Large and ASSOCIATES Consulting Engineers

The Gatehouse 1-2 Repository Road Ha Ha Rd London UK SE18 4BQ1 ☎ 44[0]20 8317 2860 *fax* 8317 2859 *mobile* 07971 088 086 mailto:largeassociates@msn.com

POTENTIAL RADIOLOGICAL IMPACT AND CONSEQUENCES ARISING FROM INCIDENTS INVOLVING A CONSIGNMENT OF PLUTONIUM DIOXIDE UNDER TRANSIT FROM COGEMA LA HAGUE TO MARCOULE/CADARACHE

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POTENTIAL RADIOLOGICAL IMPACT – LOCALITIES OF PARIS AND LYON

SUMMARY

This analysis considers the road haulage of consignments of plutonium dioxide from the COGEMA reprocessing plant at la Hague near Cherbourg to the mixed oxide fuel fabrication plants at Cadarache and Marcoule in southeast France.

Until August of 2003, consignments of about 150kg of plutonium dioxide (PuO_2) were carried in a single vehicle, but since that time the number of consignments per convoy have been doubled to a total of about 280 to 300kg PuO_2 being carried by two vehicles making up a convoy that regularly passes south of Paris on the A6 and to the east of Lyon where the A6/A7 crosses the River Rhône. The consequences of these vehicles being involved in i) a severely damaging road accident, iii) a tunnel fire, and iii) a well planned and executed terrorist attack, are assessed in terms of the radiological and potential health consequences arising from a release of plutonium dioxide are summarised as follows:

Plutonium Dioxide Release to Atmosphere: The analysis considers only a release to atmosphere, its passing and subsequent dispersion and ground deposition, omitting any consequences of the plutonium run-off into watercourses. The fraction of plutonium dioxide released in either accident or terrorist scenario, is taken directly from the authoritative United States Department of Energy (DOE) environmental impact study relating to the Eurofab project that is to involve the movement of US-sourced weapons-grade plutonium to France for conversion to mixed oxide fuel (MOX). In its study, the US DOE assumes that a severely damaging accident could result in a release of respirable-sized aerosol of 595g from the *weapons-grade* plutonium dioxide of one of three FS47 flasks carried in a single, armoured road vehicle.

For this analysis, the same US defined release conditions and fraction are applied to French-sourced consignments of *reactor-grade* plutonium dioxide carried in the unarmoured trailer compartment of each of the two vehicles making up the convoy, but with each vehicle carrying 9 full FS47 flasks compared to the 3 identical FS47 flasks per vehicle in the United States example.

These release fractions are applied to the more radiotoxic *reactor-grade* consignment for i) a severely damaging road accident in which one FS47 flask is breached, ii) a similar road accident where the same proportion of FS47 flasks fail in a single vehicle (ie 1:3 so 3 of 9 flask failures); iii) a road incident in which both vehicles of the convoy are caught in a road tunnel fire in which all flasks fail, and vi) a well planned and executed terrorist attack centred on one of the vehicles of the convoy.

INCIDENT TYPE	i) SEVERE ROAD ACCIDENT – 1 VEHICLE	ii) SEVERE ROAD ACCIDENT - 1 VEHICLE	iii) SEVERE TUNNEL ACCIDENT – 2 VEHICLES	iv) TERRORIST ATTACK 1 VEHICLE
Nº FS 47 FLASKS BREACHED	1	3	18	9
RESPIRABLE-SIZED PuO_2 RELEASED	0.595kg	1.785kg	10.71kg & 25.22kg	5.355kg

Risk and Probability: For the French consignments of plutonium dioxide considered here, unlike the projected single US road shipment evaluated by the US DOE, the road transfers of French-sourced plutonium from the COGEMA plant at la Hague to the MOX are frequent (on average, 2 vehicles each carrying about 138 to 153kg every seven to ten or so days), geared to the commercial operation of the MOX fuel plant at Marcoule (and Dessel in Belgium).

The probability of a severe road accident, say a major pile-up involving impact and subsequent fire then, setting aside that heavy vehicle road accident rates between the US and France differ (but which are generally higher in France), but taking account of the shorter distances travelled in France, the risk of accident on the French roads is significantly higher than that determined for the US DOE study, being about 0.5E-06, 1E-06 and 0.5E-09 for rural, suburban and urban situations respectively (2.5E-07 overall) for each year of future operation.

Again based on data compiled in the United States, the probability of a collision-with-truck-or-bus event at a velocity of, say, 80kph followed by impact with an unyielding object (ie a bridge abutment) and then a high-

temperature engulfing fire of 2.0 to 3.0 hours duration is 6.06E-07. For such an accident to occur within the confines of a road tunnel is even more remote, although not that remote to be dismissed to be incredible, as shown by the separate Gotthard and Mount Blanc road tunnel fires, of 1999 and 2001 respectively.

On the other hand, terrorist acts are intentionally driven by, amongst other things, behavioural factors and the taking of opportunity that are, all in all, beyond the bounds of probability. Put another way, one and then two aircraft flying into the World Trade Center was unthinkable, but on September 11, 2001 the unthinkable happened.

INCIDENT TYPE	SEVERE ROAD ACCIDENT	SEVERE TUNNEL ACCIDENT	TERRORIST ATTACK
PROBABILITY	0.5E-06/1E-06/0.5E-09 rural/suburban/urban	6E-07 once initiated in tunnel	Not Applicable

Consequences: The results of this analysis indicate that the consequences of a radiological release during the road transit of plutonium dioxide in quantities that are potentially available, from both terrorist attack and road accident, are mainly long-term in nature, giving rise to increased cancer incidence, particularly lung, bone, and liver cancer. Apart for the short-term risk to those individuals engaged in the transport activity (drivers, guards, etc) and emergency personnel attending at the scene of the incident, exposure levels are unlikely to produce early effects of radiation sickness and mortality.

Health Impact - Projected Mortality: The numbers of individuals projected to suffer late mortality are:

LOCATION	SCENARIO WITH COUNTERMEASURES	MEAN – MAX MORTALITY	
Paris Outskirts	Road Accident – 0.595kg release	**68**	**523**
Paris Outskirts	Road Accident – 1.785kg release	**204**	**1,572**
Paris Outskirts	Tunnel Fire – 10.71kg release	**613**	**4,879**
Paris Outskirts	Tunnel Fire – 25.200kg release	**1,323**	**11,520**
Paris Outskirts	Terrorist Attack – 5.250kg release	**467**	**4,691**
Lyon Outskirts	Road Accident – 0.595kg release	**34**	**141**
Lyon Outskirts	Road Accident – 1.785kg release	**103**	**424**
Lyon Outskirts	Terrorist Attack – 5.250kg release	**163**	**845**

These projections are of increased incidence of mortality arising as a direct result of the releases, with the range of the forecast being determined by weather conditions and for the two different localities (Paris and Lyon) by population density. The tunnel fire scenario applies only to Paris with the incident occurring in the cut and cover road tunnel at Versailles.

The increased (over existing from other causes) incidence of cancers would be expected to peak after a delay of 15 to 30 years, with a shorter determination for leukaemia of, perhaps, 5 years from the date of exposure. Because the populations exposed for the two sample localities are so large, not only would the impact of the health detriment and fatalities remain hidden for several decades, but the significance of the numbers directly attributable to any of the earlier plutonium releases might be masked by the high 'natural' incidence, particularly of lung cancers in smokers, in the population.

Effectiveness of Countermeasures: Countermeasures, essentially sheltering and evacuation, have little effect because, first, the main exposure route is via respiration and, second, even small delays in implementation of the most common sense precautions results in over-exposure of nearby populations.

For the terrorist triggered incident, the numbers of public requiring to shelter, around Paris for example, ranges from some 40,000 to several million individuals over an area of up to 900km² depending on the prevailing weather conditions and the particular incident scenario. Of course, such projections are hypothetical particularly because advice from the authorities to shelter might, in fact, itself prompt a mass self-evacuation. The model assumption is that, at any time, 90% of the public are indoors and thus are already sheltering at a 50% reduction in dose uptake, so the additional benefit of implementing the organised sheltering countermeasure only applies to 10% of the potentially exposed population. Self-evacuation is likely to result in more individuals coming onto the streets without much protection and, indeed, some may unknowingly move into contaminated areas and/or become trapped for hours in the jams and traffic chaos that is almost bound to arise. The conundrum for the authorities being that the introduction of countermeasures might (indeed is likely to) increase the exposure and, hence, health detriment to many more members of public.

Again for Paris as example, relocation patterns for the longer term (1 to 2 years) extend out to 15km from the centre of the incident, although such projections should be treated with caution because of the difficulties and inaccuracies of modelling dispersion over urban areas (as demonstrated by the very patchy ground and surface contamination levels in the town of Pripyat, nearby Chernobyl).

Other than not to transport such hazardous nuclear material, the next best pre-emptive countermeasure is to separate and distance large numbers of public from the hazard. Routing the plutonium carrying convoy nearby large urban conurbations, such as Paris and Lyon, introduces the potential for high (numbers of individuals) consequences – this could be avoided by relatively straightforward route changes avoiding medium and large centres of population. On the other hand, routing the convoys to lesser roads might, in turn, result in an increased frequency of accident and a greater vulnerability to terrorist attack.

Economic and Social Impact

It is also possible to model aspects of the economic impact. However, the modelling is somewhat mechanistic, giving account to the costs of relocation, sheltering and late health effects, agricultural loss, etc., but it does not, nor could it be expected to, evaluate impacts arising from negative perceptions gained and held by the public in France and, particularly, abroad.

For example, a release into or nearby Paris would undoubtedly have a very severe impact on world tourism to this World Heritage City and, at the other example location nominated for this study, the contamination of a relatively small area of the Rhône would, no doubt, blight tourism to and the export of wines from, and perhaps, throughout the valley and entire region. These economic detriments might be expected to persist for many years, irrespective of the degree of decontamination achieved in the aftermath of the release.

It is recommended that assessment of the economic and social impact be subject of a separate study and report.

In conclusion

Recent evaluation of the safety case for the transportation of plutonium dioxide in the United Sates has led to a number of harsh constraints being imposed upon such transits.

Using the same transport flask (FS47), the US restricts the number of flasks per vehicle to 3, whereas the French transport up to 9 fully loaded flasks per vehicle. The US road convoy comprises custom-built Safe Secure Transport (SST) trucks that are fully armoured and equipped with at least two systems that automatically prevent the removal of the flasks and armoured personnel carriers accompany the convoy throughout is transit, whereas the French vehicle seem to be little more that a commercial tractor unit hauling a standard trailer with an ISO container attached, with the two consignment trucks making up the convoy being accompanied by 6 to 8 Gendarmerie travelling in what seem to be a standard and unarmoured minibus and a car. Most oddly, the US analysis reaches the conclusion that the FS47 flask could fail in a road accident and that there is a potential for 595g release from each flask in transit which compares to the utter confidence of the French that the FS47 flask is failsafe, so much so that the worst credible accident would only result in a 0.07g release.

Because the French authorities do not concede that in a real incident an amount of plutonium greater than the 0.07g could be released, a maximum dose of 10mSv is assumed for any member of the public located within the immediate vicinity, and that no emergency actions will be required further than a few hundred metres from the point of release. This contrasts to the consequences of real incidents in which realistic amounts of plutonium are released, where sheltering distances extend from 1km to 110km depending on the incident severity and, even with this countermeasure being deployed, the long-term radiation dose to the lung, for example, could be several hundred milliSieverts.

JOHN H LARGE
LARGE & ASSOCIATES

POTENTIAL RADIOLOGICAL IMPACT – LOCALITIES OF PARIS AND LYON

RADIOACTIVE CONSIGNMENT AND ROUTES

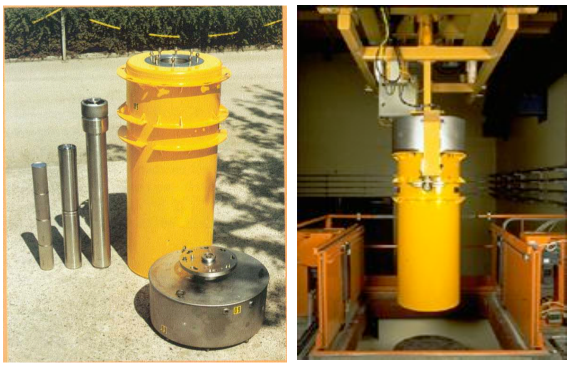
Consignments of plutonium[1] dioxide (PuO_2) powder are regularly transferred from the COGEMA la Hague reprocessing works, where the plutonium is recovered from spent fuel by chemical separation (reprocessing), to the MELOX fuel pellet sintering plant at Marcoule (and previously to Cadarache)[2] where the plutonium is blended with depleted uranium and fabricated into mixed oxide (MOX) fuel pins.

The general road route taken for the plutonium dioxide transfers is shown in **APPENDIX I.**

CONSIGNMENT PACKAGING

The plutonium dioxide is usually transferred in consignments of about 138 to 153kg, carried in a single tractor unit vehicle[3] loaded with 9/10[4] FS47 type transport flasks. Since August 2003 for reasons unknown, twice the regular amount of plutonium dioxide totalling 300 kg has been transported in a two-vehicle convoy. A single FS47 flask carries five double-skinned cans, each holding 3.4kg PuO_2 powder, with the cans stacked in a sleeved jacket that in turn is held within the inner well of the FS47 flask, giving about 17kg PuO_2 per flask.

The FS47 transport flask is cylindrical of approximately 600mm diameter by 2,030mm overall length, capped with a shock absorber at one end, in all weighing about 1,750kg. A stainless steel lined inner well of 120mm diameter receives the stack of plutonium cans – the void between the inner well and the carbon steel outer casing is filled with a dense hydrogenous polythene (probably *polyken*) neutron absorbing compound and an outer 50mm ring of plaster acting as a thermal insulant.



FS47 Flask and its component parts

The FS47 is a Type B (U) approved transport flask[5] certified in France. **APPENDIX II** provides further details of the FS47 transportation flask and the transportation rack.

CONSIGNMENT RADIOACTIVE INVENTORY

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

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Table 1 Radioactive Inventory and Composition of Plutonium Dioxide[6]

ISOTOPE	SPECIFIC ACTIVITY Bq/g	% COMPOSITION	HALF-LIFE Years	DECAY HEAT kw/kg
Pu-238[7]	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

ENVIRONMENTAL AND HUMAN IMPACTS OF PLUTONIUM

In one hypothetical scenario analysed in this study, a release of plutonium dioxide in the form of fine, respirable-sized aerosol[8] 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.[9]

There is also risk of longer-term cancers[10] 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)[11] and the cancer risk (that is the 'cancer causing dose'), because some predictions include (for weapons-grade plutonium inhalation)[12] a somewhat subjective 'high-risk factor'[13] 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[14] 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.[15] 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.[16]

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.[17] 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.

CONSIGNMENT SAFETY AND SECURITY REQUIREMENTS

Plutonium dioxide is defined by the International Atomic Energy Agency (IAEA) to be *Category I*[18] material and is thus required to satisfy specific requirements and safeguards relating to safety and security.

For nuclear safety, the physical design and performance of flasks carrying *Category I* radioactive material are required to satisfy domestic (state) legislation mostly derived from the IAEA *'Regulations for the Safe Transport of Radioactive Material'*,[19] and other regulations, etc., relating specifically to plutonium as a fissile material.[20] Essentially, these regulations (being nationally and internationally adopted) stipulate that Type B(U)/F packages meet the following functions:

- containment of the nuclear material
- shielding against radiations (gamma and neutrons)
- maintaining subcriticality conditions
- dissipation of residual heat

when subject to both normal and accidental conditions of transport.

The IAEA regulations (INFCIRC/225.Rev 4)[21] on security, physical protection systems and sabotage prevention are specified in general terms, the salient features of which are as follows:

- The physical protection system should be based on the evaluation of the threat and account should be taken of the emergency response capabilities.
- A design basis threat (DBT) developed from an evaluation of the threat of unauthorized removal and/or sabotage of nuclear material is an essential element of the physical protection system.[22]
- Emergency plans for any needed response to unauthorized removal and subsequent unauthorized use of nuclear material or sabotage of nuclear material to support and supplement, when needed, those emergency plans prepared by the carriers
- To ensure that physical protection measures are maintained in a condition capable of effectively responding to the design-basis threat (DBT), the competent authority should ensure that evaluations are conducted by the Carrier of the transport, with these evaluations including administrative and technical measures, such as testing of detection, assessment and communications systems and reviews of the implementation of physical protection procedures and should also include exercises to test the training and readiness of guards and/or response forces.

It is of interest to note that for nuclear safety, the principal dependence is upon the design and compliance of the flask alone being adequate to maintain surety of the consignment in accidental circumstances, there being no specific requirements from protection or defence against terrorist attack or sabotage. To safeguard against malicious actions (both sabotage and terrorist acts) the dependency is entirely upon the security cordon and not at all specifically related to the flask design.

In France, nothing is available from the *La Direction Generale De La Surete Nucleaire Et De La Radioprotection* (DGSNR) on evaluation of the threat and emergency response capabilities, other than a Decree that sets out radiation exposure limits for attendees of incidents. [23] In fact, the role of the DGSNR does not include matters of security which is dealt with by the senior official, *un haut fonctionnaire de défense* (HFD), appointed from within the French industry ministry. It is believed that HFD considers security on a case-by-case basis and it not known what, if any, design-basis threat scenarios are nominated and, indeed, nothing has been published on previous *Category I* transits in France.[24]

HYPOTHETICAL SCENARIOS DURING ROAD TRANSPORT OF PuO_2

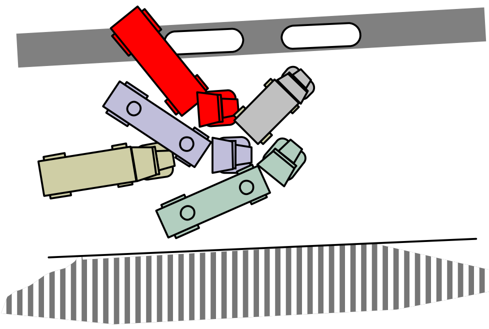
Potential scenarios that could result in an atmospheric release of the plutonium consignment are examined, these being i) four severities of road traffic accident and ii) a well planned and executed terrorist attack – see **Appendix IV**.

ROAD TRAFFIC ACCIDENTS

The less severe of the hypothetical road accidents comprises one of the convoy vehicles being involved in a collision with another vehicle or vehicles, subsequently impacting onto an unyielding object, such as a bridge abutment, followed by a fire of 1.5 hours duration. The probability of such an accident cascading through this event tree is 2.5E-7.[25]

Pile-Up accident on the I-5 Freeway San Diego, USA – involved 4 large trucks and a tanker truck – one truck burnt-out completely to a shell

The basis of this underlying type of pile-up is not that uncommon, with about 2% of all serious accidents involving commercial vehicles being followed in serious fire as shown by the pile up at San Diego in the United States in which a large truck was completely burnt out to a shell. The development of the basic accident is that the convoy vehicle heavily impacts upon and is brought to rest by an unyielding bridge abutment and, in do so, severely damages the trailer container and one or more FS47 flasks within. In this scenario, 595g aerosol of PuO_2 is released in the ensuing fire.



Synthesised accident for the 595g release – red truck is the convoy vehicle – blue truck a petrochemical tanker

At its most severe, this accident scenario represents the most severe category specified in the United States (Category VIII – NUREG)[26] for which a release fraction of 0.1 is recommended, although for the open-road scenarios analysed here the 3.5E-2 release fraction for a single FS47 flask is adopted.

In the more severely damaging road traffic accident both convoy vehicles are caught in a fire situation within a road tunnel. The vehicles themselves might or might not be involved in a collision/impact event, but they remain trapped in the tunnel and are engulfed in fire, such as the many vehicles trapped in the Mont Blanc road tunnel fire of March 1999. The high temperatures and, particularly, the duration of the fire is sufficient to fail the vehicle load compartments and all of the FS47 flasks, resulting in a total release of 10.71kg aerosol of PuO2 adopting the US release fraction and 25.20kg when the US NUREG Category VIII release fraction is adopted.

Aftermath of the Mont Blanc tunnel fire of March 1999 – the source of the fire was a truck carrying margarine and flour – the fire took 50 hours to completely extinguish

In summary, the respirable-sized releases for the accident scenarios adopted are:

Table 3 Road Accident Release Amounts

INCIDENT TYPE	i) SEVERE ROAD ACCIDENT 1 VEHICLE	ii) SEVERE ROAD ACCIDENT 1 VEHICLE	iii) SEVERE TUNNEL ACCIDENT 2 VEHICLES
Nº OF FS 47 FLASKS BREACHED	1	3	18
RESPIRABLE-SIZED PuO_2 RELEASED	0.595kg	1.785kg	10.71kg & 25.220kg□

□ A lower release fraction than the 0.1 of NUREG VIII at 0.084 is adopted as an outcome of private correspondence.

ACTS OF SABOTAGE AND TERRORISM

Acts of sabotage and terrorism are intentional actions, intelligently driven by behavioural factors that do not conform to the probabilistic (almost mechanistic) reasoning adopted by the nuclear industry to predict and defend engineered systems against accidental situations.[27] Moreover, as recent past terrorist incidents quite ruthlessly lay bare, terrorists will seek out the vulnerabilities of the system under attack and, moreover, their actions are likely to obstruct and hinder countermeasures and emergency plans, all to maximize the human, economic and environmental consequences.

Obviously, openly speculating about the ways and means by which the plutonium dioxide consignments might be attacked or hijacked in any greater detail here would not be in the public interest – for this reason, detailed information relating the following hypothetical scenarios have been omitted thus [. . . .]. That said, it has to be recognized that the knowledge and means are available to would-be saboteurs and terrorists that could pose a serious threat to the plutonium consignments – there is no rationale that somehow excludes this highly fissile and radiotoxic nuclear material from this threat,[28] nor that the terrorists themselves should not be intelligent, having sufficient knowledge and experience of the techniques, equipment and materials involved.

It follows that the outcome of a maliciously motivated act could be very different from that of an accidental event. Unlike an accidental release of radioactivity, the detailed implementation of the act might be such to create and maximise certain pre-identified consequences. Terrorists could seek to maximise the health and environment impacts, and play upon the public's adverse perception of all things nuclear (ie a fate worse than death) to prolong the psychological and economic consequences. Such factors might include:

- **modus operandi of the attack chosen to outwit or outflank the security measures:** For example, it might be delivered by an innocent-looking vehicle (a private car or innocuous commercial truck) running alongside the convoy; or remotely from a concealed roadside location by the use of infantry weaponry (RPG or similar); or one or both of the convoy vehicles might be isolated from the escort vehicles and hemmed in a confined space, such as a road tunnel or in the confines under an overbridge, where access could be tightly controlled by a few individuals; and so on.

- **attack deliberately timed and located at a place of maximum population:** For example, the density of

The Oklahoma Bomb of 1995 was transported in a 5 tonne Panel Truck population might be contrived, by first creating a road traffic jam ahead of the planned attack; or by hijacking the consignment vehicle and taking it to a concentration of population, say a football stadium or similar; and so on.

- **physical circumstances of the attack 'engineered' to optimise a release to maximize the consequences:** For example, the particulate size of the plutonium dioxide might be reduced to maximise respiratory uptake by the first of a two stage release process by introducing an incendiary,[29] or by explosion;[30] it might be rendered into a plutonium-nitrate for dispersion into a potable watercourse; or the flask itself might be adapted, with the introduction of a shaped explosive charge, neutron reflectors, etc., to form a crude criticality device; and so on.

- **environment under attack selected for best effect:** For example, one or both of the convoy vehicles might hijacked and the contents of one or more FS47 flasks unloaded. Small quantities of plutonium (say single COGEMA AA-432 cans each carrying 3.4kg PuO_2 might be transferred to other vehicles, such as a cross-country motorcycle, that could not be readily pursued. These smaller quantities of the plutonium might be dumped in water reservoirs;[31] or by introducing and spreading an aerosol in a confined system, such as an underground train network, or in the air conditioning system of an office complex; or by dispersing the material in a city centre as a radiological or 'dirty' bomb;[32] and so on.

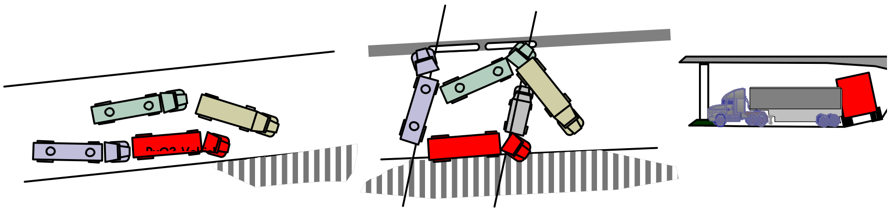
- **consignment hijacked to fabricate a primitive nuclear device:** Similarly, transferring part or all of the consignment to a number of individual 'escape' vehicles (thus creating too many pursuits for the limited number of security forces accompanying the convey) might enable the terrorist to successfully remove a sufficient quantity of plutonium dioxide with which, at some other location and with modest design sophistication produce a primitive nuclear explosive of predictable yield.[33]

The point here is that it is most unlikely that a terrorist group would be content with a crude detonation to damage the flask and disperse the plutonium dioxide material in an unpredictable fashion. Like the atrocities of September 11, such an act would be expected to be meticulously planned and resourced to maximize its (health, psychological and economic) impact and consequences.

For this analysis, it is assumed that the terrorist would endeavour to maximise the release of the PuO_2 consignment to atmosphere at a point along the route nearby a large urban population. Two sample locations are a) as the convoy passes round the southern suburbs of Paris, travelling eastwards on the A6 route where it passes through the cut and cover road tunnel on the A12 near Versailles (2.08E48.48N) about 20km southwest of the centre of Paris, and b) where the convoy passes to the east of Lyon on Route A7 in the locality where the road crosses the River Rhône (4.55E45.48N) about 10km to the east of the centre of Lyon

There are a number of viable means to just how a terrorist group might go about 'capturing' at least one of the convoy vehicles. Here it is assumed that a convoy vehicle is isolated by manoeuvring a number of heavy vehicles under the control of the terrorists, which then forcibly marshal the convoy vehicle to a dead stop under an overbridge or in a tunnel. The intercepting vehicles then deploy to form a robust cordon to the front, rear and side of the convoy, blocking the road carriageway with the overbridge providing screening from aerial surveillance. Alternatively, both convoy vehicles could be 'captured' and stopped in a road tunnel with the intercepting vehicles forming a robust cordon.

[. . .



Synthesised Capture of the Convoy vehicle under an Overbridge or in a Tunnel, followed by explosive opening

The Plutonium Dioxide Convoy with the two accompanying Gendarme vehicles – the blue car between the trucks and a blue minibus just discernable at the rear of the second truck

Observations[34] over the past two years that the convoy is manned by about 30 or so Gendarme personnel. These comprise at any one time 10 security personnel spread over three vehicles, with 2 Gendarme in the first car which runs about 5 to 10 minutes ahead of the main convoy, and with 3 to 4 Gendarme in each of two cars (minibus and a car) that run immediately ahead and behind the two convoy vehicles carrying the plutonium consignment. It is believed that the Gendarme vehicles carry light, automatic weapons along with personal body armour that are stowed in the rear of the vehicles. It is not known whether the drivers of the two a consignment carrying trucks are armed. All security and driving personal change three times over the entire route from la Hague to Marcoule, so the total staff resource dedicated to this transportation is about 100 overall.

. . .]

Once isolated, the container of the convoy vehicle(s) holding the racked FS47 flasks could be accessed either by cutting through a side panel at the higher level to access above the flask rack frame or, more directly, by slicing through the rear door bolts taking about [12] minutes in total. Then, to access the inner plutonium dioxide containers, either:-

[. . .

a) a FS47 flask or flasks could be opened up with a shaped explosive charge, scattering the PuO_2 powder contents within the container – separate charges strategically placed in the centre and between the rows of flask – each shaped charge would require approximately [0.8]kg of [C4] type high explosive;

b) or the FS47 flask could be accessed by thermic lance[35] cutting and the canister containing the PuO_2 powder opened and the contents scattered – set-up and cutting time for a flask bottom access would be [15] and [6] minutes respectively;[36,37]

c) or the outer body of the flask could be mechanical drilled through to the inner well of the flask, thence into individual plutonium double containers from which the plutonium powder could be suctioned out – repeating this process to access all five plutonium containers of each FS47 flask.

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. . .]

For the explosive opening option, there is an emerging field of literature on the response of nuclear transport flasks when subject to explosives,[38,39,40,41,42] although these relate generally to irradiated uranium dioxide fuel carrying flasks applied to a variety of flask designs.[43,44,45,46]

Both the performance of the FS47 flask under explosive loading and the amount of released respiratory-sized aerosol is alluded to in the United States Eurofab[22] environmental impact statement.[47] The US analysis considers two unspecified *accident* events both involving a FS47 package consignment of PuO_2 with the first of these being for a shipboard consignment that clearly involves (but does not describe) a high energy event with an immediate puff-like release, followed by a continuous, thermally energised release over 60 minutes. The second incident supposedly represents a severe road accident involving the so-called safe-secure transports (SST) giving rise to an immediate and continuous release.

The essential parameters of the two US scenarios are:

Table 4 US Eurofab Accident Release Scenarios[47c)]

TRANSPORT MODE	VEHICLE/VESSEL	FLASK TYPE	PuO_2 CONSIGNMENT	FRACTION RESP-SIZED	COMMENTS
Sea	PNTL Ship	FS47 9 flasks	150kg	5.E-3 750g	Two phase release 1st 150g puff for 10 minutes, 2nd a total of 600g continuous over for 60 minutes with 150kW thermal input – ie an explosion followed by fire
Road	SST (Safe Secure Transport)	FS47 3 flasks 1 fails	17kg each of three flasks in 3 separate trucks	3.5E-2 for 1 of 3 flask - 595g	Single phase release of total 595g respirable-sized aerosol but with no thermal input to plume and duration of release unspecified

In the first of the US studies (**Table 4**) the total release fraction seems to be artificially restricted by assuming that the enclosure of the ship's cargo hold limits the amount of aerosol that reaches the atmosphere. This compares to the greater release fraction (3.5/5.E+1=) x7 for the road vehicle release where the containment of the vehicle trailer is less effective in holding back (plating out) the releasing aerosol.

However, it should be noted that the proposed PuO_2 consignments for the US Eurofab transfers differ in a number of important respects to the established French transportation between la Hague and Marcoule/Cadarache, these being:

- **Special Strategic Nuclear Material:** In the United States, plutonium dioxide is defined as a *strategic special nuclear material* requiring extra measures to ensure physical security and protection of the public and to safeguard the material from illicit removal.

- **Weapons -v- Reactor Grade Plutonium:** The Eurofab consignments comprise *weapons-grade* plutonium compared to the French-sourced *reactor-grade*. As noted previously,[12] *reactor-grade* is about x4.4 more radiotoxic than its equivalent weapons-grade, although this reactor-grade material would still be considered to a *strategic special nuclear material* requiring additional protective measures.

- **Transport Arrangements:** In the United States, such consignments are transported in a specially designed Safe Secure Transport (SST) vehicle providing thermal protection to the inner contents of the cargo hold, and which is equipped with communications, radiological monitoring and other devices that physically prevent removal of the consignments. Each truck is limited to 3 FS47 flasks.

  In comparison, the French-sourced consignments are transported in what seems to be a standard ISO contained fitted to a commercial articulated vehicle carrying up to 10 FS47 flasks. The space occupied by the flask frame in the ISO container suggests that the container is unlikely to have any devices installed to prevent the physical removal of the flasks.

A 10 capacity rack with 8 FS47 flasks installed awaiting loading into the ISO container – note that the rack and flasks occupy virtually the whole of the ISO container cross section

MEANS OF DISPERSION OF PLUTONIUM DIOXIDE TO ATMOSPHERE

All of the scenarios examined, both accident and terrorist attack, assume that one or more FS47 flasks will be breached and that the convoy vehicle(s) will be engulfed in fire of intensity sufficient to loft the radioactive release plume clear of the immediate incident scene.

For the road and tunnel accident situations previous occurrences (see margin photographs of accident aftermaths) have demonstrated that roadside fires can be sufficiently fierce and prolonged to destroy the vehicle and FS47 flask containment.[48]

So, to maximise the release and to push the dispersion of the airborne aerosol further to centres of population, here it is assumed that the terrorist act will i) successfully rupture all nine FS47 flasks of a single convoy vehicle and ii) then create an engulfing fire that will maximise entrainment of the plutonium dioxide particles and loft the release plume high for a longer ranger dispersion and deposition. Adopting the US release fractions of 3.5E-2 applied to a total consignment, the potential release of respirable-sized PuO_2 from the two-vehicle convoy is:

Table 5 Potential Release Amounts for a Terrorist Attack

INCIDENT TYPE	iv) TERRORIST ATTACK 1 VEHICLE	v) TERRORIST ATTACK 2 VEHICLES
Nº OF FS 47 FLASKS BREACHED	9	18
RESPIRABLE-SIZED PuO_2 RELEASED	5.355kg	10.71kg & 25.22kg

Obviously, the nature of the terrorist act in dispersing the plutonium oxide will influence the amount of respirable-sized aerosol released. For example, an explosive dispersion mechanism will result in a greater amount of respirable-sized aerosol than dispersal by fire, although a fierce and prolonged fire is likely to result in a greater amount, and hence larger respirable-sized fraction under dispersal.[30]

RELEASE SCENARIOS FOR PARIS AND LYON LOCALITIES

For both Paris and Lyon locations, the dynamics of the developing plume concentration, dispersion and deposition fall-out are plotted using the NOAA HYSPLIT model and plume rise prediction is by Hotspot.[49] The HYSPLIT plume development utilises real time meteorological data taken over the previous 15 days for the two localities – wind directions and meteorological conditions are seasonal, although there can occur strong day-to-day variations.

The environmental impact, including human health consequences are modelled using the European Community Commission developed and approved COSYMA[50] software which is seeded with population and meteorological data for the localities analysed, with the results derived on a probabilistic basis taking account of variations, particularly weather conditions. Results are presented for individuals in terms of whole body and individual organ exposure, mortality and morbidity based on the ICRP EDE approach, together with food and crop controls and, in overall terms, economic loss – these latter agricultural and economic outputs are not considered in this analysis.

APPENDIX IV outlines the input data and controls adopted for the COSYMA analysis, together with the inputs and output of a Hotspot analysis used as a validation check of the COSYMA results.

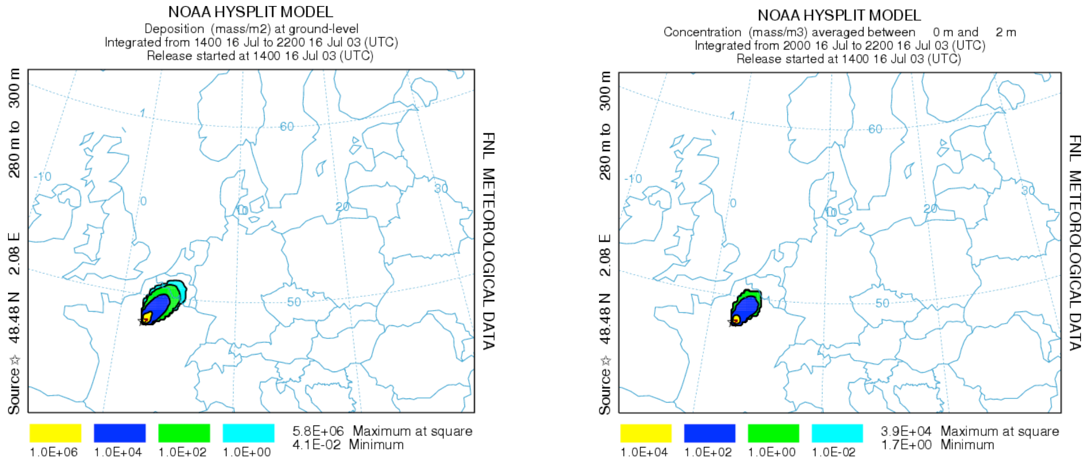
Hotspot predicts that at an average outside air temperature of 5°C, for neutral (D) atmospheric stability conditions, the height of the plume to shearing gives an effective release height of [140] to [221]m depending upon the wind velocity (range from 2 to 4m/sec). Uncontrolled fire well burn time for [15,000] litre of kerosene is approximately [4] hours, although it would be expected that the fire in the open would be brought under controlled within 3 hours[51] by emergency services fire fighters protected by contamination suits and breathing apparatus.

However, vehicle fires in tunnels are very high temperature and prolonged events that may not be accessible by fire fighting teams for many hours,[52] and the lofting and effective release height is considerably higher at [280 to 400]m. Under such conditions the release fraction adopted (3.5E-02) might be considered to be unduly light so a further case at a release fraction of 0.1 is also considered (see later).

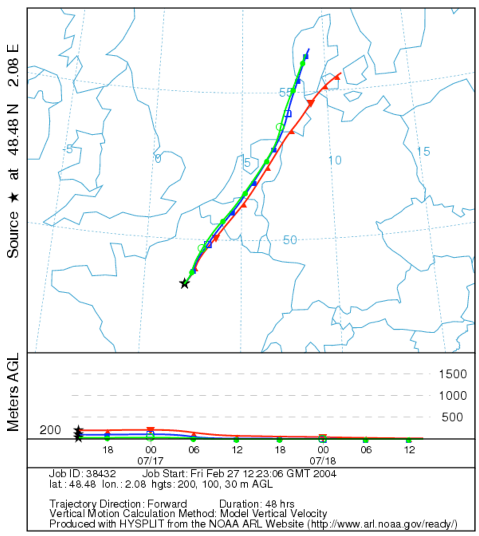
HYSPLIT Paris Locality Predictions:

HYSPLIT predictions are regional and global and, effectively, real time (using weather data for the previous 15 days). The application of local patterns and dispersions generated by HYSPLIT should be regarded with caution.

HYSPLIT predicts the following trajectory of the developing plume, dispersion of the plume and ground contamination for the hypothetical incident south-west of Paris under the weather conditions prevailing in July 2003



Development of the Airborne Plume and Ground Contamination: Atmospheric Plume Development and Ground Contamination for a tunnel fire release at Versailles at 4 hours into the release phase – units are in Bq/m^3 and Bq/m^2



Trajectories: Main flow trajectories for Versailles Tunnel Fire release of July 2003

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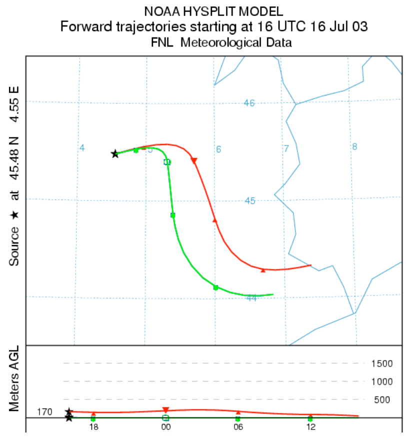
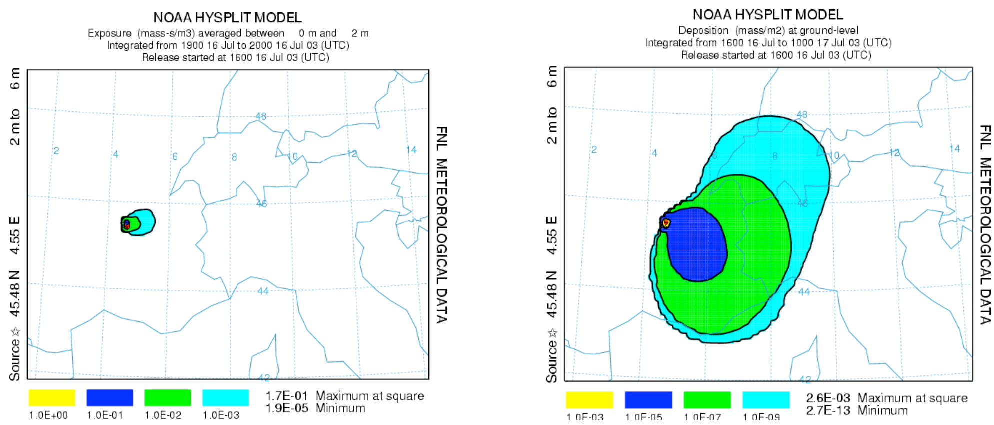
HYSPLIT Lyon Locality Predictions:

HYSPLIT predicts the following trajectory of the developing plume, dispersion of the plume and ground contamination for the hypothetical incident northeast of Lyon commencing 16 July 2003:



Plume Trajectories for a release centred at 45.48 North and 4.55 East – 16 July 2003 – the location of the incident is shown thus ★



Development of the Airborne Plume and Ground Contamination: Above Left – plume at 3 hours into the event located at ★ . Above Right, with the plume expanding to the north-west 18 hours following the event onset and 14 hours following cessation of the source fire commencing 16 July 2003.

INTERPRETATION AND APPLICATION OF THE COSYMA RESULTS

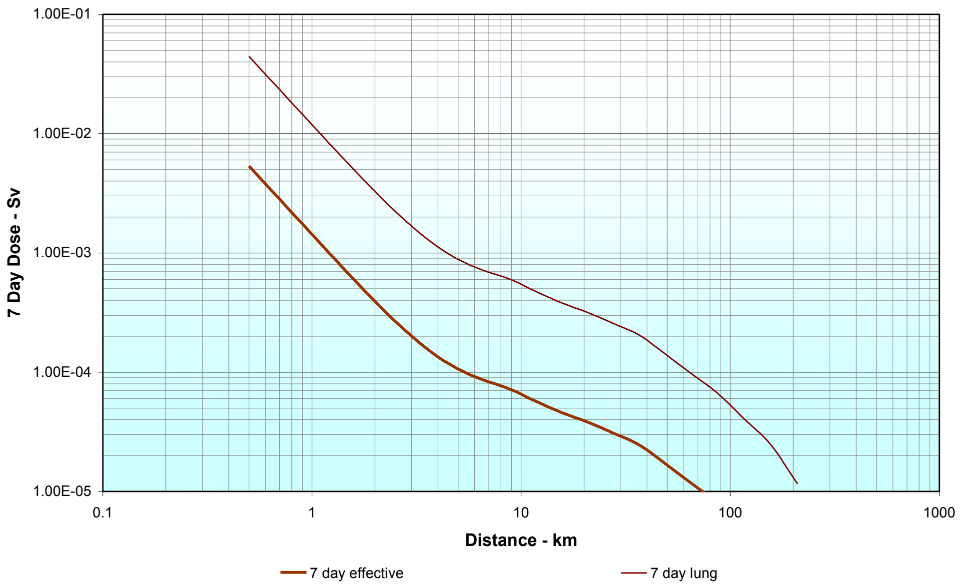
For brevity, the results of the COSYMA analyses presented here have been selected from a comprehensive results interface – the complete range of results for each case modelled is available. Also, the graphical results are presented as the arithmetic mean of the range of probable outcomes analysed.

The primary uptake route for a fine aerosol of plutonium dioxide is via inhalation during the immediate aftermath of the release as the airborne plume engulfs the subject population. Some secondary inhalation-delivered exposure is received via resuspension of radioactive particles from ground, building and other surfaces, although the magnitude of this contribution to the overall exposure diminished rapidly with time, being at one year virtually negligible if the exposure time is minimized to no more than about one month.[53]

The exposure from inhalation of plutonium aerosol is to the lung from particles retained in the pulmonary system with a proportion of the particles being transferred to the blood via the lymphatic system which are deposited in other organs, notably the liver and on bone surfaces. If the short-term levels of exposure are high enough, the resulting dose can lead to fibrosis and collapse of the lung, with death occurring within a matter of days or weeks. At exposures below the 'acute' threshold for early effects, alpha irradiation of the lung and other organs results in risk of cancer in the longer term.

The short term (7 day) exposures do not reach acute levels for any of the cases examined, although it should be noted that emergency services and other personnel caught within very close proximity of the incident (say <100m) might be subject to acute levels of exposure.

Graph 1 - PARIS 5.355kg Dose Comparisons



Graph 1 shows the <u>mean</u> short-term (7 day) lung and effective (whole body) exposures at one week assuming that effective countermeasures were implemented in the immediate aftermath of the incident. However, since much of the respired plutonium uptake during the first hours of the incident is retained within the human receptor's organs, the long-term dose is irreversibly committed at that time.[54]

The French authorities do not publish levels of exposure (or airborne concentrations, etc) at which countermeasures are to be implemented.[55] 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.[56]

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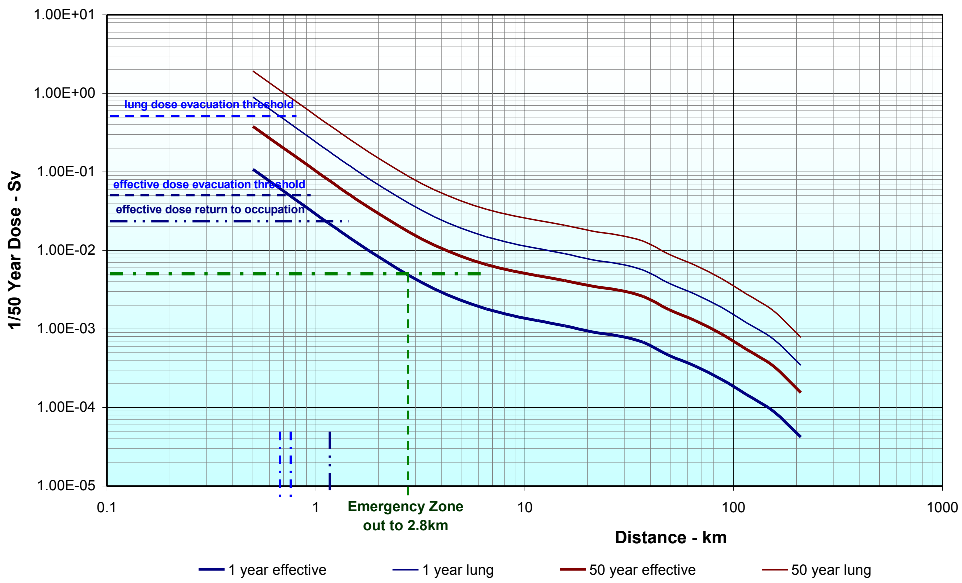
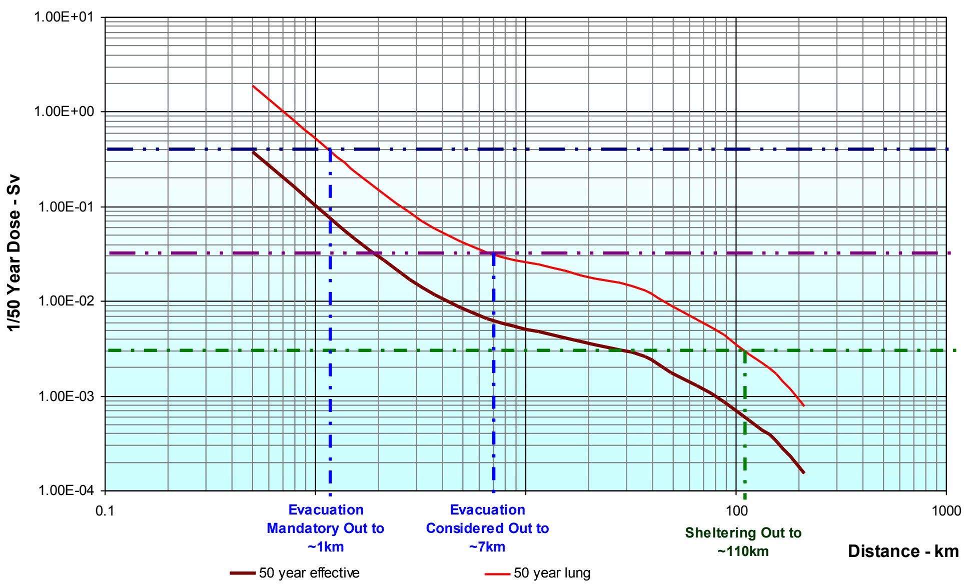
Graph 2 – Paris 25.22kg Dose Comparisons



Graph 2 shows extent of the UK system[57] 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 <u>mean</u> 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[58] 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 - Paris 25.22kg ERLs



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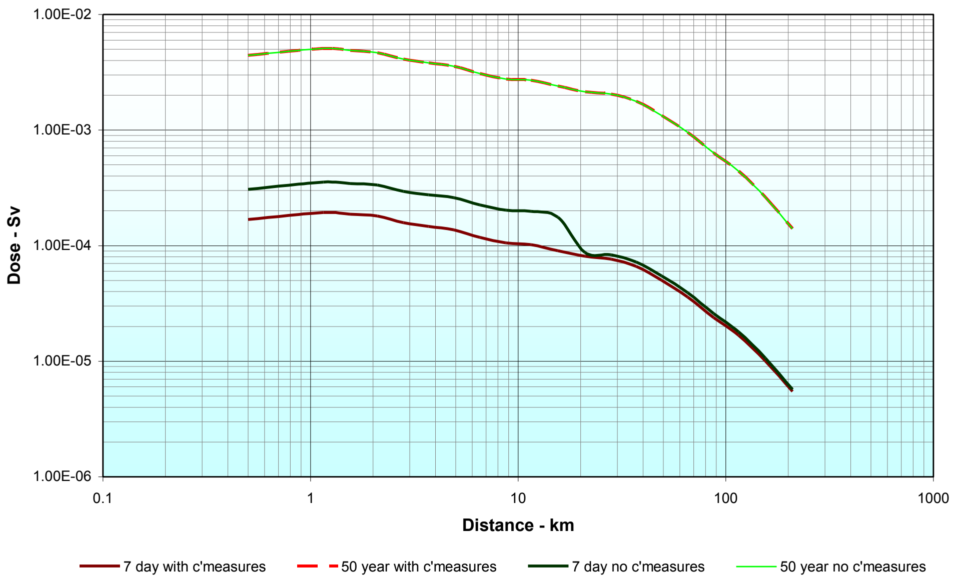
Graph 2a shows a dose derived threshold system (the Emergency Reference Levels – ERLs) that is adopted in the UK. The system requires individuals to be sheltered between the upper and lower limits of 3mSv and 30mSv and evacuated between 30mSv and 300mSv.[59] If this system is applied to the mean exposures 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 □-□ emitters where the principal dose uptake pathway is external exposure. In this case, where the radiation uptake is internal organ □ 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.

Graph 3 - Paris Sample Release Countermeasures



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As shown by **Graph 3**, these quite practicable and, to some extent, somewhat optimistic protective actions and exposure countermeasures have little effect in the longer term. This is because, first, the general assumption is that 90% of people will be indoors at any time, and thus sheltered with a 50% reduction in uptake. Second, the time required to implement practicably any countermeasures leaves the unsheltered 10% of population unprotected as the contaminated plume expands out from the point of the incident. For the sample release modelled in **Graph 3**, which involves a 9 hour tunnel fire, the main exposure uptake by inhalation during the first 4 or more hours of the release, accounts for >90% of the long term dose commitment.

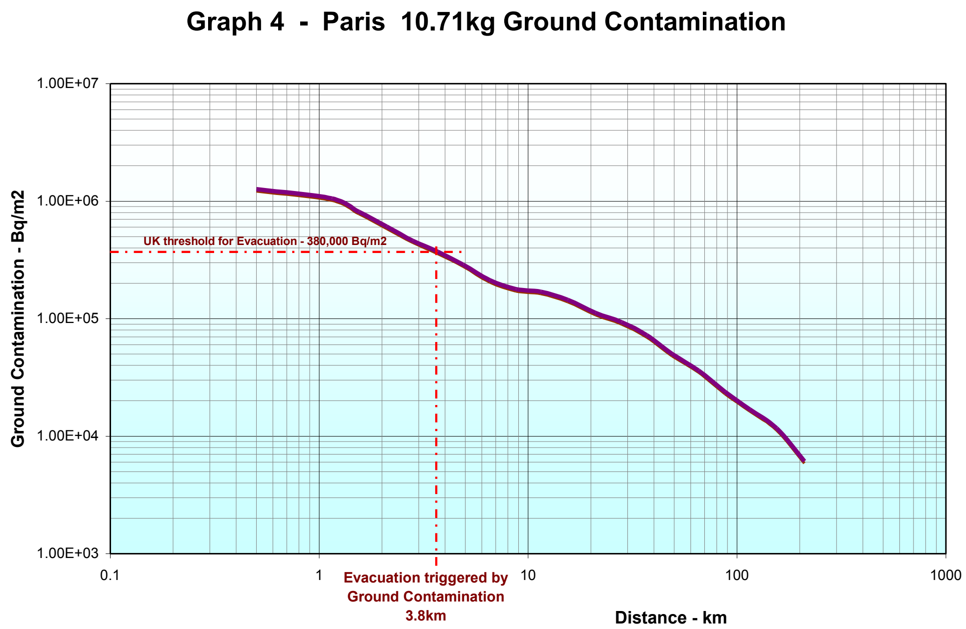
Also, the somewhat clinical approach to orderly countermeasure implementation assumed by COSYMA is unlikely to apply in practice. Once aware of the incident, members of the public, themselves, are likely to commence evacuation by any means available – indeed, it may be the implementation of limited countermeasures 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.[60]

The air concentrations and, following the release period, ground concentrations for each of the cases examined exceed the levels (in the UK) at which countermeasures are initiated in the analysis.

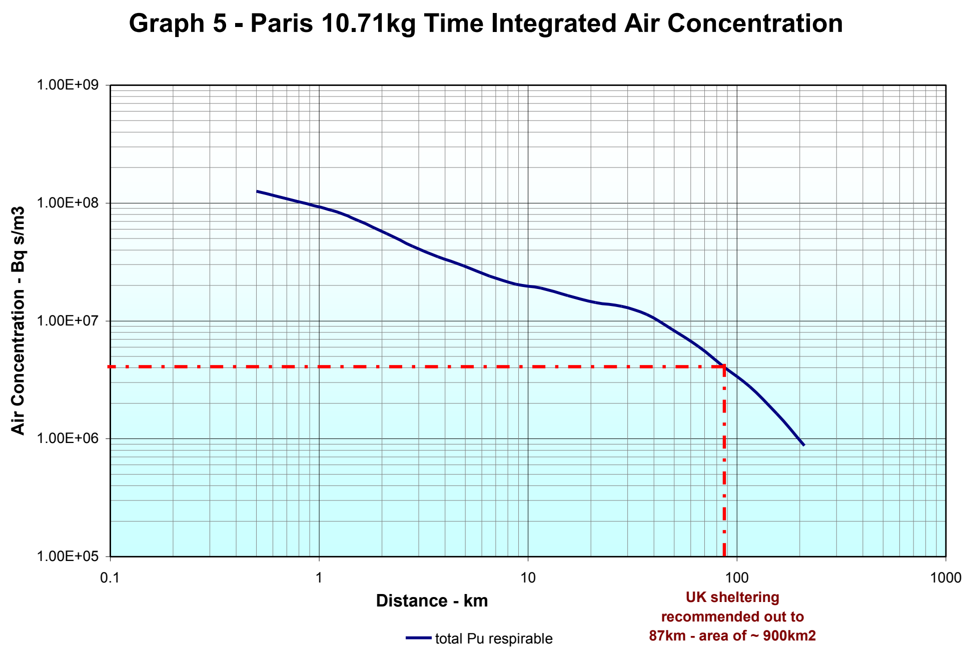
Table 6 Ground Concentrations - Plutonium-238 from 10.71kg Release

Distance km	Mean	Max.	99th	95th	90th	50th	Time(hr) max	Prob >0	Prob<1.0E+00
0.5	4.01E+04	1.55E+07	9.77E+05	3.16E+04	2.51E+03	-1.00E+00	3.417E+03	5.959E+01	2.75E-01
1.15	3.35E+04	1.95E+07	6.31E+05	2.82E+04	1.55E+03	-1.00E+00	2.969E+03	5.712E+01	2.68E-01
1.55	2.58E+04	1.47E+07	4.17E+05	2.88E+04	1.66E+03	-1.00E+00	2.969 E+03	5.632E+01	2.60E-01
2.1	1.93E+04	1.11E+07	2.88E+05	2.46E+04	1.91E+03	-1.00E+00	2.969 E+03	5.553E+01	2.52E-01
2.8	1.46E+04	8.21E+06	2.34E+05	2.82E+04	2.24E+03	-1.00E+00	2.969 E+03	5.480E+01	2.42E-01
3.7	1.18E+04	6.08E+06	1.91E+05	2.46E+04	2.19E+03	-1.00E+00	2.969 E+03	5.424E+01	2.31E-01
4.9	9.15E+03	3.69E+06	1.78E+05	2.63E+04	2.75E+03	-1.00E+00	2.969 E+03	5.357E+01	2.18E-01
6.55	6.76E+03	1.49E+06	1.62E+05	2.14E+04	3.09E+03	-1.00E+00	1.961 E+03	5.381E+01	2.07E-01
8.75	5.66E+03	1.12E+06	1.32E+05	2.24E+04	3.39E+03	-1.00E+00	1.961 E+03	5.293E+01	1.94E-01
11.5	5.38E+03	1.74E+06	1.00E+05	2.19E+04	3.98E+03	-1.00E+00	1.065 E+03	5.244E+01	1.86E-01
15.5	4.58E+03	1.79E+06	7.94E+04	2.00E+04	5.01E+03	-1.00E+00	1.065 E+03	5.203E+01	1.80E-01
21	3.55E+03	8.08E+05	6.03E+04	1.91E+04	4.79E+03	-1.00E+00	2.773 E+03	5.084E+01	1.78E-01
28	2.96E+03	5.52E+05	5.01E+04	1.78E+04	4.68E+03	-1.00E+00	2.773 E+03	4.921E+01	1.69E-01
37	2.30E+03	2.52E+05	4.27E+04	1.48E+04	3.89E+03	-1.00E+00	3.781 E+03	4.756E+01	1.67E-01
49	1.59E+03	1.15E+05	3.39E+04	1.00E+04	2.63E+03	-1.00E+00	2.101 E+03	4.605E+01	1.59E-01
65.5	1.15E+03	2.19E+05	2.24E+04	7.08E+03	1.86E+03	-1.00E+00	3.809 E+03	4.298E+01	1.46E-01
87.5	7.58E+02	7.79E+04	1.48E+04	4.68E+03	1.32E+03	-1.00E+00	3.445 E+03	3.973E+01	1.31E-01
115	5.38E+02	1.11E+05	1.12E+04	3.24E+03	7.94E+02	-1.00E+00	1.457 E+03	3.656E+01	1.19E-01
155	3.71E+02	6.84E+04	7.76E+03	1.95E+03	4.57E+02	-1.00E+00	9.250 E+02	3.252E+01	1.01E-01
210	1.94E+02	2.14E+04	4.37E+03	1.00E+03	2.14E+02	-1.00E+00	1.821 E+03	2.731E+01	7.87E-02

Table 6 shows the range of probabilities for the ground contamination levels of plutonium-238 with variations due to atmospheric stability being drawn from past climatic records for Europe.



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.



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Graph 5 applies another sheltering trigger adopted in the UK that derives directly from the assessment of the time integrated plume concentration. For the tunnel 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:

Table 7 Countermeasure Radial Distances

	i) **595g**	ii) **1.785kg**	iii) **5.355kg**	iv) **10.710kg**	v) **25.220kg**
COUNTERMEASURE	ROAD ACCIDENT & FIRE	SEVERE ROAD ACCIDENT & FIRE	TERRORIST ATTACK	VERSAILLES TUNNEL FIRE 3.5E-02 RELEASE	VERSAILLES TUNNEL FIRE ~0.1 RELEASE
SHELTERING OUT TO	5km	12km	40km	60km	110km
EVACUATION OUT TO	<1km	1.5km	2km	NA[61]	NA

The effectiveness of countermeasures is included in the safety supervision provisions for the transport of radioactive materials in France, where the road haulage mode is covered by the ADR agreement.[62] The ADR agreement places much reliance upon the toughness of the packaging, the reliability of specially equipped vehicles and efficient emergency action in response to an incident.

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.[63,64] For a plutonium dioxide consignment, IRSN assumes that the amount of PuO_2 release is limited to 0.07g for which the safety distances of 150 and 200m[65] are considered to be satisfactory, with these distances supposed to safeguard any (unprotected) member of the public receiving no more than 10mSv effective dose over a maximum of 5 hours exposure.

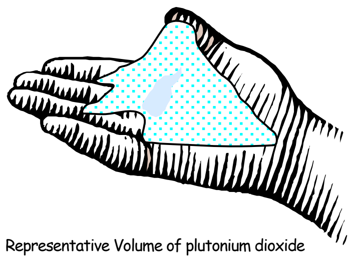
As previously noted the long term (effective) dose is committed to during the first few hours of exposure and even with prompt and well organised sheltering so relying upon a very short term effective dose provides no safeguard against the individual receiving the radiological components of the much higher long term (50 year) organ dose. For each of the scenarios considered here, maintaining the public at the IRSN reflex distances would result in a long term effective dose considerably higher than the 10mSv effective target.

In the longer term, a proportion of the inhaled insoluble particles of plutonium particles initially retained in the lung slowly migrate via the lymphatic system to the tracheobronchial lymph nodes. Plutonium entering the lungs and lymph nodes will eventually (in days and months) reach the bloodstream, of this plutonium entering the blood stream, about 20% is eventually excreted, and 80% retained, mainly in the liver and skeleton. Thus, several organs are at risk of developing cancer from the long-term dose that is committed to during the first few hours of the release, this being almost entirely due to inhalation.[66]

COSYMA also contains a database of European population distribution comprising population blocks 10km by 10km segments. With this database it is possible to derive the health impact in terms of numbers of public for both fatalities and total incidence, although the results of this should be treated cautiously because of the relatively course nature of demographic data, that dispersion and deposition in urban conurbations is very difficult to model, and because the public themselves may not behave in the aftermath of the incident in the assumed ways.

The lowest health consequence incidents modelled are road accidents at open-air locations that involve a single consignment vehicle in a severely damaging road traffic accident followed by fire of about one-quarter the load of a petroleum road tanker. The combination of impact and subsequent fire are considered sufficient to damage one or more of the FS47 flasks carried by the vehicle.

The accident damage is assumed to result in a respirable aerosol release from one of the FS47 flasks at a dispersed fraction of $3.5.10^{-2}$ or, for a 17kg flask contents, 595g of PuO_2 – this is the respirable release assumed by the United States Department of Energy analysis for its RADTRAN analysis of a FS47 flask consignment of weapons grade plutonium dioxide for the *Eurofab* programme for which each transport truck contains 3 FS47 flasks compared with the 9/10 carried for the French-sourced consignments.[12b)]



Representative Volume of plutonium dioxide released from one FS47 flask

Mortality predictions for the Paris and Lyon 595g accident scenarios are:

TABLE 8 LYON/PARIS 595g RELEASE – 50 YEAR HEALTH EFFECTS – MORTALITY/INCIDENCE

		TOTAL MORTALITY/INCIDENCE	LUNG MORTALITY	BONE SURFACE MORTALITY
LYON	maximum	**1.414E+02/1.718E+02**	1.052E+02	1.621E+1
	mean	**3.421E+01/4.309E+01**	2.545E+01	3.921E+1
	99th perc	**1.230E+02/1.549E+02**	9.120E+01	1.431E+1
	95th perc	**9.333E+01/1.175E+02**	6.918E+01	1.072E+1
	90th perc	**6.026E+01/7.586E+01**	4.467E+01	6.918E+0
	50th perc	**3.020E+01/3.801E+01**	2.239E+1	3.467E+0
PARIS	maximum	**5.235E+02**	3.892E+02	
	mean	**6.785E+01**	5.041E+01	
	99th perc	**5.012E+02**	3.715E+02	
	95th perc	**2.291E+02**	1.698E+02	
	90th perc	**1.778E+02**	1.318E+02	
	50th perc	**3.020E+01**	2.239E+01	

Table 8 expresses the incidence (expected above background) in terms of total mortality together with the contributions from lung cancer which dominates the overall health impact and, to a lesser extent, from other concentrated organ doses (bone surface and others diminishing in contribution are not shown here). This health impact is derived for the long term 50 year dose to which the greatest contributor is the lung.

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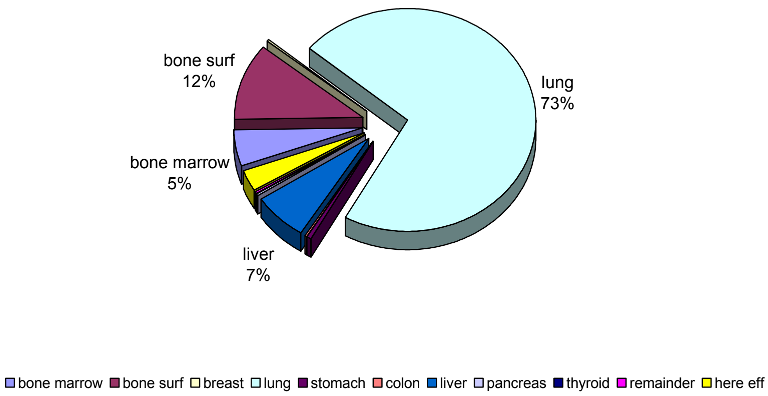
Late Health Effects - Mortality - Case v) 25.2kg Release



In completing dispersion and consequence analysis the usual approach is to order a number of subsets of conditions and circumstances and rank these in order of probability of occurrence – these probabilities are ranked in the left-hand column of **Table 8**. The consequences of a given release will vary with the release location, the wind direction and the meteorological conditions: The wind direction determines which population may be exposed and the area of land which may be contaminated; the meteorological conditions influence the rate at which the (radio)activity disperses and thus the exposure of the population and the levels of contamination. For any location there will be a statistical distribution of both wind direction and meteorological conditions resulting in a probability distribution of consequences associated with any release scenario – this probability can be expressed in terms of its mean, median and percentiles.[67] The risk to any individual (the individual risk) is also a function of the distance and direction for the site of the release.

The health consequences of the 595g release and other scenarios modelled and analysed are summarised in terms of *Total Mortality* are as follows:

TABLE 9 LATE (50 YEAR DOSE) MORTALITY PROBABILITIES FOR ACCIDENT AND TERRORIST SCENARIOS

		i) 595g ROAD ACCIDENT	ii) 1.785kg SEVERE ROAD ACCIDENT	iii) 5.355kg TERRORIST ATTACK	iv) 10.710kg VERSAILLES TUNNEL FIRE 3.5E-02 RELEASE	v) 25.220kg VERSAILLES TUNNEL FIRE ~0.1 RELEASE
LYON	maximum	1.414E+02	4.244E+02	8.465E+02		
	mean	3.421E+01	1.027E+02	1.634E+02		
	99th perc	1.230E+02	3.715E+02	6.918E+03		
	95th perc	9.333E+01	2.818E+02	4.677E+02		
	90th perc	6.026E+01	1.820E+02	3.467E+02		
	50th perc	3.020E+01	9.120E+01	1.259E+02		
PARIS	maximum	5.235E+02	1.572E+03	4.691E+03	4.897E+03	1.152E+04
	mean	6.785E+01	2.037E+02	4.667E+02	6.127E+02	1.323E+03
	99th perc	5.012E+02	1.514E+03	4.467E+03	3.311E+03	7.762E+03
	95th perc	2.291E+02	6.918E+02	1.445E+03	1.905E+03	4.467E+03
	90th perc	1.778E+02	5.370E+02	1.072E+03	1.778E+03	3.631E+03
	50th perc	3.020E+01	9.120E+01	1.995E+02	3.020E+02	6.457E+02

APPENDIX I

PREVIOUS AND PRESENT ROAD ROUTE FOR PLUTONIUM TRANSPORT

APPENDIX II

FS47 TRANSPORTATION FLASK

Two PuO2 carrying trucks in convoy with the Gendarme car in between and just visible the Gendarme minibus at the rear

Approach to the cut and cover road tunnel at Versailles – this is the location for both road and terrorist attack synthesised incidents involving fire

Comparison of French (top) and United States road transport vehicles – the French vehicle appears to be a commercial tractor unit with a standard unarmoured IOS container on the trailer – the US safe secure transport (SST) is a fully armoured custom-built vehicle with anti-access and removal equipment and devices built-in – the US vehicle is limited to 3 FS47 flasks whereas the French vehicle carries 9/10 FS47 flasks.

APPENDIX III

PRINCIPAL RADIONUCLIDE INVENTORY OF REACTOR GRADE PLUTONIUM

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APPENDIX IV

ACCIDENT AND TERRORIST SCENARIOS

i) **595g**	ii) **1.785kg**	iii) **5.355kg**	iv) **10.710kg**	v) **25.200kg**
ROAD ACCIDENT	**SEVERE ROAD ACCIDENT**	**TERRORIST ATTACK**	**VERSAILLES TUNNEL FIRE 3.5E-02 RELEASE**	**VERSAILLES TUNNEL FIRE 0.1 RELEASE**
One consignment vehicle is involved in a collision with a bridge abutment or similar, the ISO container is damaged and a number of the FS47 flasks within are damaged and exposed, immediately after the impact a petrochemical tanker catches fire in close proximity to the disabled convoy vehicle and burns approximately one-half its load, with the fire lasting about 2 hours with the release fraction being adopted from the US Eurofab study for failure of one FS47 flask.	As for i) but adopting and pro-rata number of failed flasks from 1 to 3 failures	A single convoy vehicle is isolated and brought to rest under a road overbridge or within the tunnel – the ISO container is entered and explosive charges are placed on the flasks and externally on the ISO container – the charges are detonated and the plume is developed by burning the contents of 2 petrochemical tankers of about 3 to 4 hours from a burning area equivalent to a 5m radius pool within the tunnel or in the confines under a road overbridge - it is assumed that there is no contribution from other commercial cargoes trapped in the tunnel.	In this tunnel incident, either as the result of a terrorist attack or by a road traffic incident or accident, both convoy vehicles are trapped within the tunnel, in a fire that burns for 3 to 4 hours.	In this incident, again induced by accident or terrorist attack, the fire is ferocious, burning for 10 or more hours and the flask fails to CATEGORY VIII release at a 10% release fraction.

INPUT DATA AND CONTROLS FOR COSYMA

PARAMETER		PARIS ROAD ACCIDENT	PARIS ROAD ACCIDENT	PARIS ROAD ACCIDENT	PARIS TUNNEL ACCIDENT	PARIS TERRORIST	LYON ROAD ACCIDENT	LYON ROAD ACCIDENT	LYON TERRORIST	COMMENTS
Location		1.625-48.68	1.625-48.68	1.625-48.68	1.625-48.68	1.625-48.68	4.55-45.48	4.55-45.48	4.55-45.48	
Site Conditions	Wind Speed Height - m	10	10	10	10	10	10	10	10	
	Surface	Rough	Rough	Rough	Rough	Rough	Rough	Rough	Rough	
Deposition	Aerosol Dry m/s	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	
	Wet Constant	8E-5	8E-5	8E-5	8E-5	8E-5	8E-5	8E-5	8E-5	Exponential 0.8
Source Term	2 Phases start hours	1 - 5	1 - 5	1 - 5	1 - 5	1 - 5	1 - 5	1 - 5	1 - 5	Paris3/Lyon3
	Release height m	6-8	6-8	6-8	6-8	6-8	3 - 2	3 - 2	3 - 2	
70.96	Energy MW	35.48	35.48	35.48	70.96	70.96	35.48	35.48	70.96	
	Inventory	595g Tab 1	1.785g Tab 1	1.785g Tab 1	10.715g/25.22 Tab 1	5.355g Tab 1	595g Tab 1	1.785g Tab 1	5.355 Tab 1	Source US DOE
	Pu238	1.15E+13	3.45E+13	3.45E+13	2.07E+14	1.03E+14	1.15E+13	3.45E+13	1.03E+14	
	Pu239	7.11E+11	2.13E+12	2.13E+12	1.28E+13	6.37E+12	7.11E+11	2.13E+12	6.37E+12	
	Pu240	1.22E+12	3.67E+12	3.67E+12	2.20E+13	1.10E+13	1.22E+12	3.67E+12	1.10E+13	
	Pu241	3.49E+14	1.05E+15	1.05E+15	6.28E+15	3.13E+15	3.49E+14	1.05E+15	3.13E+15	
	Pu242	6.73E+09	2.02E+10	2.02E+10	1.21E+11	6.03E+10	6.73E+09	2.02E+10	6.03E+10	
	No of Flasks Breached	1	3	3	18	9	1	3	9	Adapted from US
	Release fraction	1	1	1	1	1	1	1	1	All release respirable sized
Distribution	Population File	preset	preset	preset	preset	preset	preset	preset	preset	Paris1/Lyon1
Countermeasures		YES	YES	NO	YES	YES	YES	YES	YES	
	Sheltering/evacuation Sv	0.05	0.05		0.05	0.05	0.05	0.05	0.05	Dose based
	Initial delay hours	2	2		2	2	2	2	2	
	Drive out time minutes	60	60		60	60	60	60	60	
	Decontamination delay hours	6	6		6	6	6	6	6	
	Shelter (no evac) distance km	10	10		10	10	10	10	10	Shelter distance based
	Sheltering delay hours	2	2		2	2	2	2	2	
	Shelter duration hours	2	2		2	2	2	2	2	
	Decontamination delay hours	6	6		6	6	6	6	6	
	Shielding factor	0.5	0.5		0.5	0.5	0.5	0.5	0.5	Buildings
	Sheltering Sv	0.01	0.01		0.01	0.01	0.01	0.01	0.01	Sheltering dose based
	Maximum distance km	24	24		24	24	24	24	24	
	Relocation Intervention Sv	0.05	0.05		0.05	0.05	0.05	0.05	0.05	Groundshine/resuspension
	Resettlement Sv	0.025	0.025		0.025	0.025	0.025	0.025	0.025	
Dose Evaluation	Mortality factors	ICRP60	ICRP60	ICRP60	ICRP60	ICRP60	ICRP60	ICRP60	ICRP60	
	Breathing rate m^3/hr	3.3E-4	3.3E-4	3.3E-4	3.3E-4	3.3E-4	3.3E-4	3.3E-4	3.3E-4	adult
Run Name		P59CMR	P17CMR	P17NCMR	P10CMTUN	P53CMTER	L59CMR	L17CMR	L53CMT	
Table										

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1 Plutonium is a radioactive, silvery, metallic transuranic element, produced artificially by neutron bombardment of uranium, having 15 isotopes with masses ranging from 232 to 246 and half-lives from 20 minutes to 76 million years. The principal radiation from plutonium is the alpha particle. These alpha particles cannot penetrate the outer layer of human skin; therefore, plutonium outside the body is relatively harmless, and the primary hazard is internally via inroad to the human body by inhalation.

2 The MOX blending and pelletisation plant at Cadarache is effectively closed, although it will probably reopen in late 2004 to deal with a consignment of about 50kg of US weapons-grade plutonium under the Eurofab contract for France to manufacture 4 MOX lead fuel assemblies.

3 The tractor-trailer unit involved comprises a cab that may be armoured hauling a trailer unit with the load compartment being 2050 x 2300 x 6070mm dimension made up from what seems to be a standard ISO container piggy-backed on the trailer platform. The vehicle has a maximum payload of about 20 tonnes. The load of 9/10 FS47 flasks, with the delivery convoy comprising transport, escort and communications control vehicles, all fitted with vehicle tracking systems.

4 Typically 9 full FS47 flasks are carried together a single empty FS47 flask, all located in a rigid rack holding the flasks vertically.

5 Type B(U) in accordance with International Atomic Energy Agency (IAEA) 1996 Regulations, TS-R-1 – see also *Regulations for the Safe Transport of Radioactive Material, Safety Standards Series No. ST-l* Requirements, Edition, Vienna (1996).

6 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

7 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.

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

9 Essentially, respiratory protection in the form of breathing apparatus and the appropriate filter masks.

10 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.

11 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.

12 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 Â Haut Risqué*, WISE, February 2003) details the following which corresponds to about 4x the higher bone cancer factor adopted for weapons-grade plutonium.

Table 2 Dose Exposure per milligram PuO_2 Inhaled

ISOTOPE	UPTAKE MODE	EXPOSURE Sv/Bq	EXPOSURE Sv/mg
Pu-238	inhalation	1.6E-5	309

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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

13 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

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

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

16 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.

17 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

18 IAEA INFCIRC/225/Rev 4 gives the primary factor for determining the physical protection measures against unauthorized removal of nuclear material to be the nuclear material itself – in fact, the highly enriched uranium content is downgraded from its normal Category I status because the fuel has been irradiated which, in itself, is considered to provide an additional security barrier.

19 IAEA 1996 Regulations, TS-R-1 – see also *Regulations for the Safe Transport of Radioactive Material, Safety Standards Series No. ST-l* Requirements, Edition, Vienna (1996)

20 IAEA-TECDOC-766, *Safe Handling, Transport and Storage of Plutonium,* October 1994

21 IAEA 1996 Regulations, TS-R-1 - see also *Regulations for the Safe Transport of Radioactive Material*, Safety Standards Series No. ST-l Requirements, Edition, Vienna (1996) and *The Physical Protection of Nuclear Material* (INFCIRC/274 Rev.1 and 225 Rev 4).

22 In terms of security, there is an additional degree of physical protection required for fissile materials in transit, particularly plutonium which the United States defines as *'strategic special nuclear material'* and for which it applies, in addition to INFCIRC/225, its own *'Stored (nuclear) Weapons Standard'* because, obviously, the plutonium dioxide could be converted for use with the fissile core of a nuclear weapon - since here only French-sourced consignments of PuO_2 are being considered the US *'Stored Weapons Standard'* does not apply, although for the US *Eurofab* US Los Alamos sourced PuO_2 consignment presently under consideration for an Export Licence by the US Nuclear Regulatory Commission this US standard is likely to be required in addition to IAEA INFCIRC/225.Rev 4.

23 Décret N° 2003-295 du 31 Mars 2003.

24 When referring specifically to Eurofab (see Eurofab of Footnote 22, HFD stated *"transport measures will be confidential"*, Nuclear Engineering, No 24, November 24, 2003

25 *Reexamination of Spent Fuel Shipment Risk Estimates*, NUREG/CR-6672

26 *Final Environmental Impact Statement on the Transportation of Radioactive Material by Air and Other Modes*, NUREG-0170, December 1977.

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

28 Indeed, some observers would note that the proposed shipment of the US-sourced Eurofab material might be considered an attractive target whatever its location, that is both in the United States, on the high seas or overseas in France.

29 Following events of 11 September, terrorist attack against any nuclear consignment in transit cannot be discounted and, in recent months, the threat has heightened in Europe (apparently from the ongoing number of arrests). 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. 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 an 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 two individuals in urban environments.

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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 x 10^{-5} to 8 x 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.

30 As much as 50% of the plutonium dispersed by an explosion might be respirable, although 20% may be a better estimate, compared to a fire, by contrast, it is likely that no more than about 0.05% of the oxidized plutonium would be respirable. The release fraction assumed from the US analysis considers only respirable-sized particles. The US Eurofab release fraction of 3.52E-02 is all of respirable size dioxide.

31 [Particularly a water reservoir treated with chlorine, with the chlorine increasing the human gut transfer factor of the plutonium significantly.]

32 Barnaby, F *Nuclear Terrorism: The Risks and Realities in Britain*, Oxford Research Group, February 2003

33 Lovins A L, Nuclear Weapons and Power-Reactor Plutonium. Nature V283, February 1980

34 As reported by Greenpeace France.

35 A thermic lance comprises a mild steel tube threaded with a bundle of mild steel wires and, usually, a single aluminium wire. Oxygen is fed down the tube and ignited at the burning tip of the lance the extremely high temperature (>3000°C) iron-oxygen reaction enables other materials to be cut through at very high rates of progress.

36 Of course, it would be necessary to breach the convoy trailer unit in order to attack the FS47 flask(s) within, although the armour plating of the trailer must be relatively light gauge because, for this size of vehicle, armouring on the scale adopted for military fighting vehicles would result in excessive axle loads. Thus, a two shot attack would be necessary, first to access into the trailer unit and then a second round to breach the flask(s).

37 Details of the convoy vehicle container are not available, although the vehicle shown in Appendix II hauls what seems to be a standard swap body 7m long ISO container. At a maximum of 44 tonnes GVW, trailers with three fixed non-steer axles can carry a maximum load through the trailer bogie of around 24 tonnes, with a corresponding load imposed through the kingpin of around 11.2 tonnes. So for a standard ISO container construction the payload limited to 28.5 tonnes. The loaded FS47 flask weighs about 1.75t and its mounting frame might account for further 0.25 tonnes, so the maximum 10 racked flasks account for 17.5t of the available payload.

Armoring the ISO container would require further reduction in the load acting through the kingpin and fixed axles of the trailer – for example, using a 30mm composite armour, such a Chobham, to fully encase the container internally would add about 10 to 14 tonnes of structural deadweight which would grossly exceed the tractor kingpin loading. Hence, it is likely that the ISO container being hauled by the 3 axle tractor unit is not heavily armoured, if armoured at all.

38 *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

39 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.

40 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

41 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)

42 *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

43 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.

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

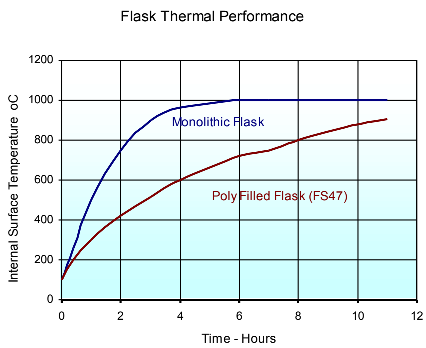
45 Shaw K, *The Radiological Impact of Postulated Accidental Releases during the Transportation of Irradiated PWR Fuel through Greater London*, NRPB-R147, 1983

46 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 charges, 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. Similar trials simulating sabotage on irradiated fuel flasks were undertaken in the early 1980s and 1990s in the United States. In the United Kingdom, the National Radiological Protection Board undertook the analysis of a radioactive release from an irradiated PWR fuel flask that had been hypothetically subject to terrorist attack by an armoured piercing round, thus setting the parameters for a radioactive release initiated by explosive conditions. All of these experimental trials were conducted on the much more robust Castor-type design of irradiated fuel transport flask with side walls of 150 to 200mm solid carbon steel and of about 100 tonnes weight, compared to the much lighter plutonium dioxide FS47 flask at 1.7 tonnes with the side walls made up as a sandwich structure of relatively thin steel shells separated by a non-structural ablative and neutron absorbing infill – as previously noted, compliance with the IAEA 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.

47 As required for the present Export License review by the Nuclear Regulatory Commission of the United States: a) *Storage and Disposition of Weapons-Usable Fissile Materials Final Programmatic Environmental Impact Statement (Storage and Disposition PEIS)* DOE/EIS-0229, December 1996) (DOE 1996a), b) *Surplus Plutonium Disposition Environmental Impact Statement (SPD EIS),* (DOE/EIS 0283, November 1999) (DOE 1999b). c) Supplement *Analysis, Fabrication of Mixed Oxide Fuel Lead Assemblies in Europe*, November 2003, US DOE/EIS-0229-SA3

48 There are four characteristic fire duration times of interest: 10 minutes being the duration of a typical automobile fire, 30 minutes the duration of a (IAEA TR-1) regulatory fire, 60 to 90 minutes the typical duration of an experimental pool fire with fuel from one tanker truck, and considerably longer but generally unspecified duration for tunnel fires.

The graph shows the thermal performance of a monolithic flask compared to a simple representation of a dense poly filled cavity flask (FS47) with the internal temperatures of this flask reaching the temperature at which the poly fill would gas (about 300oC) in little over one hour, thereafter the flask would be at increasing risk of rupture, although the flask lid seals and inner plutonium container cans would be likely to have failed before this temperature.



49 NOAA HYSPLIT is the US Air Resources Laboratory air concentration and dispersive model and Hotspot is the Lawrence Livermore National Laboratory predictive software for release plumes. Hotspot is also used to provide a check on COSYMA

50 COSYMA is the European Commission sponsored and approved nuclear accident assessment software modelling facility development of the MARIA (Methods for Assessing Radiological Impact of Accidents) code.

51 A fire outbreak in a tunnel would be expected to last considerably longer if the fuel and cargoes of other vehicles trapped behind the convoy burnt and contributed to the flames, The recent 1999 Mont Blanc fire burnt for two days and the 1996 Channel Tunnel fire burnt for 10 hours – tunnels fires of such severity could be expected to result in a significantly larger aerosol release fraction of the plutonium consignment that adopted for this study.

52 The Summit (Derbyshire - UK) railway fire involving a petroleum tanker train and which burnt for 48 hours or more and at temperatures sufficient to vitrify the brick lining; the Channel Tunnel railway fire of temperature sufficient to cause explosions in the reinforced concrete liner, and the Mont Blanc road tunnel fire which raged for 24 hours or more – see also *Fires in Transport Tunnels: Report on Full-Scale Tests*, EUREKA-Project EU499:FIRETUN Studiengesellschaft Stahlanwendung eIV. D-40213 Dusseldorf. 1995.

A summary of road tunnel fires is given by STUVAtec GmbHa follows:

						Consequences on		
Year	**Tunnel**	**Place**	**Vehicles at origin of fire**	**Probable cause**	**Duration**	**People**	**Vehicles**	**Tunnel**
1949	Holland L = 2.550 m	New York USA	1 lorry loaded with 11 t of carbon bisulfur	load falling of lorry	4 h	66 injured	10 lorries 13 cars	serious damage for 200 m
1968	Moorfleet L = 243 m	Hamburg Germany	1 lorry trailer (14 t of polyethene bags)	brakes jamming	1 h 30 min	none	1 trailer	serious damage for 34 m

1975	Guadarrama L = 3.330 m	Guadarrama Spain	1 lorry loaded with tanks of pine resin	unknown	2 h 45 min	none	1 lorry	serious damage for 210 m
1976	B6 L = 430 m	Paris France	1 lorry loaded with 16 t of polyester in bundles	unknown	1 h	12 slight injured (smoke inhalation)	1 lorry	damage for 150 m
1978	Velsen L = 770 m	Velsen Netherlands	2 lorries + 4 cars	front-back collision	1 h 20 min	5 dead 5 injured	2 lorries 4 cars	serious damage for 30 m
1979	Nihonzaka L = 2.045 m	Shizuoka Japan	4 lorries + 2 cars	front-back collision	4 days	7 dead 2 injured	127 lorries 46 cars	serious damage for 1.100 m
1980	Kajiwara L = 740 m	Japan	1 truck (4 t) with 3.600 l paint in 200 cans + 1 truck (10 t)	collision with side wall and overturning		1 dead	1 truck (4 t) 1 truck (10 t)	damage for 280 m
1982	Caldecott L = 1.028 m	Oakland USA	1 lorry + 1 coach + 1 car 33.000 l of petrol	front-back collision	2 h 40 min	7 dead 2 injured	3 lorries 1 coach 4 cars	serious damage for 580 m
1983	Fréjus L = 12.868 m	Modane France-Italy	1 lorry loaded with plastic materials	gear box breaking	1 h 50 min	none	1 lorry	serious damage for 200 m
1984	Felbertauern L = 5.130 m	Austria	1 bus	blocking brakes	1 h 30 min	none	1 bus	damage to ceiling and equipment for 100 m
1984	Gotthard L = 16.321 m	Goeschenen Switzerland	1 lorry loaded with rolls of plastic	fire in engine	24 min	none	1 lorry	serious damage for 30 m
1987	Gumefens L = 340 m	Bern Switzerland	1 lorry	mass collision on slippy road	2 h	2 dead	2 lorries 1 van	slight damage
1993	Serra Ripoli L = 442 m	Bologne Italy	1 car + 1 lorry loaded with rolls of paper	vehicle out of control and collision	2 h 30 min	4 dead some injured	4 lorries 11 cars	serious damage to lining
1994	Gotthard L = 16.321 m	Goeschenen Switzerland	1 lorry + trailer loaded with bikes wrapped in carton and plastic	friction between wheels and loading bridge	2 h	none	1 lorry + trailer	serious damage to ceiling, pavement and equipment for 50 m, tunnel closed for 2,5 days
1995	Pfänder L = 6.719 m	Austria	1 lorry + 1 van + 1 car	collision	1 h	3 dead (by crash)	1 lorry 1 van 1 car	serious damage to ceiling and equipment, tunnel closed for 2,5 days
1996	Isola delle Femmine L = 150 m	Italy (Sicilia)	1 tanker with liquid gas + 1 little bus	wet road collision of a bus with a tanker (stopped because of a previous collision), explosion	unknown	5 dead (by fire) 20 injured	1 tanker 1 bus 18 cars	damages to the tunnel lining and lighting equipment
1999	Mont Blanc L = 11.600 m	France-Italy	1 lorry loaded with 20 tons of margarine and flour	fire in engine	~50 h	42 dead 27 injured	34 vehicles	serious damage to about 100 m of ceiling
1999	Tauern L = 6.400 m	Austria	1 lorry loaded with paint	front-back collision	17 h	12 dead more than 50 injured	16 lorries 24 cars	serious damage, tunnel closed for about 3 months

53 Emergency Handbook, NRPB W19, 2001 – this indicates that resuspension to airborne dose for plutonium isotopes reduces by a factor of one thousand over one year following the incident.

54 It is not considered practicable to provide full respiratory protection to large numbers of public at the outbreak of a release of plutonium, particularly so for transportation accidents where the locality of the release area cannot be fixed as with a fixed nuclear plant.

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

56 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.

57 *The Radiation (Emergency Preparedness & Public Information) Regulations 2001.*

Large and ASSOCIATES Consulting Engineers

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

59 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.

60 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).

61 This apparent anomaly of no requirement to evacuate arises because the tunnel fire provides very effective plume lofting, thereby there is no receptor height (1.5 to 2m) plume in the immediate vicinity of the incident.

62 Saint Raymond P, Aguilar J, Jacob E & Seyer E *Safety Supervision Provisions for the Transport of Radioactive Materials in France*, Direction Generale de la Surete Nucleaire et de la Radioprotection, IAEA-CN-101/73, Vienna 2003 – the public information about such events, etc., is given by decrees 93-1272 (1993) and 2002-255 (2002).

63 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.

64 In the UK, the Ministry fo 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.

65 DN5 and DF2 respectively being defined by a low diffusion coefficient with a wind velocity pf 2m/s (DF2) and for normal diffusion and a wind velocity of 5m/s (DN5) – this paper also specifies a safety distance of. 100m where a Type b flask has been 'seriously damaged' and 500m where a Type B flask has been subject to a 'serious' fire. As previously noted, the United States adopts a respirable-sized aerosol release of 595g for a worst case road vehicle accident involving a FS47 PuO_2 carrying flask (see Table 3) when in transit in a SST protected vehicle, suggesting that the IRSN's confidence in the surety of the FS47 flask to be considerably higher (if not absolute) than the US's evaluation.

66 There also heredity effects via exposure of the gonads, with 90%+ of the exposure pathway being via inhalation.

67 The Expectation value of a probability distribution is the arithmetic mean or the average value of the distribution – it would represent the average number of consequences (outcomes) were the same accident to occur a large number of times. In general, the Expectation value will differ from the Median value of the distribution where the Median value of a distribution is the value that would be exceeded with a probability of 0.5.