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A BRIEF ASSESSMENT OF THE POSSIBLE OUTCOMES OF A TERRORIST ATTACK

ON THE

COGEMA LA HAGUE NUCLEAR REPROCESSING WORKS

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THE VULNERABILITY OF COGEMA LA HAGUE TO TERRORIST ATTACK

SUMMARY

In recent weeks, a hypothetical terrorist attack exercise by an armed insurgent group was conducted at the Areva/Cogema la Hague fuel reprocessing plant near the port of Cherbourg, Normandy. That exercise was based upon the insurgent group gaining access to the nuclear plant although details of the target(s) chosen, the terrorists' modus operandi and, importantly, the radiological outcome have not been provided in any detail whatsoever. However, on 20 October 2005 it is planned to run an emergency exercise in the public areas surrounding the la Hague plant so, it seems on this basis and assuming that the 20 October exercise is the second stage, albeit delayed, of the overall terrorist attack scenario, that Areva/Cogema acknowledge the la Hague plant is vulnerable to terrorist attack.

Other than the date of the public area exercise and that countermeasures outside the plant perimeter will involve sheltering and evacuation of a nursery, primary school and college, very little other reliable information is available, although it is believed that the countermeasure zone will be confined to a few kilometres around the la Hague nuclear plant.

This assessment briefly examines a number of possible targets within the la Hague plant that might, with a sufficiently capable insurgency group within the plant, be available for attack. The targets nominated, and the severity of the attack, have not been chosen to deliver extreme results or consequences. More to the point, is that the targets and the types of incident leading to a radioactive release have been well researched and documented by the international nuclear industry and others. The basic scenarios and outcomes assessed here being:

1) **Irradiated Fuel Flask:** In this scenario a CASTOR-like irradiated fuel flask carrying 7 fuel assemblies is subject to an attack that results in penetration of the flask and disruption and damage to the fuel within. Once the flask has been breached, the modus operandi extends to engulf the flask in a strong fire lofting the radioactive release thereby increasing its dispersion and area of eventual disposition. The health consequence of this scenario, in terms of direct radiation dose exposure and the assumed tolerable level of individual risk of contracting a fatal cancer, extends from 5 to 7 kilometres from the la Hague plant. In other words, individual members of the public out to a downstream radius of about 10km would expect to be immediately evacuated to a lesser risk area.

2) **High Level Waste Tank**: This scenario is based on a real event that took place at the former fuel reprocessing works at Chelyabinsk in the Urals. The la Hague terrorist attack somehow (and the details of how are not given for obvious reasons) manages to duplicate the conditions that resulted in a violent explosion and ejection of around 70 tonnes of high level radioactive fission product waste from a single HLW tank. Assuming a smaller fractional release to atmosphere than that that actually occurred at Chelyabinsk, but in account of the higher burn-up levels of the fuels reprocessed at la Hague, the evacuation countermeasure zone (with radiation dose rates up to 10mSv per day) would rapidly extend at least 100 km downwind spreading a plume of between 10 to 15km width. Because of the unapproachable radiation levels around the ruptured tank, and generally throughout the la Hague plant as a result of the incident, the radioactive release is likely to continue over many hours, if not days, so with changing meteorological conditions and diurnal variations, the Channel Islands and centres of population such as Cherbourg and Le Havre, would require evacuation countermeasures at some time (shortly) following the onset of contamination from the overhead plume.

3) **Plutonium Release:** It is believed that about 55 tonnes of plutonium dioxide are held in store at la Hague. The scenario involving this highly persistent and radiotoxic material is that the terrorists will seek out its location and release a relatively small quantity into the atmosphere, using a combination of explosion (to breach the plutonium store and containers) and fire for its dispersal – the mass of plutonium assumed to be released in this way is set at a maximum of about 25 kg. The aftermath of such an incident requires immediate sheltering out to 110km and the long term commitment to decontaminate the plutonium laden area to return it to some degree of habitable and economic use.

The outcome of this Briefing is disturbing: The prediction is that, once access has been gained to within the la Hague nuclear complex, it is relatively straightforward for the intelligent and well-motivated terrorist group to, first, locate the vulnerable materials and processes, and then since the plant has never been designed to resist such an internal attack, the terrorists could readily set about putting in place conditions that would efficiently disperse the hazard further afield. The French authorities now acknowledge

It is the extent of the *'further afield'* achieved by a terrorist attack that creates the challenge for the French emergency services when making decisions on how to resource the incident and, particularly, on when and where to implement the essential countermeasures of sheltering and evacuation. Of course, the response could be made more difficult, if a second group determined terrorists attacked and disrupted the emergency response itself. Confining this 20 October exercise to the sheltering and evacuation of a 1,000 or so young people, who might actually enjoy the excitement of it all and readily participate, may not be the appropriate test if such a terrorist attack was to occur in reality. If it did, many thousands of individuals would be involved, it may not be possible to order and control so many and the ensuing chaos may disrupt the emergency response and effectiveness in itself.

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THE VULNERABILITY OF COGEMA LA HAGUE TO TERRORIST ATTACK

Greenpeace with knowledge that the French authority planned an off-site emergency exercise for 20 October 2005 following an earlier terrorist (armed insurgency group) attack exercise within the Cogema la Hague plant, instructed Large & Associates to nominate and consider a range of malevolent attacks and outcomes if such were to occur at la Hague.

For this it is assumed that a terrorist cell would have access to sources of reasonable levels of technological expertise in the fields of building construction, industrial chemistry, radiation and radiological impact but, understandably, not included in this brief review are the modus operandi of the attacks, a detailed assessment of the robustness of all of the buildings and processes identified as potential 'targets' at la Hague, nor a complete evaluation of the environmental and health consequences arising from a successful terrorist attack. By staging this second exercise, obviously linked to the earlier terrorist at la Hague, the capability of a terrorist group to create sufficient damage resulting in an off-site radiological situation is, in effect, now acknowledged by the French authorities.

SAMPLE POTENTIAL TARGETS FOR LA HAGUE

The principal activity undertaken at la Hague is the chemical separation of irradiated nuclear fuel. This involves delivery and storage of intensely radioactive fuel from nuclear power plants in France and abroad; the dissolution of the fuel, its chemical separation (reprocessing) into distinct streams of depleted uranium, radioactive wastes of low, intermediate and high-level categories, and fissile plutonium; and the conversion of the plutonium into a dioxide powder for storage at la Hague.

Within these processes and activities the potential terrorist targets include:

- **Highly Radioactive Materials and Substances**: In the form of post-reprocessing residue fission product in the form of a heat generating liquor (HAL) providing the potential for the largest fraction of radioactivity that could be released from any one single source on the la Hague site.

- **Reprocessing and Processing Plants:** Processes and plants that have in place relatively energetic processes and/or which contain high-energy materials, temperature, pressures etc., that could augment the severity of release of radioactive substances within or nearby the plant, including large quantities of hazardous and flammable materials, such as spent tributylphosphate/odourless kerosene (TBP/OK).[1]

- **Plutonium**: Plutonium, as plutonium dioxide (PO_2) powder, very finely divided into small particles under an equivalent diameter of <100 down to <1 microns (PCM) that is highly dispersive and respirable.[2]

- **Irradiated Fuel Deliveries & Storage:** Storage pond buildings hold large quantities spent (irradiated) fuel awaiting reprocessing and there are frequent arrivals of with rail freighted spent fuel.[3]

TERRORIST INTENT AND MODUS OPERANDI

Until the events of 9-11 2001, the design and safeguards of nuclear plants and facilities centred around countering accidental events and human error. For example, plants would be protected against natural hazards, such as earthquake and flood, and engineering breakdown and, to a certain extent, human failure. Severe events, such as accidental aircraft impact were assessed in terms of risk and severity of damage, with the outcome that the risk being of such low frequency that such extreme accidents were considered incredible, that is so unlikely to happen by chance that it was not justified in terms of time, trouble and cost to strengthen or somehow safeguard the plant against these.

Now, following 9-11, hazardous plants have to be assessed in terms of their attractiveness as a target for terrorism, how such plants might be best defended, and whether the tolerability of the radiological consequences has to be raised.

Radiological Targets: It seems quite reasonable to assume that the primary aim of terrorism is, in furthering a cause and/or grievance, to maximise disruption and the impact of the incident. In this respect, the environmental, economic and psychological factors of even a partially successful attack on a nuclear installation is likely to have a major impact, particularly in account of the public perception of all things nuclear being that of *'a fate worse than death'*.

In fact, evidence is now emerging that a terrorist group in the UK had identified a number of UK nuclear facilities as potential targets.[4]

Defending Against Terrorist Attack: In the United States, and it is believed similarly in France, the nuclear plant operators are required to include capability to defend the plant against Design Basis Threats (DBTs) via a series of *Operational Safeguards Response Evaluation* (OSREs) tests. The US about 45% of the OSRE tested nuclear plants failed in that key critical areas had been penetrated by an armed insurgency group, and that for a vehicle bomb approach to the boundary of a plant, between 15 to 20% of US nuclear plants would sustain safety critical levels of damage.[5]

Vulnerability of Nuclear Plants: On the basis that pre 9-11 plants do not include features that specifically defend against terrorist attack and, moreover, being based on countering *accidental* situations there has been little or no account of an intentional and intelligently driven attack that seeks out the vulnerabilities of the nuclear plant and/or process targeted. Obviously, no pre-9-11 commissioned plants were designed to resist the impact of a civil commercial airliner and it has not been possible to modify existing plants to render the structures sufficiently crash resistant.

Potential Radioactive Consequences: The basis adopted for determining the radiological consequences of *accidental* releases of radioactivity is that the accident, form and level of the release would adhere to a prescribed situation and, importantly, that countermeasures would be implemented and effective. This approach of constraining the radiological impact of an accident cannot be conferred on a terrorist attack incident because, first, the terrorist modus operandi might include specific measures and actions that would maximise the release (for example by artificially inducing a high energetic release to increase the dispersion range, and or by introducing some other element to render the radioactivity more volatile) and, second, by somehow impeding the preplanned countermeasures (for example by the setting of a diversionary explosive device).

TARGETS AND CASE SCENARIOS

1) Attack on a Single Spent Fuel Flask

This scenario involves a stationary Type B(M) CASTOR type rail transportation flask carrying spent fuel awaiting reception processing into the la Hague plant. The flask is assumed to be carrying 7 PWR fuel assemblies of 5 year cooled (post reactor core) 33GWd/Ut fuel of 3.2% enrichment, totalling ~50TBq of radiologically significant radionuclides.[6]

There is now an emerging field of literature on the response of irradiated uranium dioxide fuel and fuel transport flasks when subject to explosion,[7,8,9,10,11] although these are drawn from a variety of flask designs. Following events of 9-11, terrorist attack against any nuclear consignment in transit cannot be discounted. Certainly, some national and international terrorist groups have the knowledge and skills to manufacture powerful ordnance sufficient to breach the carrying vehicle and the flask itself. Also, there is a variety of anti-tank and armour piercing weapons available in the military domain (and supposedly on the international arms black market) with virtually all of these weapons capable of breaching the typically carbon steel flask walls.[12] Certain armour piercing rounds comprise two stages, first a high brisance armour piercing stage and, once that the armour has been pierced, a second stage firing of high explosive intended to obliterate the internals of the target. Most anti-tank weapons and their rounds are portable and capable of being handled by one or just two individuals in urban environments.[13]

In the early 1990s the West German Federal Ministry of Environment, Nature Protection and Reactor Safety (BMU) required physical testing of transportation flasks against shaped explosive charge, with the practical trials were carried out in the Centre d'Étude de Gramat (CEG) in France under the supervisions of BMU in 1992, although little further information on these trials is available.[14] Similar trials simulating sabotage on irradiated fuel flasks were undertaken in the early 1980s and 1990s in the United States.[15] In the United Kingdom, the National Radiological Protection Board undertook the analysis of a radioactive release from an irradiated PWR fuel flask that had be hypothetically subject to terrorist attack by an armoured piercing round, thus setting the parameters for a radioactive release initiated by explosive conditions[16] - the release fractions adopted in this NRPB study ranged 1×10^{-4} to 1×10^{-3}.[17]

Analysis of the dispersion following an explosive attack on a flask of irradiated fuel utilized data from a source that is no longer in publication.[18] However, others referring to this work give the release of respirable-sized particles from the flask to range from 1×10^{-6} to 1×10^{-3} for actinides in oxide form (which is generally the level assumed for other fission and activation products). In the main, the experimental trials were conducted on the robust CASTOR design of irradiated fuel transport flask with side walls of 150 to 200mm solid carbon steel and of about 100 tonnes weight and, incidentally, compliance with the IAEA Type B(M) requirements would not necessarily provide a uniform resistance to explosive attack across the range of flask designs. Penetration of the CASTOR flask was caused by a shaped explosive charge with the aerosol being generated primarily by shock loading to the fuel pins, whereas an armour-piercing round would be likely to penetrate to inside the flask to deliver a second shot of explosive energy at high temperature once it had penetrated the armoured skin.[19]

In summary, an explosive disruption followed by fire provides opportunity for increased radioactive release from the fuel: First, as a puff of aerosol of fuel particles aerosolised by the explosive force and second, as prolonged as the fire itself, as further particles of the damaged and likely oxidising fuel are entrapped and swept into the rising plume of the fire.[20, 21] On this model, the hypothetical terrorist attack on the stationary flask at la Hague comprises an explosive event that penetrates the flask outer casing and inner fuel basket, either by placement of shaped charges or attack with an armour piercing rocket propelled grenade, both scenarios severely damage the fuel within the flask.

The initiating explosive phase results in a dispersed source puff release lasting overall 3 minutes and dispersing at an effective release height of 25m for about 3 minutes. Immediately following the explosion a severe fire is deliberately set to prolong the release, with this second phase lasting for 90 minutes at an effective release height of 2m. Release fractions for the two release phases are, for the initial puff, 0.3 for noble gases, 0.001 for caesium, ruthenium and all other fission products and 0.001 for actinides, and for the fire 0.0003 for caesium and ruthenium, 0.000001 for all other fission products and actinides. All elements (except the noble gases) are release in the form of 1μm AMAD aerosol.

Assuming a steady wind direction from the south-west, the risk of early effects is forecast with no early mortality occurring, but with the following average individual risks of a contracting a fatal cancer per year throughout the remaining lifetime (above natural incidence):

	AVERAGE INDIVIDUAL RISK OF FATAL CANCER PER REMAINING YEAR (AVERAGE RISK TAKING ACCOUNT METEOROLOGICAL PROBABILITIES)		
DISTANCE km	FIRE COMPONENT	PUFF COMPONENT	TOTAL RISK
0.1	10.0 E-4	7.2 E-3	7.30 E-3
5.0	7.6 E-5	13.2 E-4	13.96 E-4
1.0	24.8 E-6	5.2 E-4	5.45 E-4
10.0	6.0 E-7	20.0 E-6	20.60 E-6
20.0	20.0 E-8	7.2 E-6	7.22 E-6
50.0	4.8 E-8	20.8 E-7	21.28 E-7

Other than in the immediate locality of the flask, say within 50 or so meters, the magnitude of the combined puff-fire release is such that the largest predicted radiation dose is below the threshold normally assumed for the incidence of early health effects, so the health impact if limited to stochastic effects, of which cancer dominates. The average radiation dose exposures of individuals remaining in the deposition area close to the flask (at 0.1 km) would be about 150mSv, at 1 km 28mSv, at 10 km 4mSv and at 20 km 1.4mSv.

The *Institut de Radioprotection et de Sûreté Nucléaire* (IRSN) sets out the safety distances to be implemented as a first response to a number of incident scenarios – this safety perimeter is intended to enable emergency response teams to establish the so-called *reflex* distances of 100, 500 and 1,000m appropriate to the incident circumstances.[22,23] Implementing these reflex distances would not prevent members of the pubic receiving significant radiation dose beyond the 1km reflex extreme.

2) High Level Waste Tank Rupture and Dispersion

The second hypothetical terrorist attack within the la Hague complex involves a well planned demolition of the containment of a high level radioactive waste tank. This scenario is drawn from what is now known to have been a real accident at the former Soviet reprocessing works at Chelyabinsk 65 (Kyshtym) in the Urals in 1957.

The high level liquor stored in the waste tanks comprises a complex mix of highly radioactive finish products yielded from the irradiated fuel during the chemical separation process. The contents of each tank requires continuous cooling, agitation and off-gas venting to maintain the contents stable. At Chelyabinsk one the underground stainless steel storage tanks held in concrete trenches, holding about 300m^3 of HLW of much the same radionuclide content as that at la Hague, developed a fault with its cooling heat exchanger which was shut down in belief that that the tank was cool enough not to require continuous cooling. Then, it is believed that evaporation of the nitrate solution in the tank allowed a build-up of nitrates and acetates on the surface of the tank contents, in contact with air, before a spark from monitoring equipment detonated the contents on 29 September 1957, wit the explosion sufficient to entirely rupture the containment and eject the covering earth bund.

The Chelyabinsk incident released about 70-80t of wastes with a total activity of about 74.E+16Bq radioactivity of which about 70.E+16 Bq was deposited in the immediate area of the explosion site and about 7.4.E+16 Bq was dispersed over a large area downwind. The area with significant deposition of at least 7.4E+10 Bq/km2 extended 100 km downwind and was 10 km wide, for a total of about 1,000 km^2 - this level of contamination gives an exposure rate about 10mSv per day rate - over a period of 18 months to 2 years about 10,000 individual members of public were completely evacuated. It is believed maximum accumulative whole body exposures were as high as 520mSv from radionuclides in food and water; some studies showed blood count changes, but no acute radiation injuries were observed. Of the initial 1000km^2 land withdrawn from use, it is believed that after extensive ploughing-in programmes, about 200km^2 remains out of use for agricultural and is presently designated as a little-used military vehicle and tank testing range.

The release from Chelyabinsk 65 involved reprocessed fission products drawn from the then Soviet nuclear weapons programme. To maximise fissile plutonium production from spent fuel, the fuel burn-up (the amount of time in the reactor core and, hence, its radiotoxicity) is relatively low (at about 2000 to 5000 GWd/Ut). At la Hague, where commercial spent fuels of typically 33 to 48 GWd/Ut are reprocessed the fission product inventory is much higher so a relatively small volumetric release could have very significant environmental and health impacts.

It is not the purpose of this briefing to provide details of how a terrorist group might contrive to, first, breach a high level waste tank containment and, either simultaneously or following, create a sufficiently energetic situation to loft oxide particles into the atmosphere for dispersion and eventual disposition – such an action might require the insurgency group holding its position within the la Hague complex for about one hour or thereabouts to see through its preparations and the final suicidal act of destruction. Whatever, based on the 1957 Chelyabinsk incident and with a smaller release fraction of the tank contents, say less than 1%, and with the prevailing meteorological conditions on the peninsular (winds driving from the South-West), the dispersion patterns and levels of radiation would require short-term sheltering followed by evacuation of nearby centres of population, including Cherbourg and le Havre. In the later stages of the release, which is likely to drift on from several days, the diurnal switch to winds from on-shore could also put the Channel Islands at risk of exposure and longer term contamination.

3) Plutonium Dioxide Dispersal

Previously published work dealing with plutonium dioxide dispersion in the aftermath of a transportation incident[24] of a consignment of plutonium dioxide (PuO_2) from la Hague. The results of the transportation study, which includes a number of terrorist scenarios, are readily adapted to a terrorist incident within the la Hague plant.

The plutonium dioxide powder derives from reprocessing of commercial (light water – PWR and BWR) irradiated reactor fuel at the la Hague facility. Assuming the plutonium to be extracted from PWR spent fuel at an average of 47.5GWd/tU burn-up, the isotopic composition would be similar to:

Radioactive Inventory and Composition of Plutonium Dioxide[25]

ISOTOPE	SPECIFIC ACTIVITY Bq/g	% COMPOSITION	HALF-LIFE Years	DECAY HEAT kw/kg
Pu-238[26]	6.23E+11	3.1%	88	0.560
Pu-239	2.28E+9	52.4%	24390	0.002
Pu-240	8.39E+9	24.5%	6537	0.007
Pu-241	4.81E+12	12.2%	15	0.004
Pu-242	1.45E+8	7.8%	387000	0.0001
Am-241	(included in Pu-241)		458	0.114

In one hypothetical scenario analysed in this study, a release of plutonium dioxide in the form of fine, respirable-sized aerosol[27] is considered in terms of its health impact in the short, interim and, particularly, longer terms. Although such a release to the environment will inevitably result in contamination of ground and other surfaces, of open watercourses and foodstuffs, these sources of uptake are shown to be, in the interim and longer terms, manageable by decontamination, restriction and/or removal from use and/or access.

Generally, the health impact from plutonium exposure may be categorized as two outcomes:

There are the illnesses and deaths due to high exposures in the immediate vicinity of the point of release, occurring within weeks, months or a year or so after exposure. This incidence would be expected to occur in individuals immediately caught up in the release, such as those operating and accompanying the consignment convoy and, in the immediate aftermath of the incident, those emergency services personnel attending who will have close contact with the scene of the incident. Once that the nature of the hazard has been identified, unprotected individuals can be evacuated and emergency services personnel adopt relatively straightforward protective measures and procedures to minimize their individual exposure.[28]

There is also risk of longer-term cancers[29] arising from relatively low levels of exposure via uptake, reconcentration and retention in body organs. The exposed population at risk is remote from the immediate scene of the incident, receiving their exposure by the passing of the radioactive plume emitting from the point of release into the atmosphere that might, depending on physical and chemical conditions generated in the incident and, particularly, the meteorological circumstances, extend kilometres and tens of kilometres from the scene. For these individuals, and there may be many if the developing plume extends to urban areas, countermeasures to limit the radiation uptake can only realistically involve sheltering and controlled evacuation. Delays in implementing effective countermeasures, or with large numbers of public choosing not to follow advice (ie disorganized and chaotic self-evacuation) could result in significant numbers and levels of exposure. Also, there is uncertainty in the actual relationship between the plutonium exposure received (via respiration)[30] and the cancer risk (that is the 'cancer causing dose'), because some predictions include (for weapons-grade plutonium inhalation)[31] a somewhat subjective 'high-risk factor'[32] of 0.032 milligrams and a 'low risk factor' of about 1.4 milligrams.

In the following analysis, the computer model (COSYMA) adopts the current ICRP recommendations[33] for morbidity and mortality factors. ICRP adopts the *effective dose equivalent* (EDE) that gives the relative probability of the onset of a fatal cancer derived on a uniform exposure over the whole body.[34] To project the consequences from a release of plutonium dioxide from the consignment, the universal assumption adopted is that the health risk is linear to radiation exposure so, applied to populations, the expectation is that whatever the number of the exposed population the same human health consequences (numbers) would result.[35]

Such computer routines provide a relatively reliable means of forecasting projected radiation and contamination levels and, from these, extrapolated health impacts. However, some caution has to be applied when considering the long-term health detriment because of the influence of other health and environmental factors. Noting that lung cancer dominates the long term health fatalities of a respired plutonium exposure take, for example, a plutonium release incident that results in a long term exposure CEDEs of 0.1Sv could be expected to result in a 0.5% chance of a (late) lung cancer fatality per non-smoking person, whereas smokers exposed to the same long term exposure would be highly likely to contract a fatal cancer.[36] This disproportionality, particularly in a society where a significant proportion are smokers, serves to mask the impact of a radioactive release that would have occurred by the time the release-related fatalities occur, in 15, 20 to 30 years after the event.

The French authorities do not publish levels of exposure (or airborne concentrations, etc) at which countermeasures are to be implemented.[37] However, if and when such countermeasures are implemented these would be expected to be similar to the well defined system in the United Kingdom of Emergency Reference Levels (ERLs) giving the exposures (mSv) at which countermeasures (namely evacuation and sheltering) are i) prepared for and ii) triggered.[38]

Graph 1 shows extent of the UK system[39] of emergency planning applied in the aftermath of a release – under the UK regulations pre-prepared off-site emergency measures would have to be implemented by the transport carrier over any area in which the projected 1 year dose exceeded 5mSv. For this release the mean 1 year effective dose requires actions to protect members of public out to 2.8km [— —], although under moderately stable climatic conditions (Pasquill's F classification) the UK derived emergency zone would extend to 7 to 8km. Also in the UK, there are recommendations[40] that relate the dose to evacuation and relocation actions – these are 0.5Sv lung and 0.05Sv effective dose for evacuation [—•—] and relocation and for return 0.025Sv effective dose projected over one year of reoccupation. In the example of Graph 3 these guidelines an area about 1km downwind would require evacuation, although this zone could extend considerably under atmospheric stability F conditions.

Graph 2a shows a dose derived threshold system (the Emergency Reference Levels – ERLs) that is adopted in the UK. The system requires individuals to be sheltered between the upper and lower limits of 3mSv and 30mSv and evacuated between 30mSv and 300mSv.[41] If this system is applied to the mean exposures projected in **Graph 2a**, then evacuation would be required to be implemented at about 1km, be considered for implementation out to 7km and, similarly, sheltering would have to be in place between 7km and 110km. Once again, these countermeasure zones would extend considerably under atmospheric classification F conditions.

The UK's system of emergency preparedness centres around a release dominated by β-γ emitters where the principal dose uptake pathway is external exposure. In this case, where the radiation uptake is in[illegible] organ α deposition, via respiration, the long term dose is committed to very early in the release sequence and countermeasures, other than an immediate mass evacuation ahead of the arrival of the contaminated plume, have little effect. Nevertheless, the COSYMA analysis assumes that countermeasures will be implemented following specified delays in initiating each counteraction – these countermeasures apply just to population controls (ie evacuation, sheltering, food bans, etc) and not to means by which the magnitude and/or radioactive inventory of the release might be suppressed. The countermeasure of evacuation is triggered on a dose basis, whereas sheltering is implemented on a dose and geometrical area basis. The initial delay in initiating any countermeasure is assumed to be 2 hours, for evacuation there is assumed a 1 hour drive-out time during which there is no radiological protection (ie shielding factor = 0), and a 6 hour lapse before any activity is removed from contaminated individuals. Similarly, for sheltering there is a 3 hour delay before sheltering, sheltering is commenced within the area extending out to 18km and/or where the exposure is predicted at 5mSv, and sheltering is limited to 4 hours, with a shielding factor of 50%. For an urban situation, 90% of the population are assumed to be indoors at the time of the incident. Relocation of individuals at a short term exposure greater that 50mSv is assumed to occur at 5 days. The model assumes there to be effective controls, in the longer term, in foodstuffs and potable water rendering the ingestion, etc., uptake to a minimum.

Also, the somewhat clinical approach to orderly countermeasure implementation assumed by COSYMA is unlikely to apply in practice. Once aware of the incident, members of the public, themselves, are likely to commence evacuation by any means available – indeed, it may be the implementation of limited countermeasures by the authority that might trigger a mass self-evacuation. If so, the outcome might be a greater exposure to a larger number of individuals if many of these individuals obliviously pass into areas under the developing release plume, they might be held there because of traffic congestion, and the numbers exposed might extend further afield as contamination is spread in an uncontrolled way by individuals and vehicles.[42]

Graph 4 relates the levels of ground contamination at which, in the UK, evacuation is recommended, thereby extending out the evacuation zone to about 3.8km from the point of the incident. With the principal uptake route being inhalation, it is the resuspension of plutonium from surfaces that provides the greatest part of dose from contaminated surfaces but, as the plutonium binds into the surfaces (or is washed away and blown from exposed areas) the amount resuspended (and the dose deriving therefrom) reduces progressively by a factor of 10^3 over the 12 months following the incident.

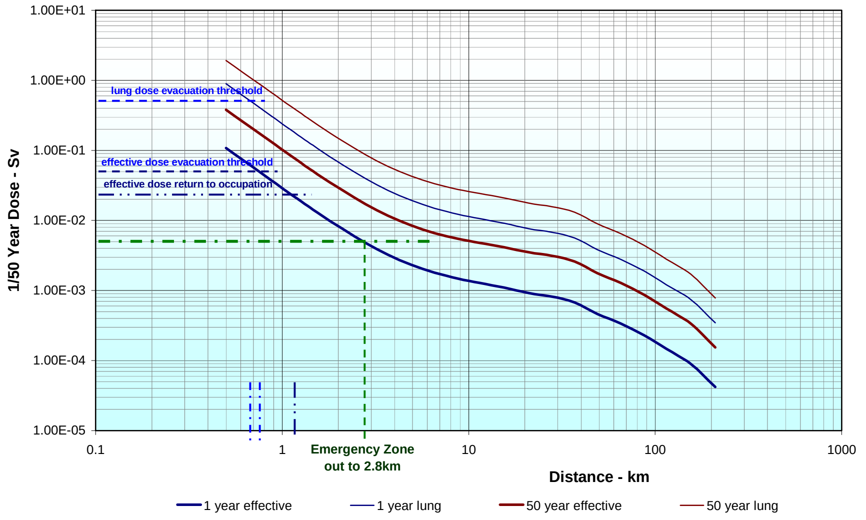
Graph 5 applies another sheltering trigger adopted in the UK that derives directly from the assessment of the time integrated plume concentration. For the release and fire conditions applied to this scenario, the sheltering area corresponds to the ERL defined system of **Graph 2a**. The impracticality of this particular approach is that the fire duration has to be assessed very early on in the incident.

Based on the UK practice, the countermeasure radial distances (again for the mean dose assessments) for the scenarios considered are:

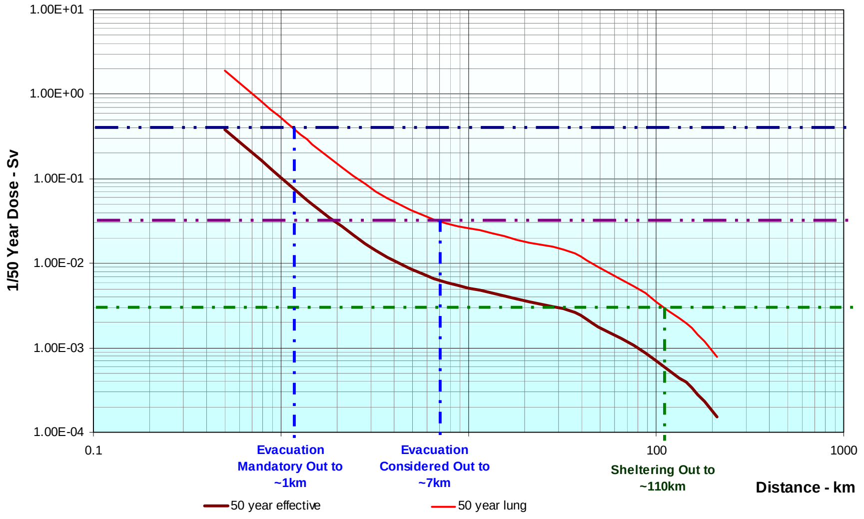
Countermeasure Radial Distances

	i) **595g**	ii) **1.785kg**	iii) **5.355kg**	iv) **10.710kg**	v) **25.220kg**
COUNTERMEASURE	**FIRE**	**FIRE**	**EXPLOSION + FIRE**	**FIRE** **3.5E-02 RELEASE**	**FIRE** **~0.1 RELEASE**
SHELTERING OUT TO	5km	12km	40km	60km	110km
EVACUATION OUT TO	<1km	1.5km	2km	NA[43]	NA

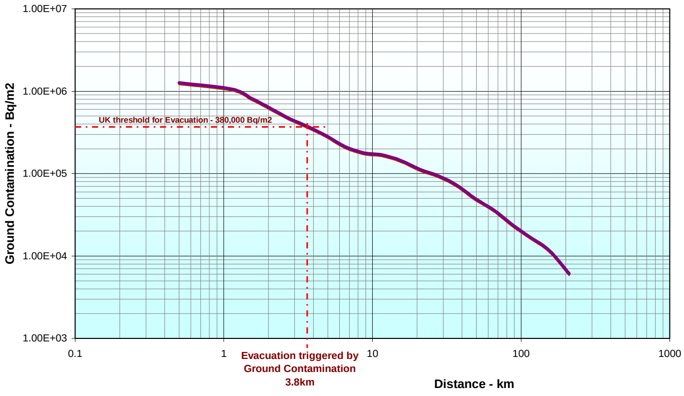
Graph 1 - 25.22kg Dose Comparisons



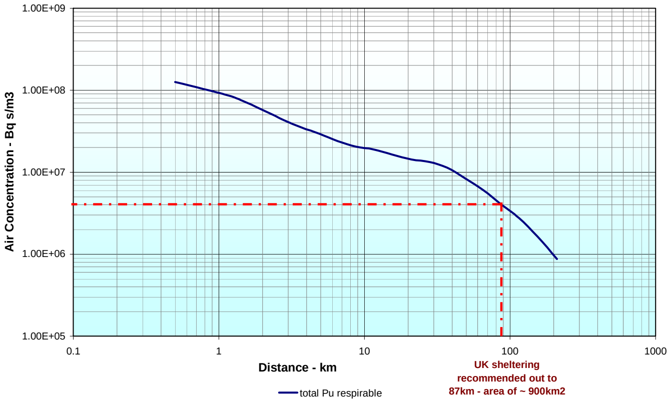
Graph 2a - [redacted] 25.22kg ERLs



Graph 4 - [redacted] 10.71kg Ground Contamination



Graph 5 - 10.71kg Time Integrated Air Concentration



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[1] There is approximately than 1,400 m^3 of highly radioactive glass, more than 10,000 m3 of intermediate rated radioactive waste hulls and nozzles, and more than 11,650 m^3 of radioactive sludge (of which only 20% is stabilized), as well as thousands of cubic meters of other less radioactive wastes and unknown quantities of chemical products, of which some are highly flammable, such as the TBK solvents.

[2] Approximately 55 tonnes of plutonium dioxide was held at la Hague in 2001 – IAEA, INFCIRC/549/Add.5/3, March 2001

[3] At 30 June 2001, about 7,500 t of various types of spent nuclear fuel was held over 5 water filled pools.

[4] See 17 October 2005,

http://www.sundaymirror.co.uk/news/news/tm_objectid=16254342%26method=full%26siteid=62484%26headline=nuke%2dbomb%2d%2dplot%2d-name_page.html

[5] Large J H The *Implications of 11 September for the Nuclear Industr*y, United Nations for Disarmament Research, Disarmament Forum, 2003 No 2, pp29-38 - http://www.largeassociates.com/terrorismUNDisarmament.pdf

[6] During normal transportation conditions the uranium fuel oxides (UO_2) are stable so there is little risk of further oxidation to the higher oxide states. Once that flask surety has failed the remaining containment is limited to the fuel cladding, which comprises a thin sheath of zirconium alloy (zircaloy) forming the fuel pin that encapsulates the stack of fuel pellets. Zircaloy is not reactive at low temperatures but violently exothermic reactions occur in the region of 850^{o}C to 1,000^{o}C, particularly in the presence of superheated steam, evolving hydrogen which can subsequent rapidly burn or explode. The melting point of the UO_2 refractory ceramic is approximately 2,700^{o}C but surface oxidation initiates at a significantly lower temperature of around 250^{o}C if the fuel is exposed to air. At relatively low temperatures exposed fuel pellets produce respirable-sized particles[6] following relatively short exposure periods. For example, 1.87% of the initial mass was rendered respirable-sized particulate when oxide fuel is exposed at 430^{o}C for 15 minutes, as compared to 0.01% at 800^{o}C. Pulverisation at the lower temperature could result in substantial particulate release in smouldering type fires that could last for many hours.

[7] *Behavior of Transport Casks Under Explosive Loading* Didier Brochard, Bruno Autrusson, Franck Delmaire-Sizes, Alain Nicaud, Institut de Protection et de Sûreté Nucléaire; F. Gil, CS Communications et Systems Group; J.M. Guerin, P.Y. Chaffard, F. Chaigneau, CEA/DAM Ile de France

[8] Yoshimura M, Luna R, *Spent Fuel Cask Sabotage Investigations,* Richard Yoshimura, Manuel Vigil, Robert Luna, SNL – see also *International Initiatives in Transportation SabotageInvestigations* Richard, SNL; Bruno Autrusson, Didier Brochard, IPSN/DSMR/SATE; Gunter Pretzsch, GRS; Frances Young, J.R. Davis, US NRC; Ashok Kapoor, US DOE, F. Lange, Gesellschaft für Anlagen-und Reaktorsicherheit - Dietrich, A.M., and W.P. Walters*, Review of High Explosive Device Testing Against Spent Fuel Shipping Casks*, Prepared by U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, Prepared for U.S. Nuclear Regulatory Commission, 1983.

[9] Halstead R, *Nuclear Waste Transportation Terrorism and Sabotage: Critical Issues*, State of Nevada, Agency for Nuclear Projects; James David Ballard, Grand Valley State University, School of Criminal Justice; Fred Dilger, Nuclear Waste Division, Clark County, Nevada - Audin, L., *Analyses of Cask Sabotage Involving Portable Explosives: A Critique*, Draft Report, Prepared for Nevada Agency for Nuclear Projects/Nuclear Waste Project Office, 1989

[10] Schmidt, E.W., Walters, M.A. and Trott, B, *Shipping Cask Sabotage Source Term Investigation*, Batelle Columbus Lab., Columbus, NUREG/CR-2472, BMI-2095 (Oct. 1982)

[11] *Experiments to Quantify Potential Releases and Consequences from Sabotage Attack on Spent Fuel Casks* Florentin Lange, Gunter Pretzsch, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH; Eugen Hoermann, Dornier GmbH; Wolfgang Koch, Fraunhofer Institute for Toxicology and Aerosol Research

[12] Current portable anti-tank weapons are:

WEAPON	**COUNTRY**	**WEIGHT**	**RANGE**	**WARHEAD Ø/KG**	**RMOUR PENETRATION**
Milan Anti-Tank Missile	France	32 kg	2000 m	133 mm/3.12 kg	>1000 mm
Eryx Anti-Tank Missile	France	21 kg	600 m	160 mm/ 3.8 kg	900 mm
Panzerfaust 3 Anti-Tank Launcher	Germany	13 kg	300 m	110 mm/NA	>700 mm
Folgore Anti-Tank System	Italy	21 kg	4500 m	80 mm/3 kg	>450 mm
Apilas	South Africa	9 kg	330 m	112 mm/NA	>720 mm
RPG-7 Anti-Tank Launcher	Soviet Union	11 kg	300 m	85 mm/NA	330 mm
C-90-C Weapon System	Spain	5 kg	200 m	90 mm/NA	500 mm
AT-4 Anti-Tank Launcher	Sweden	7 kg	300 m	84 mm/NA	>400 mm
Carl Gustav M2 Recoilless Gun	Sweden	15 kg	700 m	84 mm/NA	>400 mm
LAW 80 Anti-tank Launcher	U.K.	9 kg	500 m	94 mm/NA	700 mm
M72 66mm Anti-tank Launcher	USA	4 kg	220 m	66 mm/NA	350 mm

SMAW	USA	14 kg	500 m	83 mm/NA	>600 mm
AT-8 Bunker Buster	USA	8 kg	250 m	84 mm/NA	NA
Superdragon Anti-tank Missile	USA	17 kg	1500 m	140 mm/10.07 kg	>500 mm
TOW 2 Anti-tank Missile	USA	116 kg	3750 m	127 mm/28 kg	>700 mm
Javelin AAWS/M	USA	16 kg	2000 m	127 mm/NA	>400 mm

[13] The MI6 intelligence agency building attack in London on 21 September 2000 used a Russian-built RPG Mk 22 anti-tank weapon which has a range of 250m for a 72.5mm diameter self-propelled round – this weapon takes about 10 second to prepare, aim and discharge – the round has a two stage charge, first armour piercing penetration than a pop-off explosive grenade.

[14] The Federal Ministry of Environment, Nature Protection and Reactor Safety (BMU) instructed Dornier, Friedrichshafen to organize the trials and supervise the whole project. The Fraunhofer Institute for Toxicology and Aerosol Research (FhG-ITA), Hanover, designed and carried out the aerosol measurements. The trials were carried out in the Centre d'Étude de Gramat (CEG) in France in 1992 which is a research facility where missiles which include depleted uranium are tested for military purposes.

[15] *Physical Protection of Shipments of Irradiated Reactor* Fuel, NUREG-0561, Rev. 1, 1980

[16] Shaw K, *The Radiological Impact of Postulated Accidental Releases during the Transportation of Irradiated PWR Fuel through Greater London*, NRPB-R147, 1983

[17] More recently, there is one specific research paper that quantifies the release fraction of irradiated fuel following breach of the containment flask by an explosive charge, working on the basis of the quantity of respirable spent fuel aerosol that might be produced by a terrorist attack. The experimental-based work yields two relevant source terms that lead to values of 6×10^{-5} to 8×10^{-4} g of respirable surrogate spent fuel aerosol released from the cask per gram of surrogate fuel matrix disrupted by a sabotage attack using high-energy device acting on the exterior surface of the flask. That the explosive charge was not in physical contact with the fuel assemblies and the aerosol/particulates given off primarily derive from the shock and blast loading and the release fractions relate only to the quantity of fuel that was expelled from the flask (ie excludes fragments and particles of fuel remaining in the flask). The surrogate fuel used in this work comprised unirradiated U^{238} sintered oxide pellets sheathed into fuel pins and arranged as fuel assemblies for which the results were then factored up (x3) to model spent or irradiated fuel.

[18] Elder H, *An Analysis of the Risk of Transporting Spent Nuclear Fuel by Train*, Battelle, PNL-2682, 1981

[19] The resulting aerosol formed, particularly the range and dominance of a particle size, is dependent upon the amount of particles present at the time of fuel pin cladding failure, the dispersion of these particles within the fuel pellets, the inherent size of the particles in the matrix of the fuel, along with any retention or 'plating out' and retention of fuel particles on the surfaces of the fuel assembly, flask walls and breach through the vehicle container. The ejection of the aerosol is via those particles caught up in the highly turbulent jet stream that puffs out of the flask internals during the short spell when external and internal pressures are equalizing. In the reported trials the aerosol release was very short term, with less than 1% of the <12.5µm particles being released after 30 seconds. However, this period of release extends considerably if the flask sustains greater damage and/or if fire breaks out in or about the vehicle trailer unit.

[20] The release fractions drawn from previously published work might be summarised as follows:

CONDITION	**RELEASE FRACTION**	**COMMENTS**
Fire at 800^{o}C	1.E-4	
Impact at 0.1J/g	5.E-3	Containment of the fuel unknown
Explosive Excellox Flask	1.E-4 to 1.E-3	
ditto	6.E-5 to 8.E-4	Adapted from spent to surrogate fuel
Fire 2 hours	3.3.E-7	ditto
Explosion	1.E-1	Terrorist scenario on plutonium dioxide powder in FS47 flask shipment

[21] Another very significant factor that determines the health consequences of the radioactive release is the particle size. In the reported trials, the surrogate fuel gave off a range of particle sizes of which about 25 to 50% (depending on the flask pressure) were of respirable size (say <12.5).Only particles with aerodynamic equivalent diameters AED < 10 mm are considered to be respirable and to contribute to radiation exposure via inhalation. For other exposure pathways such as groundshine the deposition velocity which depends on the aerodynamic diameter influences the level of ground contamination from dry or wet deposition. Many of the works cited above were analyses or analytical extensions of measurements of surrogate spent (irradiated) fuel aerosols produced in sabotage-like configurations. The correlation between various test has been poor with a projection range of approximately 10 (0.7 to 12) between the lowest and highest estimates of the ratio of spent fuel respirable aerosol mass to surrogate respirable aerosol mass.

[22] Rancillac F, Sert G & Cleach T *Reflex Safety Distances to be Implemented in the Event of a Transport Accident Involving Radioactive Material*, Institut de Radioprotection et de Sûreté Nuclé, IAEA-CN-101/107, Vienna 2003 – this also accounts for terrorist action.

[23] In the UK, the Ministry of Defence issues guidance under the Local Authority & Emergency Services Information (LAESI) for exclusion and evacuation zones to be adopted in the event of a nuclear weapons accident – these extend from 600m to 5km. Also, there is a system of immediate action advice for those in charge of vehicles carrying plutonium, the TRANSPORT EMERGENCY CARD (TREMCARD) advises an immediate evacuation zone of 1km from the point of the accident, downwind over a 45^{o} arc.

[24] Large J H, *Potential Radiologial Imapct and Consequences arising from Incidents Involving a Consignment of Plutonium Dioxide under Transit from COGEMA la Hague to Marcoule/Cadrache*, Greenpeace International,), July 2004

[25] The isotopic composition of plutonium in spent PWR fuel irradiated at 47.5MWd/tU burn up with 5 years post reactor core decay - see C. Bataille, R. Galley, *L'aval du cycle nucléaire*, tome 1, Rapport de l'Office Parlementaire d'évaluation des choix scientifiques et technologiques (OPECST), Assemblée nationale, juin 1999

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[26] The most radioactive isotope of plutonium is plutonium-238, with an 87-year half-life, a by-product of the production of fissile plutonium-239. Although it is the most radioactive plutonium isotope, its specific activity (radioactivity per gram) is about 1/3 of the radioactivity of the fission products strontium-90 and cesium-137, and about 15% of the specific activity of tritium. Plutonium-239, half-life 24,600 years, has less than 1% of the specific radioactivity of plutonium-238.

[27] The particles making up the aerosol are considered respirable at 1.0µm median equivalent aerodynamic diameter (AMAD), although higher AMADs are sometimes adopted.

[28] Essentially, respiratory protection in the form of breathing apparatus and the appropriate filter masks.

[29] For inhaled aerosol, the human receptor is assumed to retain a proportion within the lung tissue (about 15 to 20%), a part of this being transferred to and absorbed by other organs, particularly bone surfaces. The principal hazard from exposure to lower concentrations of plutonium dioxide aerosols is an increased probability of cancer of the lung and of other plutonium absorbing/reconcentrating organs. A rough and ready-reckoning guide of the long term (30 year) risks arising from inhalation uptake of alpha emitting isotopes is that of 1 death per 15 Sievert (Sv) and a range of 10 to 120Sv for lung and bone respectively, which for Pu-239 and Pu-240 mixes (ie weapons-grade plutonium) converts to a total cancer risk of 3 to 11 deaths per milligram inhaled (Fetter S & Hippel von F, *Hazard from Plutonium Dispersal by Nuclear Warhead Accidents*, Science and Global Security, V2, No 1, 1990). Another authoritative source (Taub M *Plutonium*, Pergamon Press, 1964) gives a lower figure of 0.89 milligram, or about 1.12 deaths per milligram inhaled of weapons-grade plutonium dioxide.

[30] For respiration that is by far the dominant risk path – for example, using ICRP 60, the respiration or inhalation dose is 0.08mg/cancer compared with 480mg/cancer for the ingestion pathway. The short-term lethal inhalation dose is around 20mg and, on average, a person engaged in light activity breaths around 1m^3 of air per hour so to receive an acute dose in the short term (say in a matter of hours of exposure) the air breathed must be very heavily contaminated with plutonium.

[31] The previous studies referred to, considered so-called *weapons-grade* plutonium made up of Pu-239 and about 6% Pu-240. For the *reactor-grade* the inclusion of other plutonium isotopes, particularly Pu-238 and Pu-241, increase both lung and bone (and other organs) mortalities with the cancer causing exposure to plutonium dioxide being conditionally arrived at a quantity of 0.2 milligrams inhaled (Cohen L B, *Hazards of Plutonium Toxicity*, Health Physics, V32, 1977) that is 5 deaths per milligram. Another source (Sax, Dangerous Properties of Industrial Materials, 4th Ed, Van Nostrum, 1975) simply factors the toxicity of weapons-grade to reactor-grade plutonium by a factor of x4.4 and another (IAEA Database - http://www-rasanet.iaea.org/reference/doselimits.htm - see also Xavier Coeytaux, et al, *Les Transports De L'industrie Du Plutonium En France. Une Activité À Haut Risqué*, WISE, February 2003) details the following which corresponds to about 4x the higher bone cancer factor adopted for weapons-grade plutonium.

Dose Exposure per milligram PuO_2 Inhaled

ISOTOPE	UPTAKE MODE	EXPOSURE Sv/Bq	EXPOSURE Sv/mg
Pu-238	inhalation	1.6E-5	309
Pu-239	inhalation	1.6E-5	19
Pu-240	inhalation	1.6E-5	33
Pu-241	inhalation	1.7E-7	99
Pu-242	inhalation	1.5E-5	170

[32] Davis, J *Nuclear Accident Aboard a Naval Vessel Homeported at Staten Island, New York, Quantitiative Analysis of a Hypothetical Accident Scenario*, Environmental Studies Institute, 1988

[33] International Commission on Radiological Protection – ICRP 26, 30, 48 (plutonium and related elements), 68, 72 (revised metabolic models) and 60 (1990)

[34] Essentially, the ICRP EDE points to 9 cancer deaths per milligram of respirable-sized weapons-grade plutonium inhaled.

[35] That is independent of whether 100 or 1000 individuals share the exposure of, say, 1 milligram, the expected 3 to 11 deaths would apply to either group.

[36] Using rounded numbers for clarity, the relationship between smokers and non-smokers is:

RELATIONSHIP OF CANCER EFFECTIVE DOSE EQUIVALENT (CEDE) TO LATENT CANCER FATALITIES (LCFS) LONG TERM CEDE – 50 YEARS			
NON-SMOKERS CEDE Sv	**NON-SMOKERS PROBABILITY OF LUNG CANCER FATALITY**	**NON-SMOKERS LCF (WITH LONG TERM DUST RESUSPENSION)**	**SMOKERS LCF (WITH LONG TERM DUST RESUSPENSION)**
10	0.5 50% chance of fatal cancer	0.8 80% chance of fatal cancer	1 100% chance of fatal cancer
1	0.05	0.08	1
0.1	0.005	0.008	1
0.01	0.0005	0.0008	0.16
0.001	0.00005	0.00008	0.016
0.0001	0.000005	0.000008	0.0016

[37] Memo, *Plutonium Transports France - Answers to John Large*, Wise Paris, 30 September 2003.

[38] The ERLs are expressed in terms of projected whole body exposure in dose equivalent (mSv) for sheltering (3 to 30mSv) and evacuation (30 to 300mSv) where the lower limit is that when consideration should be given to implementing the respective countermeasure action, and the higher limit is that which should not be exceeded by the timely implementation of the appropriate countermeasure – for a plutonium dispersion incident the the recommendation is for sheltering above air concentrations of 7.6 10^4Bq/m^3 and, similarly, for evacuation above 4.6.10^5Bq/m^3.

[39] *The Radiation (Emergency Preparedness & Public Information) Regulations 2001.*

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[40] Current recommendations of the UK National Radiological Protection Board NRPB as these apply to ground and air concentrations.

[41] Recommendations of the NRPB – the countermeasure must be considered for implementation when the projected dose exceeds the Lower ERL and it must be in place to avert the any individual reaching and exceeding the Higher ERL.

[42] Plutonium emits alpha radiation, which is unable to penetrate ordinary clothing or even the unbroken outer layer the skin. Simple decontamination techniques, such as showering, washing with soap and water, are effective in removing plutonium particles and their presence on the skin should not compromise urgent medical treatment. Only if alpha emitting particles are taken into the body does a hazard to health result. The entry routes for this are inhalation (with particles lodging in the lungs), ingestion (particles in the digestive tract) or deep wounds and there is a relatively high natural clearance from the body of the digestive tract uptake Retained levels of plutonium may be reduced still further by medical techniques such as lung lavage to clear out the lungs, the administration of chelating agents (which encourage the body to excrete toxic materials) and deep cleansing of wounds, although such prophylactic measures are practicably difficult to administer to large numbers of members of the public, as is the provision of respiratory protection during the release (ie issuing of respirators or gas masks).

[43] This apparent anomaly of no requirement to evacuate arises because the basis of the model is a high temperature tunnel fire that provides very effective plume lofting, thereby there is no receptor height (1.5 to 2m) plume in the immediate vicinity of the incident.