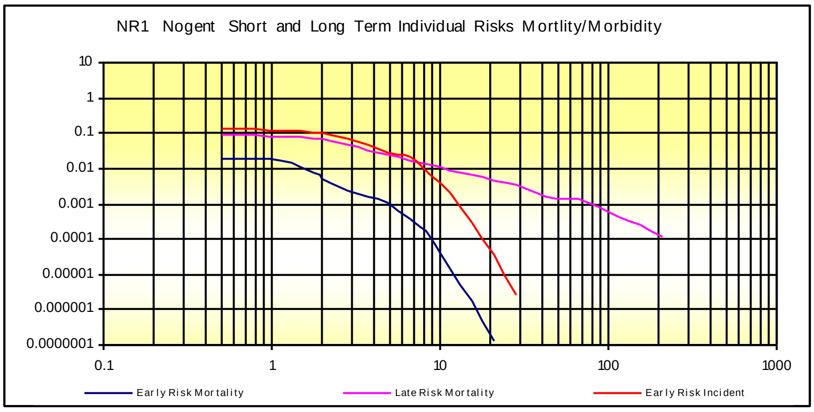
GRAPH ND4 shows the mean long term effective dose at 50 years.



INDIVIDUAL RISKS

GRAPH NR1 shows the risk to an individual of early and late effects of mortality and morbidity, even in account of the countermeasures invoked..

For example, an individual located 10km downwind of the NPP of about 1 in 10,000 of fatality in the short term. Similarly and again for 10km, the early risk of morbidity is about 1 in 125 and, in the much longer term over 50 years, about the same risk of 1 in 100 of a fatal illness contracted solely from exposure.

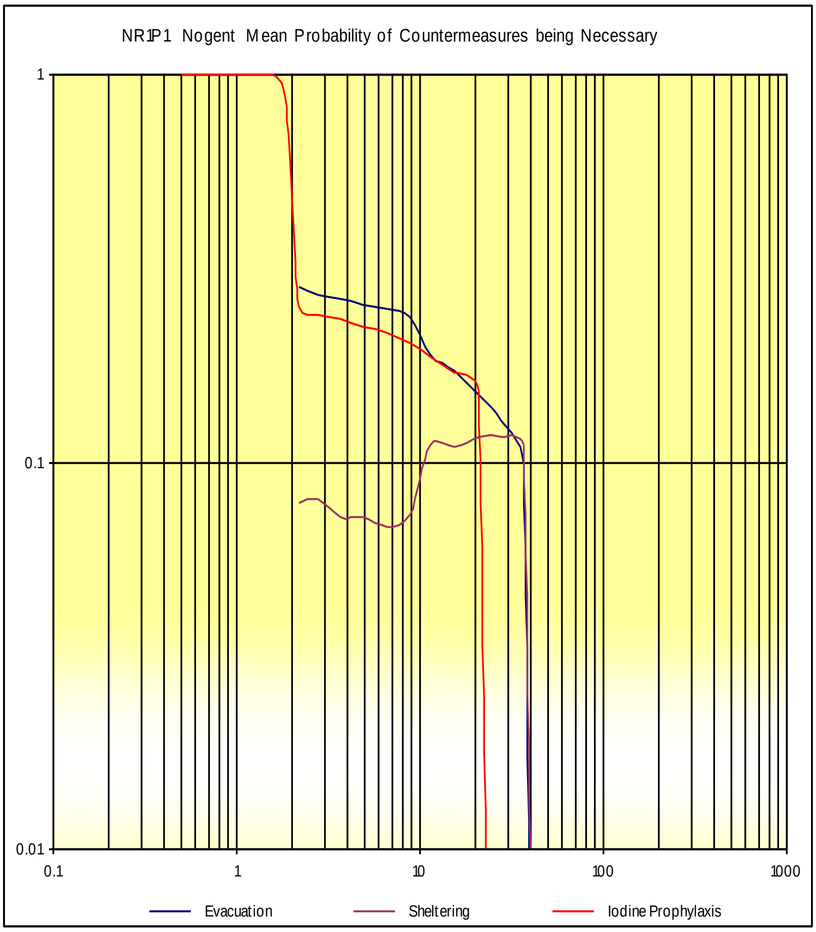


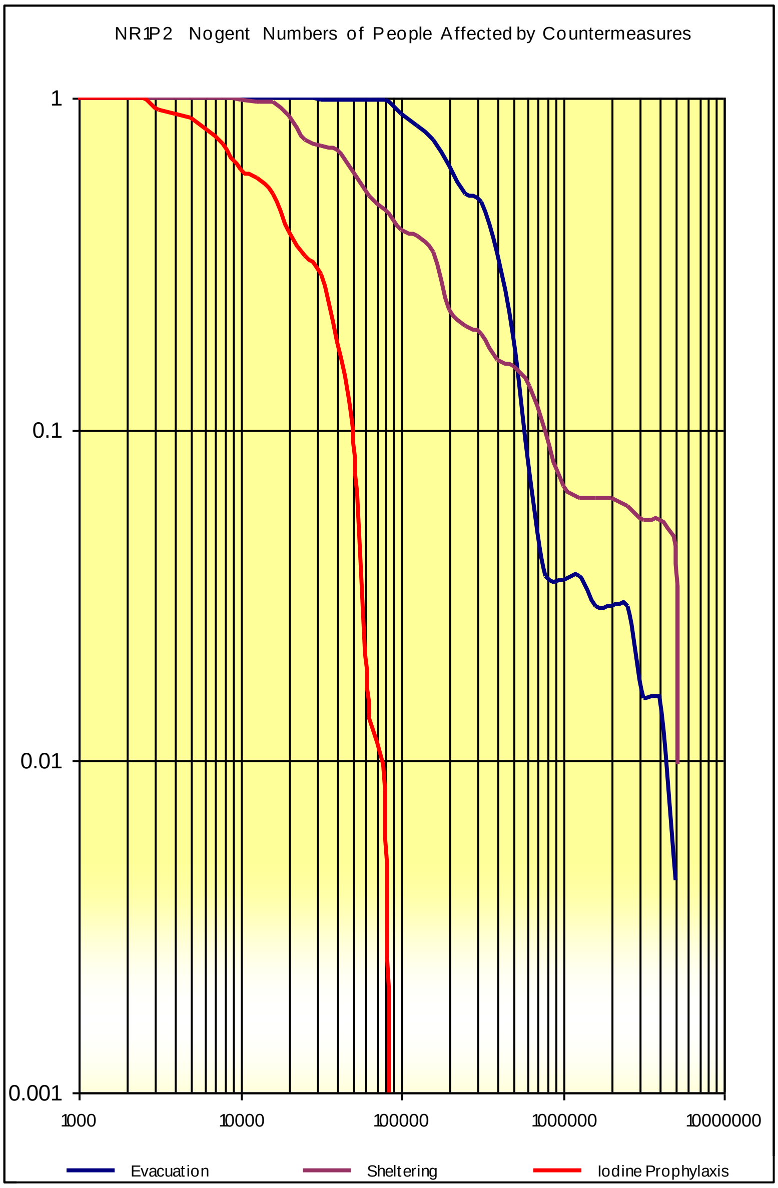
PROBABILITY OF COUNTERMEASURES

GRAPH NRP1 shows the mean probability of countermeasures being necessary (by virtue of the early radiological regime) at locations downwind of the NPP.

Out to about 2km there is a 1 in 3 chance that evacuation will be necessary, with this probability reducing to about 1 in 5 at 20km, thereafter the likely necessity for evacuation is remote (in the Mean or *Expectation Value* case).

Similarly, the probability that stable iodate prophylaxis will have to be implemented (for the French 100mSv aversion limit) will be about 1 in 10 out to about 40km downwind on the NPP.





NUMBERS REQUIRING COUNTERMEASURES

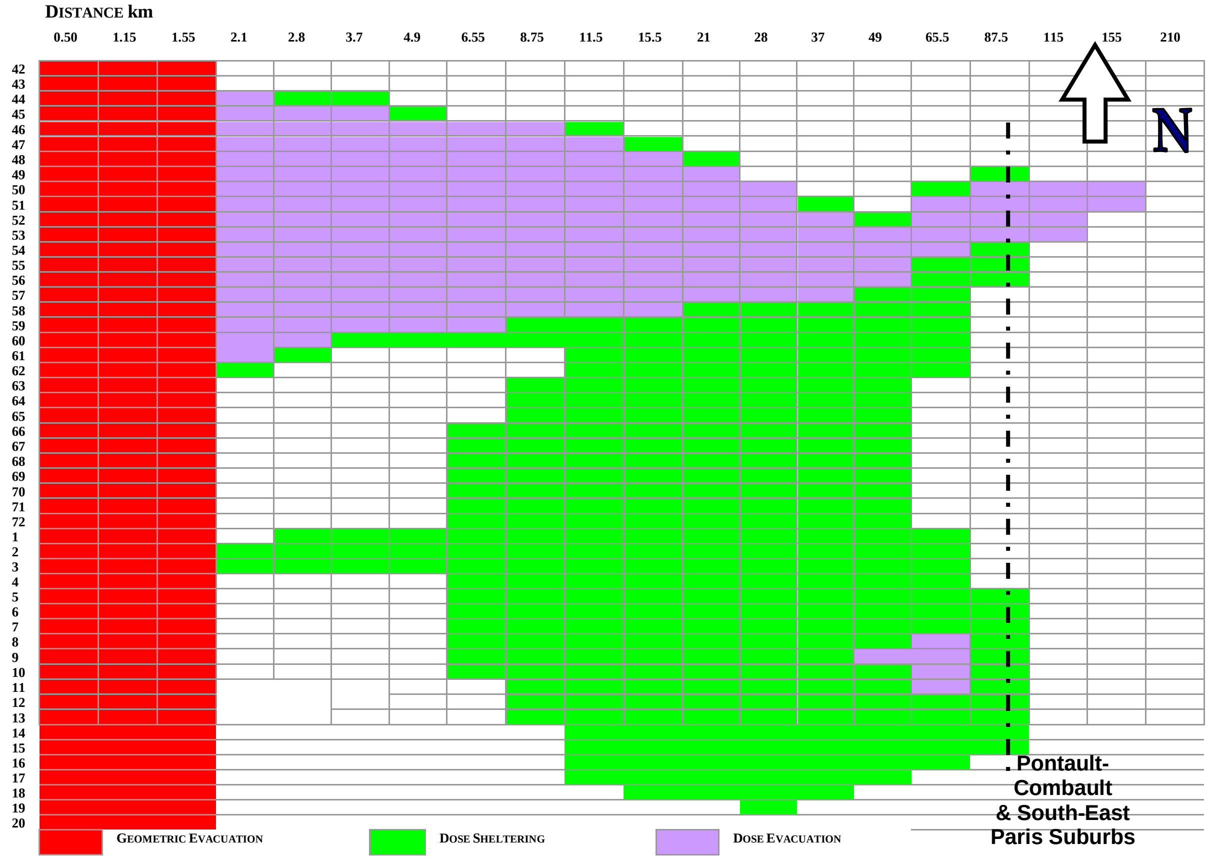
GRAPH NR1P2 shows the probabilities for the number of people requiring the implementation of countermeasures (people numbers on the horizontal axis).

Up to about 3,000 individuals are certain to require prophylaxis (according the French 100mSv aversion limit), and there is a rapidly decreasing probability that the tens of thousands will be affected.

Similarly for evacuation and sheltering there is a certainty that up to 100,000 individuals will need to be evacuated and about 2,000 should shelter.

The rapid rates of change of these probabilities demonstrate the difficulty of placing finite reserves on the emergency planning resources required.

SHELTERING AND EVACUATION – WEATHER SEQUENCE 29 - WIND FROM SOUTH WEST (250^{O})



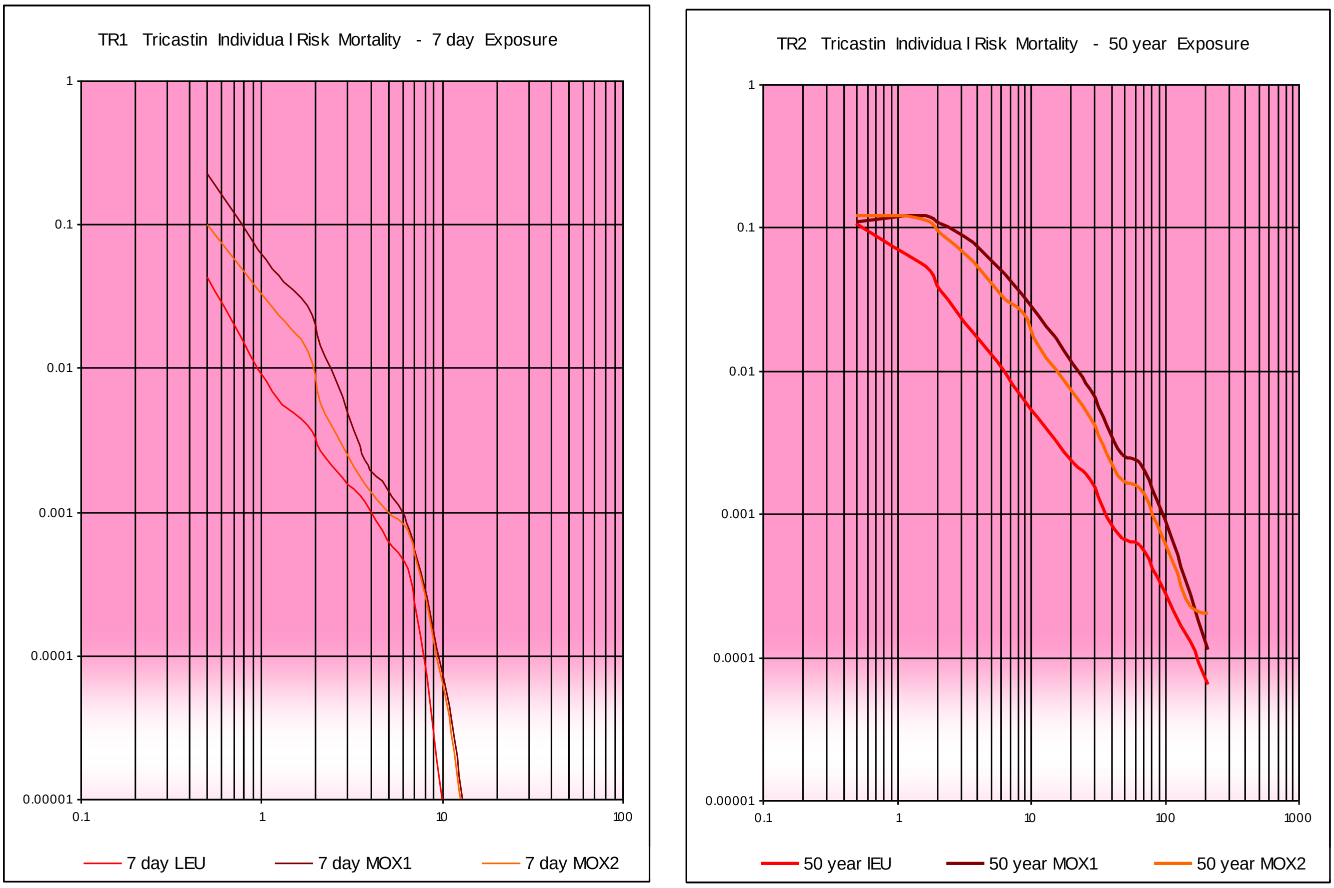
RELOCATION – WEATHER SEQUENCE 29 - WIND FROM SOUTH WEST (250^{O})

DISTANCE km

	0.50	1.15	1.55	2.1	2.8	3.7	4.9	6.55	8.75	11.5	15.5	21	28	37	49	65.5	87.5	115	155	210
42	7 days	7 days	7 days																	
43	7 days	7 days	7 days																	
44	3 month	7 days	7 days	7 days																
45	2 years	7 days	7 days	7 days	7 days	7 days														
46	5 years	2 years	30 days	7 days	7 days	7 days	7 days	7 days	7 days											
47	10 years	2 years	2 years	6 month	30 days	7 days	7 days	7 days	7 days	7 days										
48	10 years	5 years	2 years	2 years	2 years	3 month	30 days	7 days	7 days	7 days	7 days									
49	10 years	5 years	2 years	2 years	2 years	2 years	3 month	30 days	7 days	7 days	7 days	7 days								
50	10 years	5 years	2 years	2 years	2 years	6 month	30 days	7 days	7 days	7 days	7 days	7 days	7 days				7 days	7 days	7 days	
51	10 years	2 years	2 years	2 years	3 month	30 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days			7 days	7 days	7 days	7 days	
52	5 years	2 years	2 years	3 month	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days		7 days	7 days	7 days		
53	5 years	2 years	6 month	30 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days		
54	5 years	2 years	2 years	3 month	30 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days				
55	2 years	2 years	2 years	30 days	30 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days					
56	2 years	2 years	6 month	3 month	30 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days					
57	2 years	6 month	3 month	30 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days							
58	2 years	30 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days										
59	2 years	7 days	7 days	7 days	7 days	7 days	7 days	7 days												
60	30 days	7 days	7 days	7 days	7 days															
61	7 days	7 days	7 days	7 days																
62	7 days	7 days	7 days																	
63	7 days	7 days	7 days																	
64	7 days	7 days	7 days																	
65	7 days	7 days	7 days																	
66	7 days	7 days	7 days																	

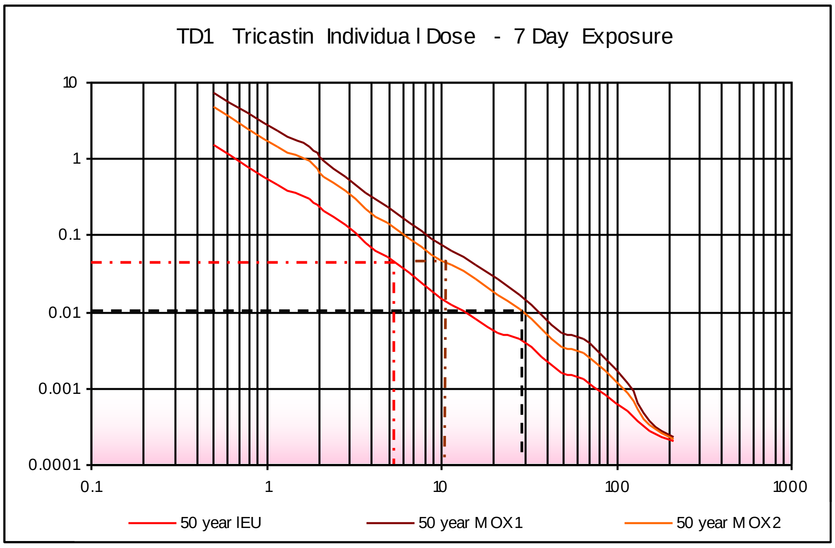
TRICASTIN ANNEX

TABLE B REF	REACTOR, FUEL & CONDITIONS	COMMENTS
TRLEU1	**EXISTING** 915MWe PWR 100% LEU core	
TRMOX1	**EXISTING** 915MWe PWR 30% MOX core	Compares current levels of MOX fuel core with 100% LEU core of Case TRLEU1 above but with x2 Group 7 Release Fractions
TRMOX2	**EXISTING** 915MWe PWR 30% MOX core	Compares current levels of MOX fuel core with 100% LEU core of Case TRLEU1 above at Sequoya Release Fractions .



MEAN INDIVIDUAL RISK – 7 DAY EXPOSURE & 50 YEAR PROJECTED INDIVIDUAL RISK

Individual risk following exposure for 7 days, comparing LEU and 30% MOX fuel cores with different Group 7 release Fractions (MOX2 adopts Sequoyah data) for both short and longer terms.



INDIVIDUAL 7 DAY DOSE

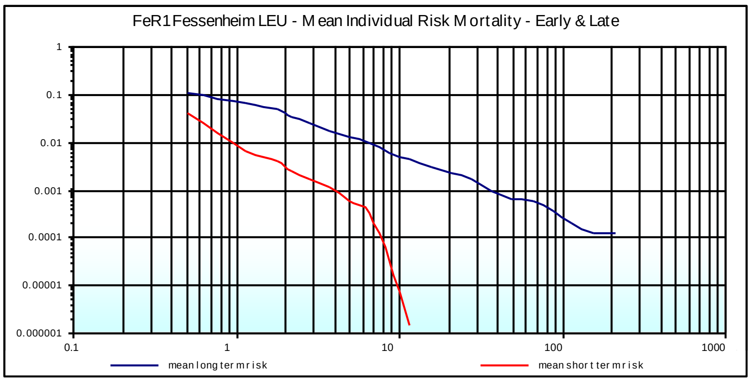
For the mean individual dose evacuation is required out to 5-6km for an LEU core or, further, out to 10km for a 30% MOX fuel core.

For the 30% MOX fuelled core, sheltering is required out to 30km, just about doubling the sheltering requirement for a LEU fuelled core.

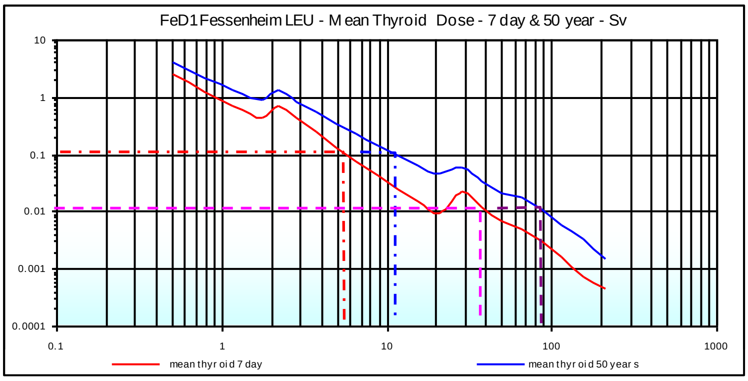
RADIOLOGICAL CONSEQUENCES OF RELEASES FROM PROPOSED EPR/PWR NUCLEAR POWER PLANTS IN FRANCE

FESSENHEIM ANNEX

TABLE B REF	REACTOR, FUEL & CONDITIONS	COMMENTS
FLEU1	**EXISTING** 880MWe PWR 100% LEU core	



INDIVIDUAL RISK MORTALITY

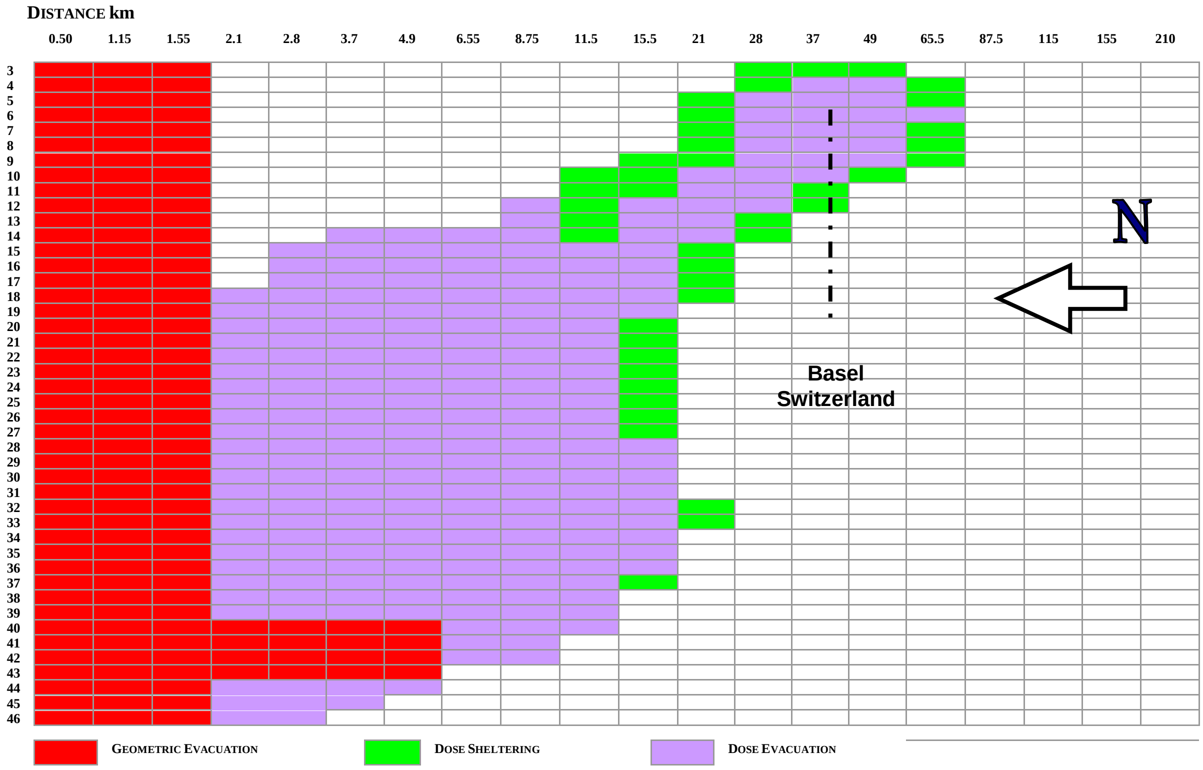


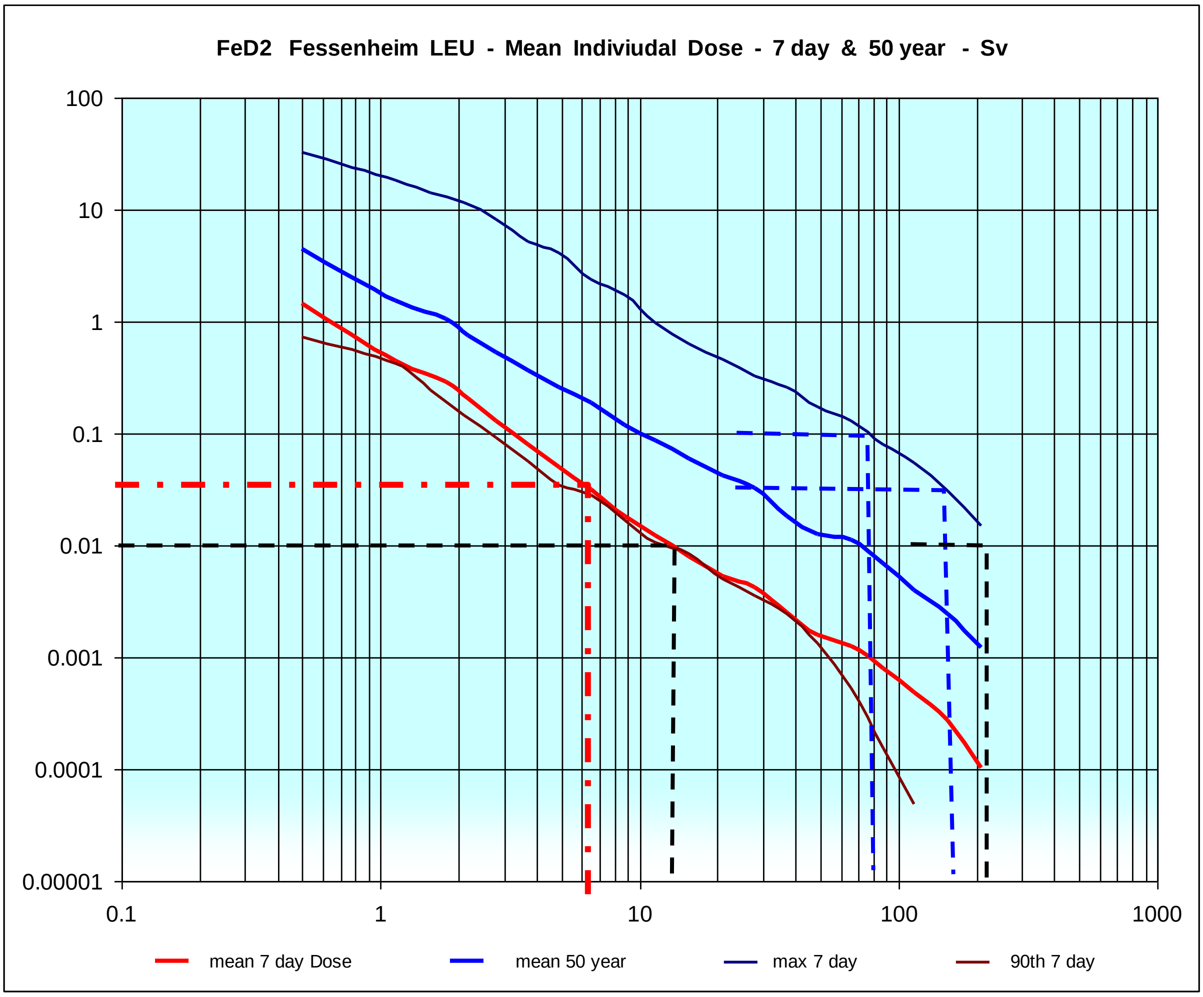
THYROID DOSE

Stable iodine prophylaxis is necessary out to 7km to avert the 7 day dose limit, out to 11km to avert the 50 year dose limit.

For World Health Organisation (WHO) recommended dose limit for the critical groups comprised neonates, children, adolescents, etc., stable iodine prophylaxis required out 40km and 90km respectively.

SHELTERING AND EVACUATION – WEATHER SEQUENCE 105 - WIND DUE SOUTH (180^{o})





EFFECTIVE DOSE

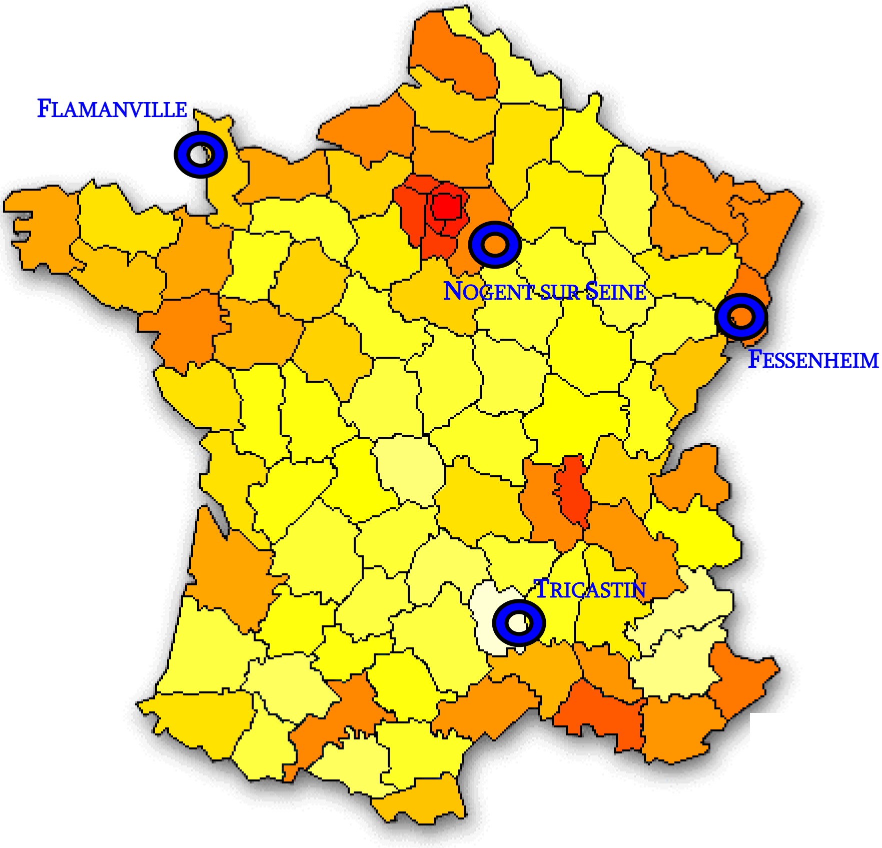
Individual effective dose for 7 day and 50 years with the probability range (90th – Mean – Max) plotted for 7 day dose.

Evacuation requirement extends from about 6km out to 160km depending on the meteorological conditions at the time of the release if, that is the 50mSv evacuation aversion limit is maintained beyond 100km downwind of the NPP. If the optional 100mSv limit is applied at and beyond 100km then the evacuation would cease at 100km.

Similarly, the range of sheltering would extend from about 13km out to 200km, although administering sheltering controls over such a large distance and potentially huge population would be impracticable.

APPENDIX I

DETAILED RESULTS



NPPS ASSESSED IN THIS STUDY LOCATED ON A POPULATION DENSITY MAP OF FRANCE

TABLE A – RADIOACTIVE RELEASE SCENARIOS AND LOCATIONS

CASE	NPP SITE	REACTOR	FUEL	PROB	TIME DELAY	RELEASE DURATION	RELEASE ENERGY	RELEASE HEIGHT	RELEASE FRACTIONS						
				yr^{-1}	hr	hr	MWt	m	Xe-Kr	I/I-Br[83]	Cs-Rb	Te-Sb	Ba-Sr	Ru[84]	La[85]
FLLEU1	Flamanville 49.3211-(-)1.5309	1,600MWe EPR existing burn-up	100% LEU	$2.4\ 10^{-9}$	1	3[86]	1	10	1 0/0.9/0.05/0.05	$2.2\ 10^{-1}$ 0/0.198/0.011/0.011	$3.5\ 10^{-1}$ 0/0.284/0.0345/0.0345	$3.0\ 10^{-1}$ 0/0.044/0.148/0.148	$1.3\ 10^{-1}$ 0/0.117/0.007/0.007	$3\ 10^{-3}$ 0/0.0019/0.0006/0.0006	$1.3\ 10^{-2}$ 0/0.0031/0.005/0.005
FLLEU1D	Flamanville 49.3211-(-)1.5309	1,600MWe EPR existing burn-up	100% LEU	$2.4\ 10^{-9}$	1	3	1	10	1 0/0.9/0.05/0.05	$2.2\ 10^{-1}$ 0/0.198/0.011/0.011	$3.5\ 10^{-1}$ 0/0.284/0.0345/0.0345	$3.0\ 10^{-1}$ 0/0.044/0.148/0.148	$1.3\ 10^{-1}$ 0/0.117/0.007/0.007	$3\ 10^{-3}$ 0/0.0019/0.0006/0.0006	$1.3\ 10^{-2}$ 0/0.0031/0.005/0.005
FLLEU2	Flamanville 49.3211-(-)1.5309	1,600MWe EPR target 65GWed/tU	100% LEU	$2.4\ 10^{-9}$	1	3	1	10	1 0/0.9/0.05/0.05	$2.2\ 10^{-1}$ 0/0.198/0.011/0.011	$3.5\ 10^{-1}$ 0/0.284/0.0345/0.0345	$3.0\ 10^{-1}$ 0/0.044/0.148/0.148	$1.3\ 10^{-1}$ 0/0.117/0.007/0.007	$3\ 10^{-3}$ 0/0.0019/0.0006/0.0006	$1.3\ 10^{-2}$ 0/0.0031/0.005/0.005
FLLEU1a	Flamanville 49.3211-(-)1.5309	1330MWe EPR existing burn-up	100% LEU	$2.4\ 10^{-9}$	1	3	1	10	1 0/0.9/0.05/0.05	$2.2\ 10^{-1}$ 0/0.198/0.011/0.011	$3.5\ 10^{-1}$ 0/0.284/0.0345/0.0345	$3.0\ 10^{-1}$ 0/0.044/0.148/0.148	$1.3\ 10^{-1}$ 0/0.117/0.007/0.007	$3\ 10^{-3}$ 0/0.0019/0.0006/0.0006	$1.3\ 10^{-2}$ 0/0.0031/0.005/0.005
FLMOX1	Flamanville 49.3211-(-)1.5309	1,600MWe EPR	30% MOX	$2.4\ 10^{-9}$	1	3	1	10	1 0/0.9/0.05/0.05	$2.2\ 10^{-1}$ 0/0.198/0.011/0.011	$3.5\ 10^{-1}$ 0/0.284/0.0345/0.0345	$3.0\ 10^{-1}$ 0/0.044/0.148/0.148	$1.3\ 10^{-1}$ 0/0.117/0.007/0.007	$3\ 10^{-3}$ 0/0.0019/0.0006/0.0006	$1.3\ 10^{-2}$ 0/0.0031/0.0051/0.005
FLMOX2	Flamanville 49.3211-(-)1.5309	1,600MWe EPR	100% MOX	$2.4\ 10^{-9}$	1	3	1	10	1 0/0.9/0.05/0.05	$2.2\ 10^{-1}$ 0/0.198/0.011/0.011	$3.5\ 10^{-1}$ 0/0.284/0.0345/0.0345	$3.0\ 10^{-1}$ 0/0.044/0.148/0.148	$1.3\ 10^{-1}$ 0/0.117/0.007/0.007	$3\ 10^{-3}$ 0/0.0019/0.0006/0.0006	$1.3\ 10^{-2}$ 0/0.0031/0.005/0.005
FLEdFLEU	Flamanville 49.3211-(-)1.5309	1,600MWe EPR existing burn-up	100% LEU	$2.4\ 10^{-9}$	1	3	1	10	$1.5\ 10^{-2}$ temporal not applied	$6.1\ 10^{-7}$ temporal not applied	$7\ 10^{-8}$ temporal not applied	$5.1\ 10^{-8}$ temporal not applied	$1.3\ 10^{-8}$ temporal not applied	$2.6\ 10^{-9}$ temporal not applied	$2.6\ 10^{-9}$ temporal not applied
TRLEU1	Tricastin 44.1950-4.4352	915MWe PWR	100% LEU	$2.4\ 10^{-9}$	1	3	1	10	1 0/0.9/0.05/0.05	$2.2\ 10^{-1}$ 0/0.198/0.011/0.011	$3.5\ 10^{-1}$ 0/0.284/0.0345/0.0345	$3.0\ 10^{-1}$ 0/0.044/0.148/0.148	$1.3\ 10^{-1}$ 0/0.117/0.007/0.007	$3\ 10^{-3}$ 0/0.0019/0.0006/0.0006	$1.3\ 10^{-2}$ 0/0.0031/0.005/0.005
TRLEU2	Tricastin 44.1950-4.4352	915MWe PWR	30% MOX higher RF at Group 7	$2.4\ 10^{-9}$	1	3	1	10	1 0/0.9/0.05/0.05	$2.2\ 10^{-1}$ 0/0.198/0.011/0.011	$3.5\ 10^{-1}$ 0/0.284/0.0345/0.0345	$3.0\ 10^{-1}$ 0/0.044/0.148/0.148	$1.3\ 10^{-1}$ 0/0.117/0.007/0.007	$3\ 10^{-3}$ 0/0.0019/0.0006/0.0006	$2.6\ 10^{-2}$ 0/0.0062/0.01/0.01
TRLEU2A	Tricastin 44.1950-4.4352	915MWe PWR	30% MOX	$2.4\ 10^{-9}$	1	3	1	10	1 0/0.9/0.05/0.05	$2.2\ 10^{-1}$ 0/0.198/0.011/0.011	$3.5\ 10^{-1}$ 0/0.284/0.0345/0.0345	$3.0\ 10^{-1}$ 0/0.044/0.148/0.148	$1.3\ 10^{-1}$ 0/0.117/0.007/0.007	$3\ 10^{-3}$ 0/0.0019/0.0006/0.0006	$1.3\ 10^{-2}$ 0/0.0062/0.01/0.01
NsSLEU1	Nogent sur Seine 48.3101-3.3109	1,310MWe PWR	100% LEU	$2.4\ 10^{-9}$	1	3	1	10	1 0/0.9/0.05/0.05	$2.2\ 10^{-1}$ 0/0.198/0.011/0.011	$3.5\ 10^{-1}$ 0/0.284/0.0345/0.0345	$3.0\ 10^{-1}$ 0/0.044/0.148/0.148	$1.3\ 10^{-1}$ 0/0.117/0.007/0.007	$3\ 10^{-3}$ 0/0.0019/0.0006/0.0006	$1.3\ 10^{-2}$ 0/0.0031/0.005/0.005
FLEU1	Fessenheim 47.5413-7.3347	880MWe PWR	100% LEU	$2.4\ 10^{-9}$	1	3	1	10	1 0/0.9/0.05/0.05	$2.2\ 10^{-1}$ 0/0.198/0.011/0.011	$3.5\ 10^{-1}$ 0/0.284/0.0345/0.0345	$3.0\ 10^{-1}$ 0/0.044/0.148/0.148	$1.3\ 10^{-1}$ 0/0.117/0.007/0.007	$3\ 10^{-3}$ 0/0.0019/0.0006/0.0006	$1.3\ 10^{-2}$ 0/0.0031/0.005/0.005

TABLE B HEALTH EFFECTS & COUNTERMEASURE ACTIONS IDEALLY IMPLEMENTED

				NUMBER OF HEALTH EFFECTS					
						VALUE AT THE nth PERCENTILE			
CASE	**NPP SITE**	**NOTES & COMMENTS**	**HEALTH EFFECT/EVACUATION**	**MAXIMUM**	**MEAN**	**50th**	**90th**	**95th**	**99th**
FLEPRLEU1	Flamanville	**EPR** 100% LEU core Existing Fuel Burn-Up Target	**EARLY** Death	222	51	28	128	182	204
			Early Morbidity	1,985	406	186	912	1,414	1,950
			LATE Fatal Cancer	17,920	4,377	3,890	9,333	12,590	14,130
			Thyroid Cancer DEATHS[87]	991	215	182	417	562	724
			Thyroid Cancer Incidence	9,911	2,151	1,820	4,169	5,623	7,244
			LAND Area (ideally) Evacuated km^2[88]	15,030	5,654	5,248	8,913	9,772	11,480
			Area (ideally) Iodine Prophylaxis km^2	1,478	317	251	661	891	1,096
			NUMBERS Persons **(**ideally) evacuated	743,800	228,200	177,800	660,700	660,700	691,800
			Persons **(**ideally) sheltered	947,900	128,200	34,670	416,900	436,500	741,300
			Persons **(**ideally) I-131 Prophylaxis	66,090	134,800	11,480	27,540	54,950	54,950
FLEPRU1D	Flamanville	**EPR** 100% LEU core Existing Fuel Burn-Up Target No short term Countermeasures Modelled	**EARLY** Death	629	119	58	316	417	525
			Early Morbidity	8,839	1,268	525	3,388	5,248	8,318
			LATE Fatal Cancer	17,570	4,419	3,631	8,710	12,020	14,130
			Thyroid Cancer DEATHS	922	251	218	427	589	692
			Thyroid Cancer INCIDENCE	9,219	2,465	2,188	4,074	6,026	6,918
FLEPRLEU2	Flamanville	**EPR** 100% LEU core Target 65GWed/tU Fuel Burn-Up	**EARLY** Death	381	81	42	214	309	331
			Early Morbidity	3,212	586	295	1,202	1,862	3,090
			LATE Fatal Cancer	26,430	6,212	5,623	12,590	18,620	19,050
			Thyroid Cancer DEATHS	1,454	309	263	589	813	1,047
			Thyroid Cancer Incidence	14,540	3,090	2,630	5,888	8,128	10,470
			LAND Area (ideally) Evacuated km^2	16,930	7,214	6,475	10,960	13,180	15,140
			Area (ideally) Iodine Prophylaxis km^2	1,541	361	257	813	912	1,230
			NUMBERS Persons **(**ideally) evacuated	1,246,000	313,00	239,900	955,000	955,000	955,000
			Persons **(**ideally) sheltered	1,163,000	125,700	34,670	363,100	489,800	812,800
			Persons **(**ideally) I-131 Prophylaxis	68,050	14,570	11,750	33,880	54,950	58,800
FLEXLEU1A	Flamanville	**EXISTING** 1330MWe PWR 100% LEU core	**EARLY** Death	179	41	23	100	145	166
			Early Morbidity	1,412	5,449	490	1,148	1,175	1,380
			LATE Fatal Cancer	15,020	3,748	3,311	7,943	10,960	12,590
			Thyroid Cancer DEATHS	824	184	158	355	479	603
			Thyroid Cancer Incidence	8,241	1,835	1,585	3,548	4,786	6,026
			LAND Area (ideally) Evacuated km^2	13,320	4,796	4,365	7,586	7,586	10,720
			Area (ideally) Iodine Prophylaxis km^2	1,445	318	2,512	549	891	1,047
			NUMBERS Persons **(**ideally) evacuated	725,300	176,800	151,400	416,900	478,600	631,000
			Persons **(**ideally) sheltered	869,500	125,800	35,480	371,500	588,800	724,00
			Persons **(**ideally) I-131 Prophylaxis	65,380	12,990	10,470	26,920	54,950	54,950
FLMOX1	Flamanville	**EPR** 30% MOX core	**EARLY** Death	322	67	34	159	275	322
			Early Morbidity	1,898	392	178	851	1,349	1,862
			LATE Fatal Cancer	29,260	6,295	5,754	12,020	14,130	19,050
			Thyroid Cancer DEATHS	984	212	186	390	513	616
			Thyroid Cancer Incidence	9,630	2,116	1,862	3,890	5,129	6,166
			LAND Area (ideally) Evacuated km^2	36,540	11,660	10,000	21,880	22,390	30,200
			Area (enforced) Iodine Prophylaxis km^2	314	78	63	135	148	246
			NUMBERS Persons **(**ideally) evacuated	3,246,000	567,600	537,000	1,259,000	1,259,000	1,698,000
			Persons **(**ideally) sheltered	1,078,000	132,300	45,710	426,600	602,600	676,100
			Persons **(**enf'd) I-131 Prophylaxis	13,070	3,228	2,570	5,888	6,607	10,960
FL100M2	Flamanville	**EPR** 100% MOX core	**EARLY** Death	650	147	85	355	550	603
			Early Morbidity	1,745	283	140	631	977	1,202
			LATE Fatal Cancer	60,760	8,055	7,586	14,790	19,050	23,440
			Thyroid Cancer DEATHS	1,307	161	110	347	468	575
			LAND Area (ideally) Evacuated km^2	44,810	13,300	11,750	23,990	25,700	38,020
			Area (ideally) Iodine Prophylaxis km^2	7,3214	2,360	2,138	3,388	5,495	6,761
			NUMBERS Persons **(**ideally) evacuated	3,319,000	662,200	549,500	1,380,000	1,585,000	2,696,000
			Persons **(**ideally) sheltered	957,800	116,900	45,710	426,600	478,600	645,700
			Persons **(**ideally) I-131 Prophylaxis	376,000	69,260	33,110	190,500	263,000	316,200
EDFLEU1	Flamanville	**EPR** 100% LEU High Burn-Up Target & EDF Release Fractions English Version x10^{2}	**EARLY** Death	0	0	0	0	0	0
			Early Morbidity	0	0	0	0	0	0
			LATE Fatal Cancer	11	4	4	7	8	11
			Thyroid Cancer DEATHS	1	0	0	0	0	0
				123	32	50	87	122	118

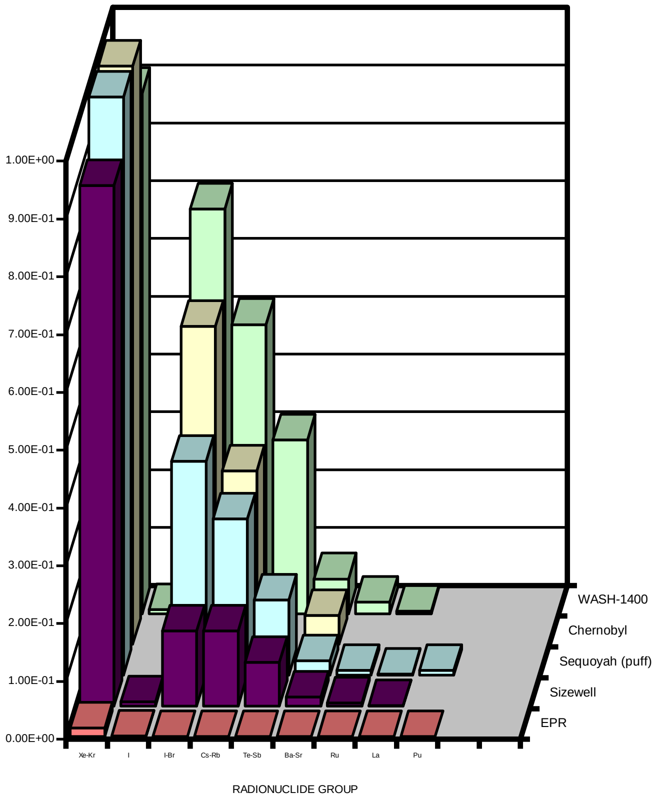
			Thyroid Cancer Incidence	5	2	2	3	4	5
			LAND Area (ideally) Evacuated km^2	123	57	50	87	112	118
			Area (ideally) Iodine Prophylaxis km^2	12	10	10	10	10	11
			NUMBERS Persons (ideally) evacuated	2,952	2,458	2,239	4,266	4,786	5,888
			Persons (ideally) sheltered	40,520	3,759	1,380	11,480	17,778	22,910
			Persons (ideally) I-131 Prophylaxis	630	560	562	575	575	630
TRLEU1	Tricastin	**EXISTING** 915 MWe PWR 100% LEU core	**EARLY** Death	28	6	2	16	19	26
			Early Morbidity	424	75	3	19	25	31
			LATE Fatal Cancer	11,890	3,234	3,020	6,026	7,079	8,710
			Thyroid Cancer DEATHS	530	165	166	302	331	437
			Thyroid Cancer Incidence	5,302	1,653	1,660	3,020	3,311	4,365
			LAND Area (ideally) Evacuated km^2	6,320	2,261	1,995	3,890	5,888	5,888
			Area (ideally) Iodine Prophylaxis km^2	1,281	275	209	447	851	891
			NUMBERS Persons (ideally) evacuated	712,000	181,600	123,000	457,100	537,000	537,000
			Persons (ideally) sheltered	1,784,000	270,100	131,800	588,800	1,047,000	1,549,000
			Persons (ideally) I-131 Prophylaxis	100,900	18,610	15,490	30,200	61,660	77,620
TRMOX2	Tricastin higher RF at Group 7	**EXISTING** 915MWe PWR 30% MOX core	**EARLY** Death	123	22	11	52	79	112
			Early Morbidity	813	122	41	360	371	813
			LATE Fatal Cancer	29,330	10,290	10,470	17,780	19,950	27,540
			Thyroid Cancer DEATHS	753	240	246	417	447	631
			Thyroid Cancer Incidence	7,528	2,401	2,455	4,169	4,467	6,310
			LAND Area (ideally) Evacuated km^2	23,990	8,704	8,318	13,800	15,490	21,880
			Area (ideally) Iodine Prophylaxis km^2	3,142	72	60	123	138	214
			NUMBERS Persons (ideally) evacuated	2,341,000	652,600	602,600	1,259,000	1,479,000	1,995,000
			Persons (ideally) sheltered	2,330,000	323,7000	145,000	1,047,000	1,288,000	1,288,000
			Persons (ideally) I-131 Prophylaxis	25,290	2,258	2,042	6,918	12,020	13,180
TRMOX2A	Tricastin	**EXISTING** 915MWe PWR 30% MOX core	**EARLY** Death	69	15	8	34	49	59
			Early Morbidity	759	117	42	323	347	692
			LATE Fatal Cancer	20,200	7,207	7,244	11,480	14,450	17,780
			Thyroid Cancer DEATHS	733	238	240	427	467	631
			Thyroid Cancer Incidence	7,332	2,380	2,400	4,266	4,467	6,310
			LAND Area (ideally) Evacuated km^2	18,820	6,546	6,918	8,710	10,000	`18,820
			Area (ideally) Iodine Prophylaxis km^2	3,142	72	60	123	138	214
			NUMBERS Persons (ideally) evacuated	1,798,000	502,200	41,690	1,148,000	1,480,000	1,514,000
			Persons (ideally) sheltered	2,099,000	308,000	123,000	871,000	1,072,000	1,148,000
			Persons (ideally) I-131 Prophylaxis	15,290	3,258	2,042	6,918	12,020	13,180
NsSLEU1	Nogent sur Seine	**EXISTING** 1310MWe PWR 100% LEU core	**EARLY** Death	434	41	15	87	166	316
			Early Morbidity	6,428	582	155	1,413	2,455	5,129
			LATE Fatal Cancer	109,900	11,510	4,898	12,020	19,950	38,900
			Thyroid Cancer DEATHS	4,670	354	257	513	813	1,778
			Thyroid Cancer Incidence	46,700	3,535	2,570	5,129	8,128	17,780
			LAND Area (ideally) Evacuated km^2	13,530	4,841	4,365	7,762	7,762	10,470
			Area (ideally) Iodine Prophylaxis km^2	1,445	320	251	550	891	1,047
			NUMBERS Persons (ideally) evacuated	6,386,000	424,000	263,000	575,400	724,400	5,129,000
			Persons (ideally) sheltered	8,399,000	527,600	74,130	776,200	4,677,000	7,943,000
			Persons (ideally) I-131 Prophylaxis	88,530	22,000	17,380	47,860	57,540	67,610
FLEU1	Fessenheim	**EXISTING** 880MWe PWR 100% LEU core	**EARLY** Death	194	26	10	69	85	102
			Early Morbidity	1,497	320	158	891	1,096	1,445
			LATE Fatal Cancer	36,010	10,340	8,913	20,420	36,010	36,010
			Thyroid Cancer DEATHS	2,599	492	479	851	1,600	1,600
			Thyroid Cancer Incidence	15,990	4,919	4,786	8,511	15,990	15,990
			LAND Area (ideally) Evacuated km^2	6,188	2,206	1,950	3,802	5,888	5,888
			Area (ideally) Iodine Prophylaxis km^2	1,268	273	200	434	832	891
			NUMBERS Persons (ideally) evacuated	2,960,000	563,300	331,100	1,778,000	2,960,000	2,960,000
			Persons (ideally) sheltered	3,851,000	605,000	338,800	2,089,000	2,188,000	2,952,000
			Persons (ideally) I-131 Prophylaxis	502,900	90,180	31,150	239,900	363,100	457,100

APPENDIX II

HYPOTHETICAL 1,000MWe PWR FUEL INVENTORY FOR 35GWd/t LEU & RG 34.5GWd/t MOX CORE CHARGES

FISSION PRODUCTS	**100% LEU CORE Bq**	**30% MOX CORE Bq**	**50% MOX CORE Bq**	**100% MOX CORE Bq**
Kr-85	**2.59E+16**	**2.24E+16**	**2.00E+16**	**1.42E+16**
Kr-85m	**7.63E+17**	**6.73E+17**	**6.13E+17**	**4.63E+17**
Kr-87	**1.53E+18**	**1.34E+18**	**1.21E+18**	**8.89E+17**
Kr-88	**2.13E+18**	**1.85E+18**	**1.66E+18**	**1.19E+18**
Rb-86	**4.18E+15**	**3.61E+15**	**3.23E+15**	**2.28E+15**
Sr-89	**3.05E+18**	**2.60E+18**	**2.31E+18**	**1.57E+18**
Sr-90	**2.22E+17**	**1.86E+17**	**1.62E+17**	**1.02E+17**
Sr-91	**3.72E+18**	**3.27E+18**	**2.98E+18**	**2.24E+18**
Sr-92	**3.93E+18**	**3.54E+18**	**3.29E+18**	**2.64E+18**
Y-90	**2.32E+17**	**1.94E+17**	**1.68E+17**	**1.05E+17**
Y-91	**3.93E+18**	**3.43E+18**	**3.11E+18**	**2.29E+18**
Y-92	**3.96E+18**	**3.57E+18**	**3.31E+18**	**2.66E+18**
Y-93	**3.00E+18**	**2.77E+18**	**2.62E+18**	**2.23E+18**
Zr-95	**5.18E+18**	**4.90E+18**	**4.72E+18**	**4.26E+18**
Zr-97	**4.81E+18**	**4.70E+18**	**4.63E+18**	**4.44E+18**
Nb-95	**5.20E+18**	**4.91E+18**	**4.73E+18**	**4.26E+18**
Mo-99	**5.54E+18**	**5.50E+18**	**5.47E+18**	**5.41E+18**
Tc-99m	**4.87E+18**	**4.83E+18**	**4.81E+18**	**4.75E+18**
Ru-103	**4.50E+18**	**4.93E+18**	**5.22E+18**	**5.94E+18**
Ru-105	**3.00E+18**	**3.51E+18**	**3.85E+18**	**4.69E+18**
Ru-106	**1.33E+18**	**1.78E+18**	**2.08E+18**	**2.83E+18**
Rh-105	**2.82E+18**	**3.31E+18**	**3.64E+18**	**4.47E+18**
Sb-127	**2.44E+17**	**2.76E+17**	**2.96E+17**	**3.48E+17**
Sb-129	**9.28E+17**	**9.80E+17**	**1.01E+18**	**1.10E+18**
Te-127	**2.40E+17**	**2.72E+17**	**2.94E+17**	**3.47E+17**
Te-127m	**3.88E+16**	**4.57E+16**	**5.03E+16**	**6.17E+16**
Te-129	**8.82E+17**	**9.34E+17**	**9.68E+17**	**1.05E+18**
Te-129m	**1.78E+17**	**1.91E+17**	**2.00E+17**	**2.21E+17**
Te-131m	**5.69E+17**	**6.21E+17**	**6.55E+17**	**7.40E+17**
Te-132	**4.23E+18**	**4.26E+18**	**4.29E+18**	**4.35E+18**
I-131	**2.94E+18**	**2.99E+18**	**3.03E+18**	**3.12E+18**
I-132	**4.30E+18**	**4.35E+18**	**4.38E+18**	**4.47E+18**
I-133	**6.09E+18**	**6.06E+18**	**6.04E+18**	**5.98E+18**
I-134	**6.77E+18**	**6.66E+18**	**6.59E+18**	**6.41E+18**
I-135	**5.80E+18**	**5.79E+18**	**5.78E+18**	**5.75E+18**
Xe-133	**6.09E+18**	**6.06E+18**	**6.04E+18**	**6.00E+18**
Xe-135	**1.43E+18**	**1.73E+18**	**1.92E+18**	**2.41E+18**
Cs-134	**3.90E+17**	**3.86E+17**	**3.83E+17**	**3.75E+17**
Cs-136	**1.16E+17**	**1.40E+17**	**1.55E+17**	**1.94E+17**
Cs-137	**2.95E+17**	**2.94E+17**	**2.93E+17**	**2.92E+17**
Ba-139	**5.40E+18**	**5.27E+18**	**5.19E+18**	**4.99E+18**
Ba-140	**5.44E+18**	**5.33E+18**	**5.25E+18**	**5.06E+18**
La-140	**5.62E+18**	**5.49E+18**	**5.40E+18**	**5.18E+18**
La-141	**4.94E+18**	**4.82E+18**	**4.75E+18**	**4.55E+18**
La-142	**4.83E+18**	**4.69E+18**	**4.59E+18**	**4.35E+18**
Ce-141	**5.00E+18**	**4.89E+18**	**4.81E+18**	**4.63E+18**
Ce-143	**4.64E+18**	**4.44E+18**	**4.30E+18**	**3.95E+18**
Ce-144	**3.61E+18**	**3.37E+18**	**3.22E+18**	**2.83E+18**
Pr-143	**4.56E+18**	**4.35E+18**	**4.22E+18**	**3.88E+18**
Nd-147	**1.99E+18**	**1.96E+18**	**1.94E+18**	**1.89E+18**
Np-239	**5.49E+19**	**5.20E+19**	**5.00E+19**	**4.51E+19**
Pu-238	**6.73E+15**	**2.98E+16**	**4.51E+16**	**8.34E+16**
Pu-239	**8.34E+14**	**1.87E+15**	**2.56E+15**	**4.28E+15**
Pu-240	**1.09E+15**	**4.08E+15**	**6.07E+15**	**1.10E+16**
Pu-241	**3.32E+17**	**1.05E+18**	**1.52E+18**	**2.71E+18**
Am-241	**3.04E+14**	**2.66E+15**	**4.22E+15**	**8.13E+15**
Cm-242	**9.27E+16**	**6.13E+17**	**9.58E+17**	**1.82E+18**
Cm-244	**5.50E+15**	**3.96E+16**	**6.22E+16**	**1.19E+17**

FIGURE 1 - RELEASE FRACTION COMPARISON



NOTES & REFERENCES

---

[1] For the water-filled spent fuel storage ponds, the most obvious incident is loss of the pool water that cools and shields the highly radioactive spent fuel assemblies. This is considered to be a *Design Basis Fault* condition which is catered for by redundancy and diversity in the engineered safety and backup systems, although post 9/11 reviews have identified a number of weaknesses suggesting lack of resilience against terrorist acts, particularly aircraft crash and a following aviation fuel fire. Perhaps the most important concession was made in June 2001, when the NRC staff reported that terrorist threats against spent fuel ponds are credible and cannot be ruled out, stating that *"Until recently, the staff believed that the [design basis threat] of radiological sabotage could not cause a zirconium fire"*. Several other events could cause a loss of pool water, including leakage, evaporation, siphoning, pumping, earthquake, accidental or deliberate drop of a fuel transport cask, reactor failure, or an explosion inside or outside the pool building, although the counterargument maintain that personnel would have sufficient time to provide an alternative cooling system before the spent fuel caught fire.

Even in the absence of an externally initiated fire, loss of pond water exposes the heat generating fuel and this could result in an explosive and catastrophic fire with radiological consequences as potentially significant as a reactor meltdown. NPPs store spent fuel in high-density pools such that drain down of the water exposing the fuel zircaloy cladding to a mixture of air and steam, could give rise to an exothermic reaction at about 1,000°C. Typically, after about 15 to 20 years of operation, a NPP spent fuel pond holds 5 to 10 times more long-lived radioactivity than a reactor core, particularly caesium-137. The 1997 report for the NRC by Brookhaven National Laboratory found that a severe pool fire could render about 600km^2 downwind land area uninhabitable and give rise to cause as many as 28,000 cancer fatalities.

For further details see US Nuclear Regulatory Commission, *Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants* (NRC, NUREG-1738, 2001Alvarez, R et al., *Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States*, April, 2003, Science& Global Security, Spring 2003, although the NRC has criticised and disputed a number of the findings of this latter assessment, see NRC, *Fact Sheet on NRC Review of Paper on Reducing Hazards From Stored Spent Nuclear Fuel*, NRC August 2003.

[2] *Reactor Grade* plutonium typically comprises - see *Plutonium Fuel: An Assessment* Paris:OECD/NEA, 1989:

Pu-238	**Pu-239**	**Pu-240**	**Pu-241**	**Pu-242**	**Am-241**
2.3%	56.2%	24.2%	9.0%	6.9%	1.4%

[3] The higher loading of burnable absorbers (ie the control rods) for MOX fuelled reactor cores has not been taken into account in the assessment.

[4] Bowman S, Hermann W, Brady M. *Scale-4 Analysis of Pressurised Water Reactor Critical Configuration Sequoyah Unit 2 Cycle 3,* ORNL/TM-12994/V2 Oak Ridge National Laboratory, March 1995

[5] In this assessment the BSL and BSO targets and limits are for members of public or persons located off the NPP site – there are similar limits etc for employees and persons located on the NPP site.

[6] *The Tolerability of Risk from Nuclear Power Stations*, Health & Safety Executive, HMSO 1992

[7] The BSL/BSO system adopted in the UK is as follows:

OFF-SITE MEMBERS OF PUBLIC – EFFECTIVE DOSE		
TARGET	**TARGET DOSE**	**FAULT FREQUENCY PER ANNUM**
BSL	1mSv 10mSv 100mSv	greater than 1.10^{-3} between 1.10^{-3} and 1.10^{-4} less than 1.10^{-4}
BSO	0.01mSv per annum	

[8] For the UK:

OFF-SITE MEMBERS OF PUBLIC – EFFECTIVE DOSE		
TARGET DOSE	**FREQUENCY PER ANNUM**	
mSv	BSL	BSO
0.1 – 1	1	1.10^{-2}
1 – 10	1.10^{-1}	1.10^{-3}
10 – 100	1.10^{-2}	1.10^{-4}
100 – 1000	1.10^{-3}	1.10^{-5}
> 1000	1.10^{-4}	1.10^{-6}

[9] Large J H *Exploratory Review of the EdF Presentation Note: Application for Authorisation to Construct and Operate a 3rd Nuclear Power Unit Flamanville*, States of Jersey, July 2006

[10] This involves interpretation of the public perception of risk and the complex differentiation in valuing the detriment of, say, a single accident involving a road bus accident involving a few deaths in a single accident which will cause great public concern, concern to the almost unnoticed passing of many more deaths daily from many roads accidents.

[11] Hughes D, *The Revision of Dose Limits For Exposure to Ionizing Radiation*, Annal of Occ Hygiene, V34 No 5, 1990

[12] These values for societal BSL and BSO are those adopted in the United Kingdom and there does not seem to be an equivalent in French regulatory system.

[13] Large J H, *Decommissioning Nuclear Plants - Openings for the Terrorist Threat*, 10th Global Conference & Exhibition on Decommissioning Nuclear - Taking Experience Forward, IBC London 20-22 November 2006.

---

[14] *Application for the Authorisation to Create a 3rd Nuclear Power Unit on the Flamanville Site, Ch V1, Consequences of Radiological Accidents*, p33, EdF May 2006

[15] During normal operation, the heat from nuclear fission in the fuel core of a PWR is abstracted from the pressurised water coolant, passed to steam generators where part of the heat is dissipated in generating electricity via turbo-alternators with the remaining (about two-thirds of the total) heat being dumped to the environment via the condenser. If because of some adverse event or circumstances, this heat cannot be dissipated in a managed way then the nuclear fuel in the reactor core will be subject to increasing higher temperature, at some point it will fail and result in a release of fuel particles into the primary coolant circuit of the reactor. Increasing temperature and pressures, loss of fuel core geometry might then provide conditions conducive to a release of thermo-mechanical energy sufficient to break throughout the containment of the reactor primary circuit and its surround building enclosure.

[16] 10^{-6} that is a chance in a million years for each year that the reactor operates.

[17] Eg a risk of 10^{-7} is a chance of 1 in 10 million each year for each year of reactor operation.

[18] These are probabilistic forecasts which, of course, cannot be applied to intelligent and intentional human acts, particularly malevolent acts and terrorism.

[19] Essential design details are: primary circuit design pressure 176b and outlet temperature at 327°C (311.7°C and 155b average at 60 to 100% power output), RPV internal dimensions 4.85m diameter and 12.78m height, with 250mm wall thickness, fuel core 241 17x17 rod assemblies, each of 533kg Uranium at 4.4% single zone enrichment, total core fuel load ~128.5t.

[20] The design pressure of the secondary reactor containment (the domed building) is 0.53Mpa with a design volumetric leakage rate of 0.5% over the first 24 hours. This containment comprises inner and out domed structures in reinforced concrete with the inner containment fitted with an internal steel plat liner. The annulus between the two containment skins provides cooling in the aftermath of a severe accident, venting via HEPA and iodine filters.

[21] Essentially, the EPR is a descendant of the French N4 (Chooz and Civaux) and German Konvoi nuclear reactors (Isar 2 and Neckarwesttheim 2), both models currently in service. From the N4, the new reactor derives its designs for containment and the primary system, its instrumentation and control system, and its control room. The EPR's in-core measurement system and four-train architecture are taken from the Konvoi design of plant.

[22] Hirsch H, *Ongoing Dangers of Operating Nuclear Technology in the 21st Century*, Greenpeace International, April 2005

[23] The reactor primary circuit containment building is a large, double walled building of about 80,000m3 capacity. The inner containment shell is about 1.3m thick, prestressed concrete lined with 6mm steel plating and the prestressed concrete outer shell varies in thickness of 1.3m at the base increasing to 1.8m thick in the dome. The containment is sub-divided into accessible and non-accessible sections whilst the reactor is operational. The annulus between inner and outer shells is 1.8m, being gas tight and maintained at negative pressure it serves as a filtered route from the inner containment for any air suspended radioactive particles.

During outages there is a large containment access hatch that is normally open into the reactor area of the containment and should a release incident occur during an outage then the hatch has to be closed with closure and sealing times varying between 30 minutes to 6 hours depending upon prevailing conditions.

[24] Of course, there is no certainty about the potential for and/or nature of terrorist attack against nuclear power plants – what may be perceived to be an active threat in one country may be entirely different and benign in another. Nor should it be assumed that a future attack would follow the same or a similar modus operandi as the World Trade Centre and Pentagon attacks because it could, for example, involve a passive or active *'insider'* within the plant, it might derive from a device planted during the construction phrase but which lays dormant for years, and so on and so forth. Even if an aircraft attack is assumed, it may not be necessary to break through the containment to initiate a severely damaging event, the impact resonance through the nuclear equipment might be sufficient to disable to safety systems; an aviation fuel fire outside the containment might incapacitate all but a few individuals operating and overseeing the safety of the reactor plant. The possible opportunities of severely damaging disruption to an operating NPP (as is human (terrorist) ingenuity) are endless – see Large J H, *Decommissioning Nuclear Plants - Openings for the Terrorist Threat*, 10th Global Conference & Exhibition on Decommissioning Nuclear - Taking Experience Forward, London 20-22 November 2006

[25] In the closing stages of a severe incident culminating in a low pressure core fuel melt, the corium penetrating through the bottom of the reactor pressure vessel is directed into an enclosed pit below. The catchment pit serves to collect the (100 or so tonnes of) corium where it is retained until it burns through a dam to allow flow into an adjacent spreading and cooling area. The time lags between retention of the corium in the catchment pit, burn through of the dam gate and eventual spreading into the cooling area are critical in order to, first, collect as much of the molten fuel corium as possible, providing adequate mass (head) to achieve a sufficient mass flow, and hold a low viscosity (flowability) to maximum the spread over the cooling floor of the spreading area. The periods over which the corium is cooled to a solidified crust are reckoned to be:

RPV DISCHARGE	**>>>**	**DAM BURN-THROUGH**	**>>>**	**CORIUM SPREAD**	**>>>**	**COOL TO CRUST**
50 - 100 minutes		>2 hours		< 10 seconds		hours to a few days

This entirely novel feature of the EPR has yet to be proven by reasonably scaled trials – the sole European facility at Cadarache (France) can melt a depleted uranium batch of simulated corium of just 80kg compared to the $140,000^{+}$kg that could arise in a full fuel core melt of the Olkiluoto 3 EPR (see Pascal Piluso, et al *Corium Behaviour Research at CEA Cadarache: The PLINIUS Prototype Corium Experimental Platform*, Nuclear Energy for New Europe, Slovenia September 2002). In reality, the formation, stability and transfer of the melt corium is likely to be quite complex, perhaps dominated by combined secondary influences that cannot be reliably modelled and, indeed, attempting to manage 100 or more tonnes of molten radioactive material in a highly charged steam atmosphere may introduce other deleterious factors, some of which do not seem to have been identified.

Independent analysis of the EPR corium or core catcher design suggest oversights and inadequacies. After melting through a bulkhead, the molten corium then passes through an outlet conduit and spreads in specifically designed area. By means of passive features, the water of the IRWST is then released for flooding and cooling the core melt in this area. The floor of the spreading area is provided with a cooling system to avoid excessive temperatures in the structural concrete of the reactor building. However, even before the melt reaches the core catcher, a violent steam explosion could take place in the reactor pressure vessel, possibly leading to containment failure. Furthermore, steam explosions can also occur later in the course of the accident, when the melt in the spreading area comes into contact with IRWST water. Even if this does not happen, it is not clear that effective cooling of the spread molten core will be possible. A solid layer on the surface of the melt could form, preventing heat removal, and the core could eat into the concrete below the spreading area. – see Hersch H, et al *Nuclear Reactor Hazards, Ongoing Dangers of Operating Nuclear Technology in the 21st Century*, April 2005

[26] This absorption demand is high in the Cycle 1 of the core burn-up and to limit the boron in solution absorption coatings such as zirconium-diboride are used, although details of the French MOX fuel are unknown.

[27] Fuel storage incidents resulting in radioactive release are not considered in this assessment, although it should be noted that very significant radiological consequences could arise from a spent fuel incident.

[28] Long term neutron irradiation of the RPV results in embrittlement of the vessel steel and a raising of the brittle failure threshold temperature at which extant defects are susceptible to rapid propagation to catastrophic failure. MOX fuel can contribute to an increased rate of over-cooling because the greater negativity of the moderator temperature coefficient which, together with a lower delayed neutron fraction, the rate at which the power increases will be greater, reducing the time margin for activation of safety systems to prevent over-cooling. MOX will also contribute to increased embrittlement of the RPV because plutonium-239 fission yields a greater flux of embrittlising *fast* neutrons being absorbed into the RPV walls.

[29] Lyman E, *Public Health Risks of Substituting Mixed-Oxide For Uranium Fuel in Pressurized-Water Reactors, Science &* Global Security, 2000, Volume 9, pp.1–47

[30] Siswas D, et al, *Neutronics and Safety Characteristics of a 100% MOX Fueled PWR Using Weapons Grade Plutonium*, American Nuclear Society 1994 Topical Meeting on Advances in Reactor Physics, Tennessee April, 1994

[31] These probability values are taken for a Westinghouse PWR – *Sizewell B Probabilistic Safety Study*, Westinghouse Electric Corporation, Rev 1, 1982.

[32] Large J H *The Implications of September 11th for the Nuclear Industry*, Monitor, Royal United Services Institute, London, February 2003, V2 Nº 1

[33] The *RRC-A* class of incidents are defined as those that might commence with a simple initiating event from which multiple failures cascade to form a sequence that ultimately leads to a core meltdown of degrade and which will include a high-pressure core degrade.

The *RRC-B* class of incidents include low pressure core meltdown which, in mitigation, effectively rely upon the as yet to be proven cooling of the core melt that has burnt through the reactor pressure vessel with EdF claiming that other severely damaging fault scenarios, such as high pressure meltdown, prompt criticality incidents, zirconium-steam reaction hydro detonation and steam-molten metal explosions have been practically eliminated. *Practically eliminating* the high pressure meltdown and zirconium faults means that the threat to rupturing the reactor containment levels is removed and, other than a containment bypass event, the containment is deemed to be effectively sealed and failsafe.

[34] Direction Générale de la Santé, Order of 13 October 2003.

[35] Effective Dose is the whole body dose equivalent (ie the entire dose received from external and internal emitters).

[36] Dose due to the thyroid reconcentrating radio-iodine, namely I-131 fission products.

[37] In the UK this long-term consequence is projected over 100 years.

[38] The core degrade incident at the Three Mile Island PWR NPP in 1978 was effectively a high pressure core meltdown in which the operators failed, or had little or no control, over the pressure transients in the RPV primary circuit.

In this incident sequence the condensate polishing plant (on the steamside, non-nuclear circuit) tripped because of an instrument fault, following which the condenser tripped out and the reactor control system automatically began to shut down the reactor power. Within 3 seconds the RPV pressure rose to the set trip point of the pressuriser relief valve, the valve opened and 4 seconds later the reactor tripped as the RPV pressure dropped. At 7 seconds the operators implemented start-up of a second pressuriser pump to offset the RPV pressure drop but this failed to trigger because of an incorrect start up procedure and by 12 seconds into the sequence the pressuriser valve failed to automatically close at the low pressure set point. At 30 seconds the steam generators began to boil dry so a second make up pump was this time successfully started, thereafter at 121 seconds high pressure injection commenced automatically. The operators assumed manual command of the injector pumps endeavouring to control the pressuriser water level and the bubble, the water level in the pressuriser oscillated over 15 seconds after which the bubble was lost and the steam generators boiled dry. At 15 minutes into a steadily deteriorating situation, the RPV instrumentation indicated the presence of a void in the fuel core, after which the situation was unrecoverable.

Although there were a number of causes and operator decisions leading to the eventual concession at about 2 hours 55 minutes that recovery of the reactor plant was not possible, the initiating decision or operator error was made by just 12 seconds into the overall sequence – that was the point at which the operators unsuccessfully tried to start-up the standby pressuriser pump but failing to do this because the operator did not hold the pump start up switch closed long enough for the pressuriser pump's lubricating oil pump to build up sufficient oil pressure to permit pump start up.

[39] This postulated incident in loosely based on the Three Mile Island meltdown of 1978 but with the sequence modified and foreshortened – see Kemeny J et al, *Report of the President's Commission on the Accident at Three Mile Island*, US Government Printing Office, Washington 1979

[40] US Nuclear Regulatory Commission, *Reactor Safety Study, an Assessment of Accident Risks in US Commercial Nuclear Power Plants*, WASH-1400, NRC 1975

[41] Kelly, G et al, *An Assessment of the Radiological Consequences of Releases from Degraded Core Accidents for the Sizewell PWR*, NRPB-R137, 1982

[42] The COSYMA code used for the dispersion and consequence analysis does not facilitate handling of this probabilistic subset, although individual runs could be undertaken to explore the range.

[43] Sequoyah, Tennessee – 1350MWe PWR commissioned in 1981.

[44] Davis, R. et al *Reassessment of Selected Factors Affecting Siting of Nuclear Power Plants*, NUREG/CR-6295 NRC, 1997

---

[45] *Application for the Authorisation to Create a 3rd Nuclear Power Unit on the Flamanville Site, Ch V1, Consequences of Radiological Accidents*, p33, EdF May 2006.

[46] There may be a misinterpretation of the meaning of Table V.1.2.4.2.2 of the preceding reference wherein the release fractions are expressed a '% IC', that is a percentage of the reactor core inventory so the tabulated data has been scaled by xE-2, even so the EdF release fractions remain small compared to accepted studies.

[47] Large J H, *Chernobyl – A Nuclear Catastrophe 20 Years On - A Review of the Present Situation in the Ukraine*, November 2006

[48] *Current Topics about the Radiological Consequences by the Chernobyl Accident*, Research Reactor Institute, Kyoto University

[49] *Released Radioactivity by the Chernobyl Accident*, Seo T, Imanaka T & Koide H. Kagaku, 58 Nº 2 (1988)

[50] *The Final Report of the Research Grant of the Toyota Foundation*, Imanaka T. et al 1993

[51] *Minchernobyl - Ten years after the accident at Chernobyl NPP*: National Report of Ukraine, 1996

[52] *Release of Radionuclides from the Destroyed Reactor at Chernobyl NPP*, Borovoi A. A.& Gagarinsky A. Atomnaya Energiya, 90 No.2 (2001)

[53] *Environmental Consequences of the Chernobyl Accident and Their Remediation: Twenty Years of Experience* Report UN Chernobyl Forum Expert Group 'Environment' (EGE) August 2005

[54] This is based on an incident where the reactor pressure vessel fails and there is a following hydrogen burn/combustion that results in early secondary containment failure.

[55] The release factor subset includes factors of 2, 4,10 and 20 lower that those derived from WASH-1400 and arise because of more detailed consideration of particular isotopes and their form and interaction in the environment. For example, the release of iodine is assumed by WASH1400 to be released mostly in its elemental form whereas if it was combined as caesium iodide then its behaviour in the containment might result in a greater fraction being held back. This also has implications for the behaviour of iodine through the environment, particularly the dry deposition velocity which is about one order of magnitude slower than the elemental form, hence the dispersion pattern would extend the deposition further away from the release locality and a reduction in the individual dose uptake form this radionuclide.

[56] COSYMA does not, however, have facility for modelling a release fraction probability subset within each individual release scenario.

[57] According to EdF these *'practically eliminated situations'* include i) Hydrogen detonation during a core meltdown for oxidation of the zirconium cladding and assembly debris, ii) steam explosion via transfer of the energy of molten fuel, and iii) high pressure meltdown wherein a gas bubble blocks flow in the primary circuit. Critics of the EPR note that such safety features would be more impressive had not EDF's N4 class of plants (the Civaux and Chooz B reactors) on which the EPR's design is in part based, already experienced serious safety-related problems.

[58] In the UK this compact is referred to as *'Acceptable Risk – Tolerable Consequences'* which means that if there the risk is *acceptable* if the consequences are *tolerable*. Put another way, providing that the risk of the incident occurring are very (*acceptably*) low then the consequences can be *intolerable* because the event is very unlikely to ever happen.

[59] Hesketh K et al. Plutonium Management in the Medium Term, a Review on the OECD/NEA Working Party on the Physics of Plutonium Fuels and Innovative Fuel Cycles (WPPR), NEA4451, OECD/NEA, 2003.

[60] The original design for the EPR intended that up to 50% of the core be composed of MOX fuel, that the uranium in the standard fuel be enriched to up to 4.9% uranium 235, that the fuel be discharged at a burn-up of >60GWd/t, that the plant remain in service 60 years, that fuel reloads and regular maintenance require less than 20 days of down time, that plant availability average at least 90%..

[61] Development of MOX fuels in France is focused on the MOX-UE concept, which seems to be the option most compatible with the existing fuel cycle facilities. The MOX-UE is a homogeneous 17 by17 PWR assembly with 36 additional water rods to provide for extra moderation. The plutonium content of the first cycle MOX is about 9 wt-% and the uranium enrichment about 0.25 wt-%. When the plutonium quality degrades after successive recycles, both the plutonium content and the uranium enrichment are increased to gain more reactivity. The neutron absorber material is gadolinium in oxide form present as a homogeneous mix with the fuel matrix, although erbium may also be used as a burnable absorber

[62] Leppanen J *Preliminary Calculations on Actinide Management using Advanced PWR MOX Technology.* PRO1/P1007/05 VTT Processes, March 2005

[63] *Shell Release Rate* refers to the release of fuel products through breaches in the fuel pin cladding

[64] *Application for the Authorisation to Create a 3rd Nuclear Power Unit on the Flamanville Site, Ch V1, Consequences of Radiological Accidents*, p33, EdF May 2006

[65] Lyman (see Lyman E, *Public Health Risks of Substituting Mixed-Oxide For Uranium Fuel in Pressurized-Water Reactors, Science &* Global Security, 2000, Volume 9, pp.1–47) reports that for spent fuel held at a temperature of 1780K for one hour, the caesium release fraction for a MOX fuel rod with a burn-up of 41 GWD/t was 58%, compared to only 18% for an LEU rod with a burn-up of 47 GWD/t.

[66] KISSANE, M et al *Post-VERCORS needs for analytical experiments on fission-product release*, Fuel Safety Research Meeting, Tokyo, Japan, March 2005 which identifies a number of shortfalls and 'gaps' in the VERCORS test programme, including:

- There remained gaps for existing fuels such as TU2-type MOX and accident conditions such as air ingress.
- Improvement of the understanding of fission-product release processes by confirming or improving conclusions reached in experiment interpretation, most notably with the MFPR code.
- Based on the existing, detailed-modelling capability, means is needed (a tool) capable of predictive applications in order to anticipate the consequences of evolutions in fuel design and fuel-cycle management - this will not only improve confidence in results of detailed analyses but also in analysis of accident sequences.
- Further experiments are required to substantiate or improvement of assumptions used in the simplified release modelling in the following specific areas:
- micro-characterization of fuel (SEM, EPMA, etc.) before and after annealing in inert, oxidizing and reducing atmospheres;

- and for fission product release (rate and amount)
- experiments on MOX fuel, especially TU2-type, in a variety of reducing/oxidizing conditions;
- experiments in air ingress conditions for LEU and MOX fuels;
- primarily the amount, from high burn-up LEU and MOX fuels in design-basis LOCA conditions, this not being an immediate concern but necessary in the mid-term.

[67] Included in the Lanthanum (La) release grouping, including Y, La, Zr, Nb, Ce, Pr, Nd, Np, Pu, Am and Cm

[68] Lyman interprets[65] interprets a recent review of the Chernobyl source term that about 3.5% of the actinides were release and that some proportion of this was transported away from the immediate vicinity of the plant – see Devell, L et al *The Chernobyl Reactor Accident Source Term: Development of a Consensus View*, OECD/GD(96)12 (Paris: Organization for Economic Co-Operation and Development, 1995).

[69] COSYMA – **CO**de **SY**stem from **MA**RIA which is an adaptation of the mainframe *Methods for Assessing Radiological Impact of Accidents*, EUR 16240 EN.

[70] ICRP – International Committee on Radiological Protection, *Recommendations of the ICRP 1990* – the adoption of ICRP60 is not intended to support or imply that the ICRP60 recommendations and risk factors are proven and certain but these are generally accepted by individual nations as the international standard upon which much domestic radiological protection legislation is based. If required COSYMA will accept other user-defined risk factors

[71] Pasquill Atmospheric Stability *Class D* – Neutral, Overcast Day or Night

[72] The range of probability (p=1 to p=99.9) is the extreme of chance that the number of fatalities tabulated in the columns will actually occur, with p=99.9 being the least likelihood (at 1 in 1000) – the percentiles may be expressed as, for example, the 90th percentile where the value or outcome would be exceeded once in ten instances and at the 99th percentile where the value would be exceeded once in one hundred instances . The probability distribution is dominated by the meteorological conditions that might occur at the time of the release and throughout its sequence – the COSYMA mathematical model used calculates the outcome for each of seven meteorological stability categories and then grades each of these according to the probability of occurrence using past records. p=50 is the arithmetic mean of the probability range and the classically defined *Expectation Value E* is the value entered in the MEAN column which is the value which if the incident occurred many, many times would be the most likely outcome

All of that said, the unsinkable ship, the Titanic, sank on its maiden voyage!

[73] Circular DGS/SGCISN/DDSC number 2001/549 of November 14, 2001- this Circular specifies a trigger level of 100mSv for the administration of stable iodine tablets which compares with the World Health Organisation recommendation of prophylaxis being triggered at a projected dose of 10mSv for infants, pregnant women and those nursing neonates

[74] These countermeasure trigger limits are given in the *Application for the Authorisation to Create a 3rd Nuclear Power Unit on the Flamanville Site, Ch V1, Consequences of Radiological Accidents*, p33, EdF May 2006

[75] Intervention levels for emergency response are for national authorities to decide, but the latest information suggests that stable iodine prophylaxis for children up to the age of 18 years be considered at 10 mGy, that is 1/10th of the generic intervention level expressed in the *International basic safety standards for protection against ionizing radiation and for the safety of radiation sources*. For adults over 40, the scientific evidence suggests that stable iodine prophylaxis not be recommended unless doses to the thyroid from inhalation are expected to exceed levels that would threaten thyroid function. This is because the risk of radiation induced thyroid carcinoma in this group is very low while, on the other hand, the risk of side effects increases with age.

See *Guidelines for Iodine Prophylaxis following Nuclear Accidents*, 1999, WHO/SDE/PHE/99.6

[76] HYSPLIT – **HY**brid **S**ingle-**P**article **L**agrangian **I**ntegrated **T**rajectory – computes simple air parcel trajectories in account of atmospheric stability and dispersion equations using archive weather data.

[77] This data for 100km from the NPP and these proportions are for each of the periods defined and not, of course, that the radiation exposure during each of the periods is the same.

[78] In the United Kingdom countermeasures are introduced via a series of *Emergency Reference Levels* (ERL) specified in terms of bands of *Lower* and *Upper* dose limits at 30 and 300mSv, compared to the French single limits of TABLE 6. The sheltering countermeasures does not have to be implemented below the *Lower* 3mSv total effective dose but it must be in place to *avert* the Upper limit dose of 30mSv. Similarly, for evacuation should be actively considered for dose over 30mSv *Lower* and in place to avert a dose 300mSv *Upper*.

[79] Of course, the time of the incident will be a decisive factor in the countermeasure implementation with, for example, a late night or early morning incident onset setting back the evacuation by several hours as resources are mustered and the public awakened. The possibility that the state authority may choose not to immediately inform the public, for fear of prompting panic, should also not be entirely dismissed.

[80] Here the dry deposition velocities are assumed to be for aerosols 0.001m/s, elemental iodine 0.01m/s and organically bound iodine 0.005m/s and one-hundredth of the iodine released is assumed to be in organic form.

[81] Application for the Authorisation to Create a 3rd Nuclear Power Unit on the Flamanville Site, Ch V1, Consequences of Radiological Accidents, EdF May 2006.

[82] In the UK decontamination levels are recommended in a number of codes of practice, such as the *NRPB Derived Limits for Contaminants,* DL2 NRPB 1979 and also *Review of Decontamination and Clean-Up Techniques in the UK following Accidental Release of Radioactivity to the Environment*, NRPB R288 1996 – the general limits recommended levels not exceeding for surface contaminants are 0.4Bq/cm^2 for α and 4 Bq/cm2 for βγ. The Health Protection Agency has published advice on the designation of radioactively

---

contaminated land in response to proposals from DEFRA for new regulations on the clean-up of contaminated sites. For contamination spread fairly evenly over an area the Agency recommends that a radiation dose rate of 3 mSv per year (3 mSv/y) above background should be adopted as the basis for designating land as radioactively contaminated. This dose rate is comparable to the average natural background radiation dose received in the UK each year (2.2 mSv y-1). For very uneven contamination, perhaps comprising a few widely spaced highly radioactive "hot particles", the probability of an individual receiving a dose might be low, but the dose, if received, may be high. Here the Agency recommends that any decisions on whether the land should be classified as radioactively contaminated should be taken on a case by case basis, with full regard to the likelihood and severity of direct injury should the exposure occur, and practical issues regarding detectability and remediation. If land is designated as radioactively contaminated measures should be taken, where appropriate, to reduce the doses. In some circumstances such measures may not be appropriate for a variety of reasons. Equally, where land is not designated as radioactively contaminated, this would not automatically preclude the use of simple measures to reduce doses. The costs and benefits of remediation should be assessed in both cases – see *Dose Criteria for the Designation of Radioactively Contaminated Land,* Documents of the Health Protection Agency, Radiation, Chemical and Environmental Hazards, RCE-2, March 2006.

[83] Assumed to be released in elemental form.

[84] Includes Ru, Rh, Co, Mo and Tc.

[85] Includes Y, La, Xr ,Nb, Ce, Pr, Nd, Np, Pu, Am and Cm

[86] In this case the release fractions are the aggregate over the 3 hours release with the bulk of the release for the groups Xe-Kr, I and I-Br, Cs-Rb, and Ba-Sr occurring during the first hour, thereafter the release in these groups is assumed to reduce by an order of magnitude for the following 2 hours. For groups Te-Sb and La the release is assume to increase by an order of magnitude following the first hour, and for the Ru group the release remains reasonably constant.

[87] Caution has to be applied when interpreting this and the other tabulated projections for thyroid deaths – COSYMA assumes that 10% of the thyroid incidence will progress to a fatal cancer.

[88] This and the following data depend on the effectiveness of implementing the appropriate countermeasures in time to avoid exceeding the (assumed *aversion*) dose for evacuation and sheltering. Obviously, it would be totally unrealistic to assume that such a large number of individuals (in this particular scenario about 4.75 million) could be evacuated and it is likely that the evacuation dose criteria would be revised once the magnitude of the task had been recognised. For example, reducing the evacuation Emergency Reference Level to the 300mSv upper limit adopted in the UK would reduced to 697,200 maximum, 101,300 Mean and the land area subject to evacuation would be 11,130km^2 Maximum and 3,329km^2 Similarly, iodine prophylaxis reduces to 699,300 Maximum and 127,700 Mean and the land area subject to evacuation would be 11,130km^2 Maximum and 3,329km^2.