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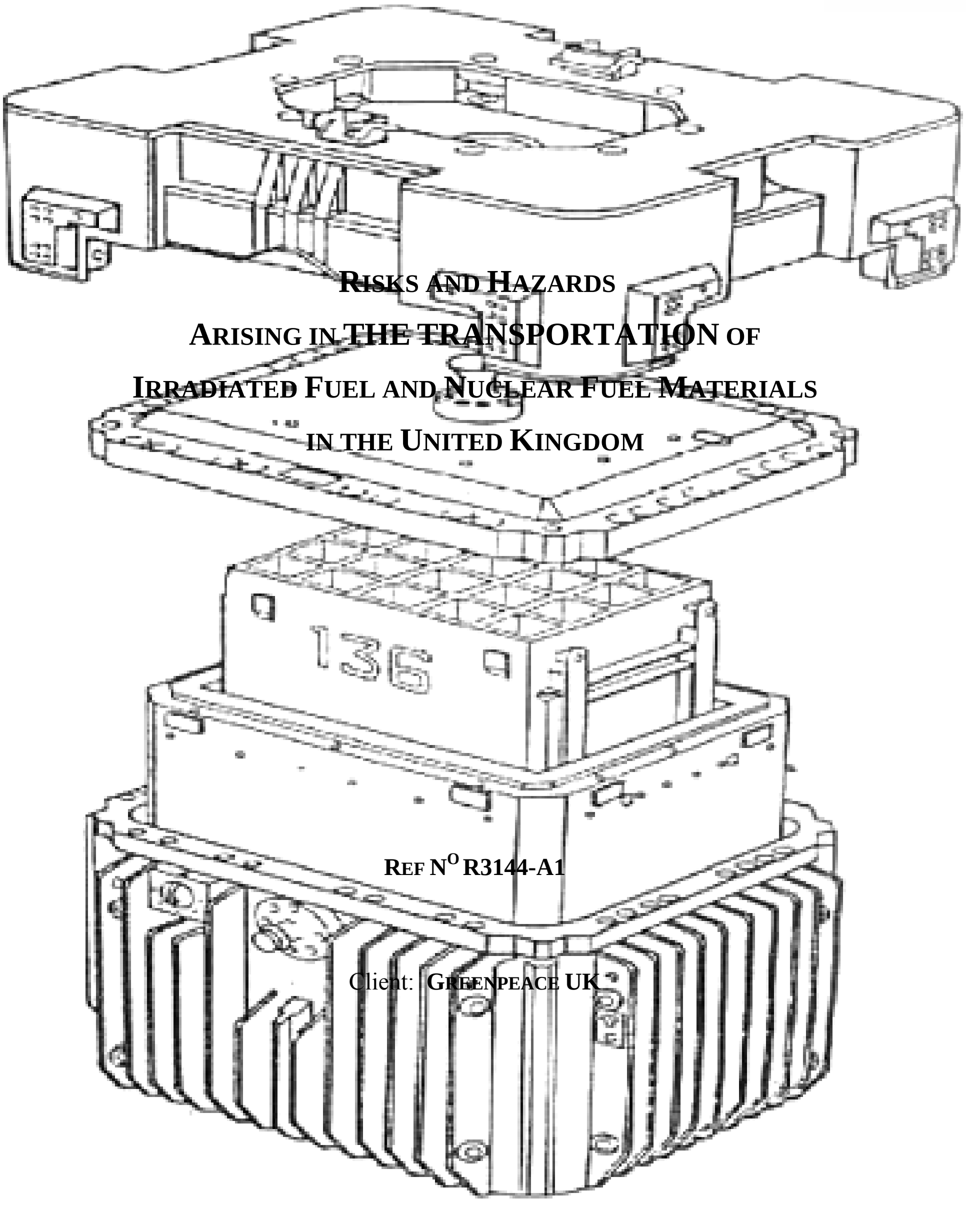

RISKS AND HAZARDS
ARISING IN THE TRANSPORTATION OF
IRRADIATED FUEL AND NUCLEAR FUEL MATERIALS
IN THE UNITED KINGDOM

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Cover: Diagrammatic of AGR spent fuel transport flask with its lid shock absorber cover.

RISKS AND HAZARDS OF THE TRANSPORTATION OF SPENT FUEL IN THE UK

SUMMARY

This Review examines the hazards, risk and potential consequences associated with the transport movements of irradiated (spent) nuclear fuel in the United Kingdom.

The Review identifies potential accidents and malevolent acts that could severely damage a spent fuel transportation flask, thereby enabling the release of radioactivity, in the form of particles and aerosols, and the corresponding health risk imposed on unprotected members of public. Because the rail routes take the spent fuel trains through major urban conurbations (London, Bristol, etc) many thousands of population could be subject to radiation exposure in the aftermath of such an event.

Rail Routes and Flask Loading Localities: Spent fuel is hauled to Sellafield by goods trains dedicated to this nuclear traffic. These trains feed spent fuel to Sellafield, weaving their way from nuclear power stations in the south-west (Hinkley Point, Somerset and Oldbury, Gloucestershire), south (Dungeness, Kent), east (Sizewell, Suffolk), south and the north (Hartlepool, Co Durham and Heysham, Lancashire) in England, from Ynys Môn (Wylfa) in Wales, Hunterston (Ayrshire) and Torness (near Edinburgh) in Scotland. During any week, at least one train hauling several flask loads of Magnox and/or AGR fuel will be in transit somewhere on the public rail network in the United Kingdom, sharing the railway with local and national passenger, freight and hazardous good trains.

Some of the nuclear power stations do not have direct access to a railhead. From these power stations it is necessary haul the spent fuel flasks by road to the nearest railhead for loading onto the flatrol wagons of the dedicated spent fuel train. For example, the Hinkley Point AGR power station makes this transfer in the centre of the market town of Bridgwater in a small compound that is directly opposite the station platform and within a few tens of meters of a primary school. When the power station is dispatching more than one flask, the train has to marshal each rail flatrol wagon into the short spur of track under the hoisting gantry, transfer the full flask to the flatrol, then move the flatrol and full flask to an adjacent track spur so that a second flatrol containing an empty flask can be positioned under the gantry for transfer to the road vehicle. The single articulated road unit goes back to the power station and then returns with the next fuel flask, and so on until a complete train load of spent fuel is made up. The whole process of loading a train in the centre of Bridgwater might take 4 or more hours, throughout which the train and batches of spent fuel remain in the siding with little physical protection against terrorist attack.

The Review considers general means by which the highly radioactive, respirable-sized particles of spent fuel might be released and how such a release and its dispersion could impact upon the environment and population. These include both realistic accidents and, now in the post 11th September 2001 and 7/21 July 2005 climates, acts of terrorism.

Flask Resistance to Accidental Events: The range of possible and reasonably foreseeable accidents are assessed and some of these are considered to be capable of severely damaging the flask to the extent that a significant radioactive release could occur, particularly where the spent fuel train is somehow held up in tunnel, say by derailment, and there is an outbreak of fire from, say, the locomotive fuel or by another train cargo also disabled in the accident. The nuclear industry dismisses the credibility of such a severely damaging accident by, first, referring to its past record of safe haulage of spent fuel over the last fifty or so years and, second, by its compliance with international guidelines for spent fuel transportation flasks. This Review counters these claims in that a past record, however excellent, is no portend of the future and that the international standard relied upon is considered not to represent the severest of accident situations, particularly tunnel fires which could devastate the flask containment and enable a radioactive release. Such a situation involving flasks carrying Magnox spent fuel could result in very significant radiological consequences because the Magnox fuel, itself, will burn and disperse via a long ranging radioactive plume.

Targeting by Terrorists: It is now known that one group planning a terrorist outrage in London had acquired plans of Sizewell nuclear power station and the location of radioactive waste storage facilities in the UK and, with much the same intent, another group is alleged to have attempted to procure a nuclear warhead for use in the UK.[39,37] Obviously such an interest in the specific hazards associated with nuclear facilities and devices shows that these terrorists had no reservations about the use of radioactivity to create the mayhem and health consequences that would surely follow a successful attack on a strong source of radioactivity such as a spent fuel flask. Whereas, hijacking and absconding with the highly radioactive spent fuel is considered not to be at all practicable, those minded to might be able to sufficiently damage a flask(s) carrying spent fuel and contrive a ‘dirty bomb’ situation (explosion, fire, or the like) whereby there would arise a efficacious release and dispersion of radioactivity. If such an incident occurred in a densely populated urban environment, say in London, then the radiation dose received by many individuals could be very significant indeed.

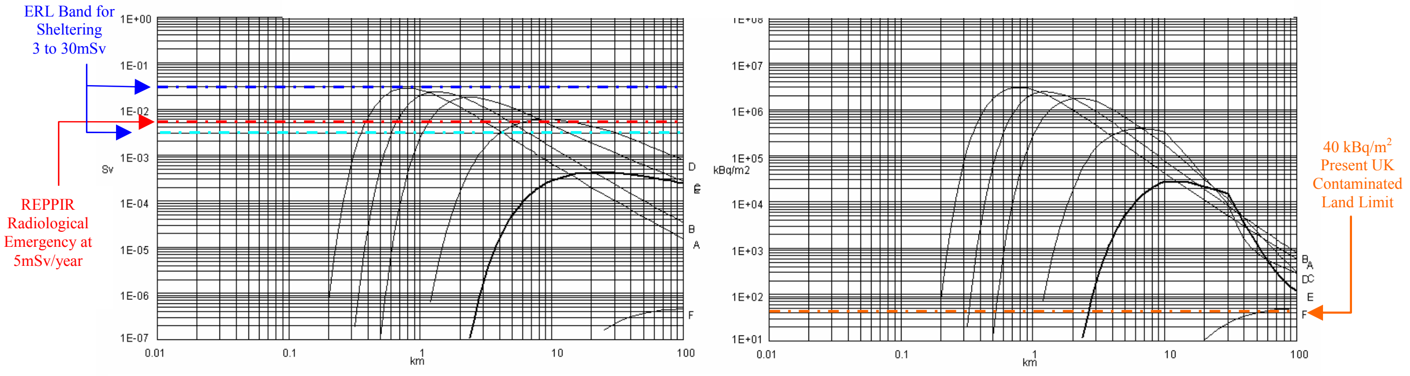
Potential Terrorist Incidents: Unlike accidents that are, after all, unintentional and unintelligent events, a terrorist attack will be intelligent and intentional, seeking out vulnerabilities of the system that could include elements to deliberately hinder any post-incident countermeasure implemented to mitigate the consequences of the release. It is the latent ingenuity and outrageousness of the terrorist act that renders it so difficult to counter. The Review concluded that it is not possible to identify all potential modus operandi that could be adopted by the terrorist, and where and when such an attack could occur. The terrorist has the choice of a powerful arsenal of devices and situations with which, first, to attack the surety of the flask and then, once the containment had failed, to maximise the radioactive release and its dispersion beyond the local area. In undertaking and discharging the attack on a spent fuel train, either when in transit or stationary when loading the flasks, the terrorist might then move on to confuse and delay the emergency response that is essential to mitigate the exposure to radiation of the population and the thousands of individuals that might be caught in the dispersion and fall-out of the radioactive release.

Nuclear terrorism is, quite rightly, a very sensitive area so the Review does not attempt to compile specific and detailed accident/incident scenarios and identify target locations where the radiological and health consequences might be maximised. Instead, the abnormal conditions at which the spent fuel flask would be expected to fail are examined in general terms. The broad range of past published work identifies the response of spent fuel flasks to armour piercing ordnance, shaped explosive charge and engulfing fire. Experiments and realistic tests on actual flasks included in this work shows that LWR spent fuel flasks are vulnerable to fire and explosive attack and, although nothing has been published on the UK flask designs in this respect, the Review concludes that the design and materials used for the UK Magnox and AGR cuboid shaped flasks provide no extraordinary safeguard against terrorist attack. In fact, extreme thermal conditions present the greatest challenge to the UK water filled cuboid flask, with prolonged engulfing fire being its greatest weakness and most direct route to failure. Such extremes of temperature and fire duration apply to both accidents, such as the high and sustained temperatures involved in a tunnel fire, and to explosion and fire circumstances that might be generated by any number of terrorist attack scenarios.

The flask structure (the steel lid and base shells), particularly the AGR flask with its structural wall thickness of 90mm compared to the Magnox flask of about 280mm thickness, are also shown to be susceptible to being punctured by an armoured piercing explosive round or a crudely shaped explosive charge. A flask or flasks attacked in this way, especially if followed by a fierce fire within the confines of a tunnel or in a contrived enclosure concocted at one of the road-railhead loading points, is reckoned to result in a very significant radioactive release to the environment.

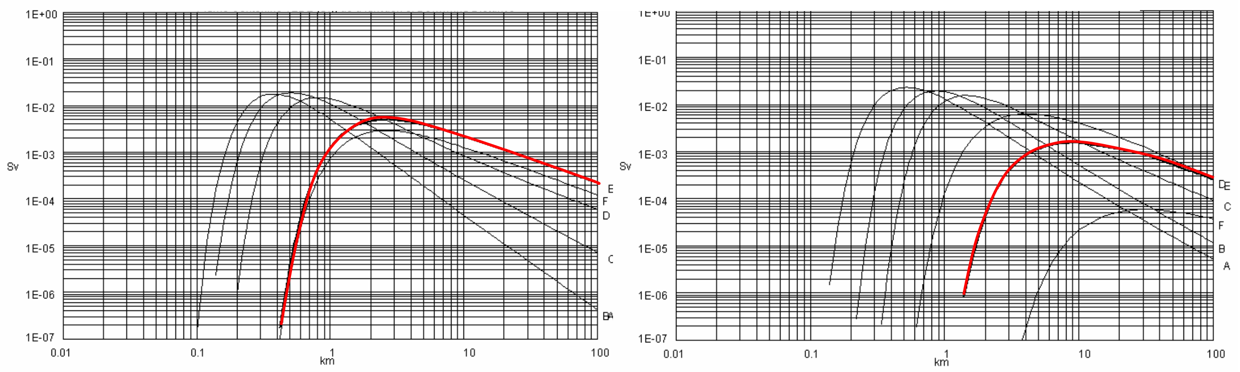
Security: The nuclear industry and its security regulator (OCNS) are, as expected, coy about the terrorist threat. The facts are that the arrangements and transportation systems serving spent fuel movements were established in times when little was done to secure the routes against terrorist act; that ordnance has advanced considerably over recent years, with knowledge of and access to this military technology now very available via the internet and, especially, terrorism training camps abroad; and, most recently in the UK, there are the allegations that two separate UK-based terrorist groups have sought information on nuclear facilities and radioactive materials thereby identifying these to be potential terrorist targets. Yet, despite this concern details of how, when and by which routes the spent fuel is moved, although not published in advance, are well known with the transits being both regular and frequent. Even casual observations suggest that the physical security accompanying the spent fuel trains is minimal, the staffing is by regular railway personnel and there is no special security or police in attendance, and at the off-site railheads full flasks of spent fuel can be left standing in the open for several hours.

Flask Performance and Potential Consequences of Accidents and Incidents: The results of failure of the flask, for both a tunnel scenario and in the open at one of the road-to-rail railheads, are analysed at two hypothetical locations with the spent fuel flasks subject to a range of incident conditions, including for variations in flask containment damage severity, fraction of the radioactive contents released, climatic stability, and so on.



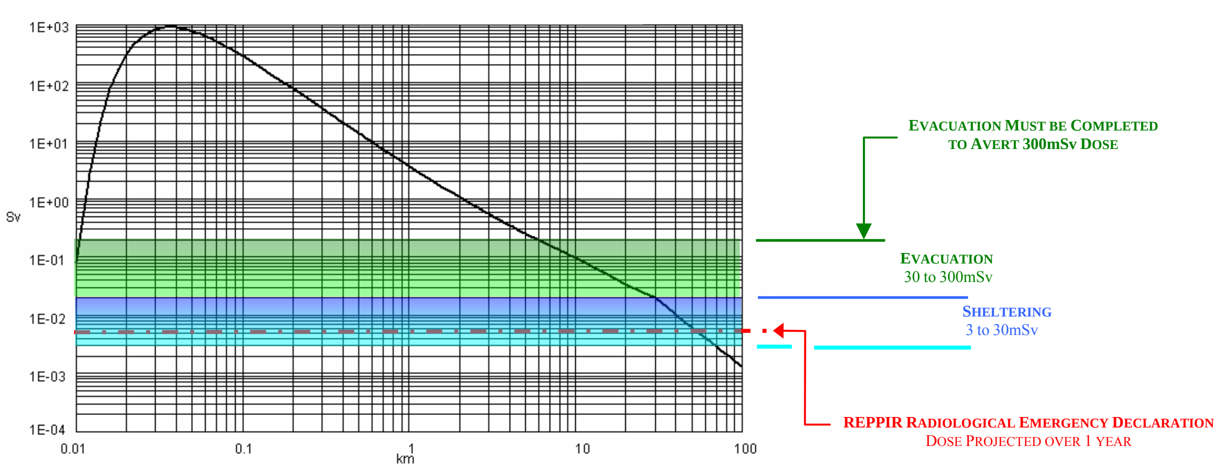
A) SINGLE LWR FLASK - ATMOSPHERIC PLUME & GROUND DEPOSITION FOR OPEN AIR 145 MINUTE FIERCE FIRE
DATA FOR CENTRE OF PLUME WITH ATMOSPHERIC STABILITY CLASSES – ASSUMES NO COUNTERMEASURES AND FOR 1 DAY TOTAL EFFECTIVE DOSE SV

The above Graphs A) show the extent of the plume developed from a single damaged LWR spent fuel flask subsequently involved in a fuel fire of 145 minute duration – the different curves labelled A to F are the meteorological stability categories which, in effect, account for the range of probabilistic radiological outcomes. The scenario is set about an open air accident or terrorist attack, say at a level crossing with a fully laden road petroleum tanker being hijacked and brought to the incident site to fuel the flames. Depending on the atmospheric stability (weather conditions) sheltering would be required out to 30km and, possibly, for *Stability Category A* evacuation would have to be considered at around the 1km distance. In terms of deposited contamination (RH graph) the present clearance level of 40kBq/m^2 βγ would require decontamination action out to 100km and further, although in the event of such an incident the present levels of decontamination might be relaxed as a matter of necessity, or redefined in terms of effective dose over a set period (ie 3mSv/year).[65,66]



B) SINGLE AGR FLASK SUSPENDED UNDER GANTRY IN COMPARING URBAN AND OPEN TERRAIN LOCALITIES
EXAMPLES OF REMOTE RAILHEADS AT BRIDGWATER (LH GRAPH) AND DUNGENESS - CENTRE OF PLUME 1 DAY TOTAL EFFECTIVE DOSE SV – COMPARE RED **E** STABILITY CATEGORY

Graphs B) compares the release from an explosive ordnance damaged AGR flask subject to fire in two different types of terrain, comparing town and open country terrains, here taken to represent the remote railhead compounds in the town of Bridgwater and on the marsh levels of Dungeness, both for the ‘slightly stable’ E stability category.



C) THREE AGR FLASKS, PROLONGED FIRE IN TUNNEL – PLUME RELEASE
FLASKS CONFINED IN TUNNEL – EXTREME CASE – SHELTERING AND EVACUATION DISTANCES – E STABILITY

DISTANCE km	1 DAY EFF DOSE Sv	AIR CONCENTRATION Bq-sec/m^3	GROUND DEPOSITION kBq/m^2	SURFACE SHINE DOSE Sv/hr	ARRIVAL TIME hr:min
0.030	8.2E+02	9.4E+13	1.7E+10	2.9E+00	<00:01
0.100	2.9E+02	3.3E+13	1.9E+08	1.6E-01	00:01
0.200	7.9E+01	9.1E+12	3.1E+07	4.0E-02	00:03
0.300	3.6E+01	4.1E+12	1.3E+07	1.8E-02	00:05
0.400	2.1E+01	2.4E+12	7.2E+06	1.0E-02	00:07
0.500	1.3E+01	1.5E+12	4.6E+06	6.5E-03	00:09
0.600	9.5E+00	1.1E+12	3.3E+06	4.6E-03	00:11
0.700	7.1E+00	8.1E+11	2.4E+06	3.4E-03	00:13
0.800	5.5E+00	6.3E+11	1.9E+06	2.7E-03	00:15
0.900	4.4E+00	5.1E+11	1.5E+06	2.1E-03	00:17
1.000	3.7E+00	4.2E+11	1.2E+06	1.8E-03	00:19
2.000	1.1E+00	1.2E+11	3.6E+05	5.2E-04	00:39
4.000	3.5E-01	4.0E+10	1.2E+05	1.7E-04	01:18
6.000	1.9E-01	2.2E+10	6.5E+04	9.4E-05	01:57
8.000	1.3E-01	1.5E+10	4.4E+04	6.3E-05	02:36
10.000	9.9E-02	1.1E+10	3.3E+04	4.8E-05	03:15
20.000	3.5E-02	4.0E+09	1.2E+04	1.7E-05	06:30
40.000	1.0E-02	1.2E+09	3.4E+03	4.9E-06	13:00
60.000	4.1E-03	5.0E+08	1.3E+03	2.0E-06	19:30
80.000	2.1E-03	2.8E+08	6.9E+02	1.0E-06	>24:00

Graph C) illustrates the outcome of an entire spent fuel train being confined within a tunnel under fierce and prolonged fire conditions, such as the Derbyshire Summit Tunnel fire of 1984.

In this somewhat extreme scenario, all three AGR flasks are expected to completely fail and the fuel cladding rupture, releasing the entire clad gap radionuclide inventory and a fraction of fuel aerosol, some of which is retained by the tunnel surfaces.

If sheltering and evacuation countermeasures are implemented then, for the stability conditions (E) assumed here, along the centreline of the overhead plume sheltering would extend out to 30 to 70km and evacuation would have to be undertaken out to about 6km to avert a dose of 300mSv. The table (right) indicates the times over which the respective countermeasures would have to be implemented if the appropriate nationally-set dose Emergency Reference Levels were to be complied with.

The difficulty here is that the emergency services and local authorities generally do not have the capability and resources to make these dose predictions in the time available, and the NAIR (National Arrangements for Incidents Involving Radioactivity) is not designed to cope with such a large-scale release. Also, it is very unlikely that the nuclear industry would be able to respond with its national RADSAFE on site arrangements in sufficient time to advise on the implementation of countermeasures in the public domain for which, incidentally, it has no specific responsibility. Other difficulties are likely to arise in informing members of the public in an urban area where it may not be practicable to evacuate such large numbers, or in a rural situation where individuals may be unaware of the incident and who, scattered about the countryside, may be difficult to locate and advise in time.

Environmental Clean-Up and Costs: Graphs A) and C) and the above table indicate the extent of the area that would become contaminated in the tunnel fire incident. The current levels of beta-gamma radioactive contamination at which decontamination is required has been set by the NRPB at 40kBq/m^2 (4.E+04) which, as highlighted in the table and, particularly, the RH plot of Graphs A), would require decontamination out to about 100km$^+$ from the incident site. For the terrain conditions modelled, the plume would have developed to about 5km wide at this point, so the area subtended under the plume set by a steady wind direction would be approximately 250km^2 about one-half of which would yield a ground deposition fall-out >40kBq/m^2, so about 125km^2 area contaminated in excess of the minimum recommended.

The cost of decontamination of a townscape subject to a similar spent fuel incident projected to occur in a tunnel fire that actually happened (but did not involve radioactivity) in the US city of Baltimore in 2001 was $14B for a contaminated area projected at 70km^2 (see Table 10 main text following). Obviously, depending on the location of the hypothetical UK incident, not all of the contaminated area would be townscape which is difficult and expensive to clean-up, so the UK costs would be expected to mirror the US example at around £8.5B. However, it might be that the UK would not go so far as to decontaminate down to 40kBq/m^2 in account of the recent Health Protection Agency's advice to DEFRA that the land could be designated as *radioactively contaminated* where a dose rate of up to 3mSv/year would be tolerable which, if applied, represents a reduction in the area requiring clean-up.

Potential Radiological and Health Consequences: In this Review the radioactive release and its radiological and health consequences are projected by the European standard COSYMA dispersion-health model for reasonable levels of countermeasure intervention for both accident and terrorist act conditions. The results are given in terms of areas and population numbers required to shelter and evacuate, the distributions of individual and collective radiation dose, and early and late fatalities and non-fatal health effects. These are compared with earlier analysis (1983) by the then National Radiological Protection Board and others, all summarised as follows:

			NUMBER OF LATE FATAL HEALTH EFFECTS - PROBABILITY[1]		
	SCENARIO	RELEASE FRACTION Cs^{137}	EXPECTED VALUE E	p=1	p=99.9
NRPB LWR – OUTER URBAN	Explosive 3 min release	1.E-3	**45**	4.4	670
NRPB LWR - OUTER URBAN	Explosive 3 min Short-Cooled Fuel	1.E-3	**99**	9.5	1,300
3 MAGNOX - OUTER URBAN	Explosion + 6 hour Tunnel Fire	3.E-2	**2,815**	-	8,491
3 AGR - OUTER URBAN	Explosion + 6 hour Tunnel Fire	1.E-3	**1,511**	-	3,022

In this analysis,[2] the lower radioactive inventory of a Magnox fuel flask is assumed to have a significantly larger release fraction than the AGR fuel. This is because the pyrophoric character of the elemental metal Magnox fuel compared to the more temperature stable ceramic uranium dioxide AGR (and LWR) fuels.

Currently under Review by government is the decision whether to proceed with a new programme nuclear power stations. If the Energy Review favours new nuclear build then the UK reactor programme is likely to feature the Generation III light water reactors, either or both AP 600/1000 and EPR. These reactors aim to achieve fuel burn-ups in excess of 65,000MWd/tU so it follows that the transportation of spent fuel from these reactors will carry with it a greater unit quantity of radioactivity (Bq/tonne) and, hence, a greater radiotoxic potential in the event of a release over the projected 60 year operating life (compared to 40 years for Sizewell B PWR) of these Generation III nuclear power plants.

The analyses undertaken for this Review are not intended to provide precise forecasts of the radioactive releases and consequences at the hypothetical localities. This is because much greater detailed input is required to define the near field data, population density and meteorological conditions, for each locality and how the population would react, particularly if left uninformed of essential information and direction on what best to do. However, the results do provide both trends and indices of the probability of health impact should a release from a spent fuel consignment occur. In terms of radiation dose uptake and longer term health risk (probability of mortality and morbidity) the consequences arising from incidents of severe flask damage followed by fire, particularly in a confined space such as a rail tunnel, significant long-term health detriments extend up to and beyond 50km from the incident centre even with the appropriate countermeasures being implemented in a timely and effective manner. Even in an extreme release it is unlikely that any individual member of the public would suffer from immediate and acute levels of exposure, although emergency services personnel – firefighters, police, medics – attending close to or at the scene of the incident would be at greater risk of acute dosage.

In an incident in an urban area the estimated numbers of public requiring to shelter, around London for example, is around 350,000 over an area of about 50km^2 for the Magnox spent fuel, all depending on the prevailing weather conditions. 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. However, should the public undertake self-action, particularly self-evacuation, many more are likely to be on the streets without much protection and/or in poorly shielded vehicles and, indeed, some may unknowingly move into contaminated areas becoming trapped for hours in the jams and traffic chaos that are almost certain to arise. In such circumstances, the public may receive a greater radiation exposure than if, generally, they remained indoors sheltering.

Public Information and Preparedness: Thus because of the risk of disorganised self-action by the public, the implementation of countermeasures presents a conundrum for the authorities in balancing the advantages and disadvantages of alerting the public that a radiological incident has occurred. In the London July 2005 bombings, there was suspicion that the authorities held back an immediate and full explanation of the bombings preferring, so it seems, for a time to let the rumour run that electricity equipment serving the tube had accidentally and explosively failed, although this apparent subterfuge rapidly collapsed when the newscasters realised that the Tavistock Square bus explosion was somehow linked to the disruption underground. Later, it has been alleged, that the cellular (mobile) telephone systems in the Central London area were being selectively managed in order, so it was claimed, to facilitate communications for emergency services personnel. The point here is that, whereas and if true, delaying public awareness in the July bombing incident may have facilitated the effectiveness of and eased the pressure on the emergency services, introducing such a delay in the immediate aftermath of a radiological release incident would place the public at greater risk of continuing radiation exposure and, hence, a larger health detriment. Such a delay in sheltering or evacuation increases the risk because the principal radiation dose uptake route is via respiration with the health detriment over the longer term (via organ dose) being committed in the first few hours of exposure of the incident aftermath.

Of course, in planning such an attack the terrorist group might seek to maximise the radiological and psychological impact of the incident. For example, the radiological impact might be more severe if the release occurred sometime during a summer weekend when larger numbers of public are out in the open; or the flask train might be held hostage in the confines of a defendable location, say a tunnel, and the situation exploited to play upon the public's general perception of radiation *'being a fate worse than death'*; and/or once the release was underway a second terrorist group might implement attacks on the local authority emergency control operations centre (readily obtainable on most local authority web sites and usually given in the published emergency plans) so as to hamper the emergency response.

Emergency Plans: That said, there are no spent fuel flask-specific emergency plans in place by the local authorities along the route and there is no requirement for the authorities to provide information to the general public of the risks of spent fuel transportation, nor are the

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[1] The two sets of NRPB analysis dates from 1983 when the ICRP fatal cancer risk factor was 4x lower than that in use today so, cautiously, the NRPB tabulated results could be increased by x4.

[2] In explanation, the above table includes the *Release Fraction* which is the amount of radioactive material that is expelled from the flask with, here, 1.E-3 being 0.001 or one-thousandth of the total caesium-137 content of the fuel, and which is representative of the quantities of other radionuclides also released during the incident but which, for brevity, are not included in the table. The range of probability (p=1 to p=99.9) is the extremes of chance that the number of fatalities tabulated in the columns will actually occur, with p=99.9 being the least likelihood (at 1 in 1000). The probability distribution is dominated by the meteorological conditions that might occur at the time of the release and throughout its sequence – the COSYMA mathematical model used calculates the outcome for each of seven meteorological stability categories and then grades each of these according to the probability of occurrence using past records – this gives rise to the *Expectation Value* ***E*** at which is the value which is most likely, on average, to occur. All of that said, the unsinkable ship, the Titanic, sank on its maiden voyage!

authorities required to prepare spent fuel hazard-specific information for distribution to the public should an incident and radioactive release actually occur. The appropriate legislation, the European Council Directive 96/29/Euratom that requires specific emergency plans be prepared and practised, as enabled in the UK as the *Radiation (Emergency Preparedness & Public Information) Regulations (REPPIR)*, do not apply because spent fuel consignments undertaken in IAEA Type B flasks are exempt from the UK application of the Directive. In place of any REPPIR planning, the nuclear industry's own emergency response scheme RADSAFE is very scant in detail of how and when the RADSAFE teams and advisors would respond; and for cities such as London, the local authorities (in London the LFCDA) do not seem to have spent fuel incident-specific plans in place.

The remote railheads introduce special security and risk challenges. At Dungeness the rail track leading from the remote railhead passes across the end of the main runway of Lydd Airport which necessitates all incoming and outgoing flights having to be suspended whilst the spent fuel train trundles past. Dungeness, Leiston and the other remote railheads are generally within the pre-prepared off-site emergency plan area of the power station required under REPPIR (even though these requirements do not strictly apply to spent fuel flasks) so, in the event of an incident, some countermeasures be might be cobbled together from the existing plans to deal with incidents at the nuclear power station. However, the railhead at Bridgwater is about 12 miles from Hinkley Point power station and well outside its 3.5km REPPIR specified off-site emergency zone, so there is no emergency radiological cover in Bridgwater that could be adapted should an incident occur, even to the extent that the most recent inquiries have established that the nearby school and local residents in the immediate locality of the railhead have no pre-prepared information to hand should an incident occur.

In Conclusion: So, in conclusion, consignments of highly radioactive and hazardous spent nuclear fuel continue to be loaded in publicly accessible places and share the local and national rail networks with high-speed passenger, mixed goods and hazardous freight trains, and it does so in times in which the terrorist threat is heightened and, particularly, now that it is established that those minded to do so consider nuclear facilities and radioactive materials to be attractive targets. Yet the nuclear industry and its security regulator continue to turn a Nelsonian eye to this threat, in doing so seemingly relying upon the outdated, if not archaic, approach that spent fuel flasks could never be breached, even by those who have a determined mind to seek out the vulnerabilities of these highly hazardous radioactive cargoes. As a result there are no flask-specific emergency arrangements for providing the public with information in the aftermath of such an incident, possibly extending, if at all, little beyond broadcasting the mantra *'Go In, Stay In and Tune In'* which, some might consider, will not serve to calm concern but, more likely, would trigger self-action and evacuation and all of the confusion and chaos that that would bring about.

The Review concludes that a terrorist attack on a spent fuel consignment, either in transit or, particularly, when loading at a railhead (such as at Dungeness, Leiston near Sizewell, Torness in Scotland and as exampled at Bridgwater in Somerset) involving one or more fuel flasks, cannot be entirely discounted and, other than the physical robustness of the flasks themselves, there seems to be little additional security to defend a spent fuel flask train and, where used, the road haulage vehicle and the railhead compound from attack.

Finally, it should be noted that the results generated by computer based models, such as COSYMA, have to be considered with caution. Accurately modelling radioactive release, the subsequent dispersion, deposition and human dose uptake is fraught with difficulty and uncertainty. This includes fundamental assumptions on how much radioactivity is released, its chemical form and volatility, the particle size distribution, how this will disperse and deposit over a complex urban terrain and, perhaps most of all, how the individuals of the population caught up in the aftermath will react. Each of these factors can introduce elements of not insignificant uncertainty and error, so much so that the results produced in this Review should be regarded only to illustrate trends of how a radioactive release from a spent fuel flask might be expected to develop.

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RISKS AND HAZARDS OF THE TRANSPORTATION OF SPENT FUEL IN THE UK

BACKGROUND

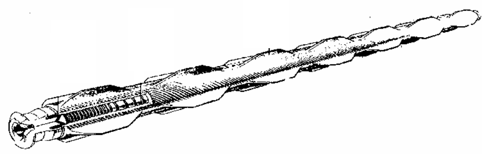
In the United Kingdom nuclear fuel and other highly hazardous nuclear materials are routinely moved by rail.

The main component of this traffic is the movement of irradiated or spent nuclear fuel from the nuclear power stations to the fuel reprocessing (chemical separation) works at Sellafield. UK domestic traffic comprises spent fuel from the Advanced Gas Cooled Reactor (AGR) and Magnox nuclear power stations located around the mainland coast, with the exception of the Sizewell B Pressurised Water Reactor (PWR) station which is to store its fuel on site until its closure in or about 2035, or later. All of the overseas fuel contracted for reprocessing at Sellafield has now been imported, although any new overseas fuel contracts that might be contracted to Sellafield would arrive by ship at Barrow-in-Furness and be hauled along the west coast to Sellafield, although there is nothing in law that forbids overseas spent fuel entering the UK by other ports, such as in the past into Dover and Harwich, or by rail via the Channel Tunnel. Other nuclear fuel materials in transit by rail within the UK include highly irradiated and highly enriched Royal Navy submarine reactor cores, from Devonport and, shortly to cease, Rosyth to Sellafield where the cores are stored; consignments of unirradiated (fresh) mixed oxide fuel (MOX or plutonium based fuel) from the Sellafield MOX plant (SMP) to Barrow or Workington for export but in future, possibly, to UK mainland nuclear power stations; and uranium hexafluoride imports and exports as part of the nuclear fuel enrichment process.

As well as being nuclear fuel or part of the nuclear fuel process, all of these transits have to be transported in the highest category of transportation container, being a *Type B* compliant with the *International Atomic Energy Agency* (IAEA) recommendations TS-R-1 the *Regulations for the Safe Transport of Radioactive Materials* which, essentially, means that the containers are considered to be failsafe under all credible circumstances. A second commonality is that being transported in a Type B compliant flask, all such consignments are exempt from the specific requirements of the *Radiation (Emergency Preparedness & Public Information) Regulations 2001* (*Regulation 3.4a* - REPPIR), thus not being subject to specific emergency planning by the carrier or the local authority in which any untoward incident may occur, although the all-hazard approach would be expected to apply and, it is claimed, be sufficient for the worst credible release of radioactivity. None of the international or domestic legislation relating to the movement of these radioactive materials includes for specific resilience and countermeasures against terrorist and other malicious acts. The nuclear industry has organised itself into providing emergency cover to incidents via its nationwide RADSAFE plan, although the publicly available versions of this plan is sparse in detail, being confined to *"If a nuclear fuel flask has been involved in a fire, spray cool with water for at least 30 mins, if possible"* and, similarly, the procedure manual dealing with major incidents by the London Emergency Services Liaison Panel (LESLP) has no reference whatsoever to the very large radioactive sources term consignments of irradiated fuel in rail transit across London.

Present transportation routes within and to and from the UK are well documented. Future movements are subject to policies and national strategies that have yet to be finalised and/or put in place and will depend, amongst other things, if a new-build programme is initiated and if, for these nuclear power stations, the irradiated fuel is to be stored on site, moved to a reprocessing plant, or disposed of directly following some yet-to-be defined interim storage period; the commercial success of the Sellafield SMP (MOX) plant; and the practicable implementation of any strategy that might be identified and promoted by the *Committee on Radioactive Waste Management* (CoRWM) due to report in July 2006.

Fuel Design and Fabrication (See Appendix IV for Spent Fuel Irradiation)



MAGNOX FUEL ELEMENT

Magnox: The uranium component of Magnox fuel is in the form of natural uranium[3] rod of elemental metal which has been alloyed with a trace of aluminium to facilitate machining at the fuel fabrication stage. The fuel rod, about 28mm diameter by 1.07m length is enclosed within a magnesium alloy (hence 'Magnox') casing which has herringbone finning to aid heat transfer and protruding lugs to locate each fuel element in the fuel channels of the reactor core. Eight fuel

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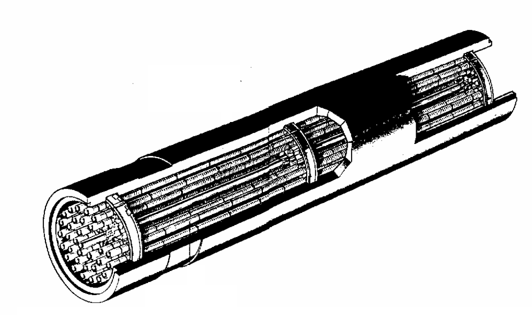
[3] Some of the Magnox reactors may now be fuelled with slightly enriched fuel (~0.8%) to offset the irradiation changes to the graphite moderator (radiolysis).

elements are stacked in each fuel channel of the cores of the twin reactors (600MW$_e$ rating each) at the Wylfa Magnox station, with the entire fuel load comprising 49,248 elements or a total of 594 tonnes of uranium in each reactor.

AGR: The 2 to 3.5% enriched AGR fuel is in the form of pellets of sintered uranium dioxide contained within a sealed sheathing of stainless steel. Each fuel pin is 987mm long and 16mm diameter, with 36 pins arranged in a radial cluster inside a graphite shell. Seven or eight fuel modules, depending on particular reactor design are threaded together onto a central tie bar to form fuel stringers which operated within 300 or so fuel channels with, in all, about 96,000 fuel pins or about 100 tonnes of uranium in each of the twin 600MW$_e$ reactors of a typical AGR power station.



AGR FUEL MODULE

LWR: PWR fuel comprises an assembly of fuel pins or rods held together by braces and top and bottom nozzles. Most PWR fuel is assembled into a lattice bundle of 264 fuel rods with additional guide and thimble tubes making up a square lattice array of 17 by 17 elements. Most BWR fuel comprises 64 fuel rods held in an 8x8 array held together by tie plates. PWR and BWR fuel assemblies provide top and bottom nozzles and intermediate bracing grids. Each individual fuel rod is approximately 37.5mm in overall diameter and consists a zirconium alloy thin walled (typically 0.57mm thickness) tube filled with uranium oxide (1J0 pellets - the fuel pellets (each typically 13 length by 8.19mm diameter) occupy the lower two-thirds of the pin length with the higher plenum section including a preload spring. The plenum is charged with helium at about 24b (b - bar or one atmospheric pressure), although this pressure increases during irradiation of the fuel. The length of the fuel assemblies varies to suit the particular reactor, ranging from about 3 to 5m overall with the reactor core, again depending on the particular design and power output, loaded with about 100 fuel assemblies of about 120 tonnes of uranium in total.

TRANSPORTATION OF SPENT FUEL

In the UK the purpose of transporting civil nuclear fuels, that is spent fuel from the Magnox and AGR reactors but not at present the PWR reactor at Sizewell B, is to transfer the fuel to the British Nuclear Group (BNG)[4] works at Sellafield for eventual reprocessing, storage and/or direct disposal. The transport is by rail and undertaken by a specialised rail freight Direct Rail Services (DRS).[5]

Other spent fuel consignments transported to Sellafield include (occasional) research reactor fuels and 1 to 2 cores each year of Royal Navy submarine propulsion reactor fuel which is placed in storage and not destined for reprocessing.

Current movements of spent fuel in the UK involve only Magnox and AGR fuels. At some time in the future, spent fuel from the Sizewell B PWR will have to be moved from the cooling station ponds to Sellafield for reprocessing or, either to Sellafield or elsewhere,[6] for interim storage if the reprocessing facilities at Sellafield are not available.[7]

Pre-Transportation Cooling: Once withdrawn from the reactor, irradiated fuel is 'cooled' for a period over which there is a rapid natural decay of the shorter-lived radionuclides, particularly radioiodine, and overall heat generation of the fuel. This cooling is undertaken in a water pond at the power station site.[8] The water cover of the fuel storage pond provides both radiation shielding and the medium for dissipating the heat generated by the fuel. Post reactor, short-term cooling of spent fuel enables certain short-half life volatile radionuclides, such as iodine-131, to decay naturally during the first one to five years

When in storage, irradiated fuel continues to generate heat by virtue of the intensity of the radioactive decay processes underway within the fuel. This radioactive decay continues for tens, hundreds and thousands of

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[4] BNG now acts as a contractor to the facility which is owned by the Nuclear Decommisioning Authority (NDA).

[5] DRS was formed in 1998 by BNFL DRS is now wholly owned by the Nuclear Decommissioning Authority. DRS hauls spent fuel from of the UK's nuclear power stations (except Sizewell B where the fuel is stored) and imported spent fuel that arrives at Barrow in Furness.

[6] It is unlikely that a dedicated interim fuel store will be constructed on the Sizewell site if reprocessing at Sellafield is abandoned.

[7] At this time the THORP reprocessing plant is closed with a serious failure in the Feed Clarification Stage and it could, if the option not to restart THORP is taken, then the present stocks of LWR and AGR fuel would be exported overseas for reprocessing at, say, the COGEMA plant in France - see *Leak of Radioactive Liquor in the Feed Clarification Cell at BNG THORP Sellafield, Review of the Management and Technical Aspects of the Failure and its Implications for the Future of THORP,* November 2005 – this option would involve considerable volumes of AGR and LWR transports from Sellafield.

[8] Except at Wylfa where the fuel is initially cooled in carbon-dioxide filled stores and then transferred to air storage.

years. However, there is considerable benefit to be gained from short-term cooling, since many of the shorter lived radio-isotopes dissipate to a great extent during the first one to five years. During this initial bout of radioactive decay, the heat emission rate falls off rapidly thereby reducing the need for extraordinary cooling and shielding means during transit. Secondly, before the fuel may be transported it is prudent to allow the volatile and highly radio-toxic fission products of iodine (I^{131}) to decay since accidental atmospheric release of radio-iodine could be accompanied by radiological consequences arising from uptake and reconcentration of radioiodine into the human thyroid.

For these and other reasons, irradiated fuel remains immersed in the cooling pond at nuclear power station sites for periods of between six months to five years, and longer, before dispatch. Decay of the fission product I^{131} sets the minimum pre-transport storage period of about 90 days for low burn-up fuels from Magnox reactors and, longer, for the higher burn-up fuels with AGR fuel being retained for a minimum of 150 days and LWR fuel for 1 to 5 years.[9]

Spent Fuel Transportation Routes: In the UK, domestic spent fuel is transported from the nuclear power stations to Sellafield by rail with short road journeys being required to reach the power station off-site railheads at Dungeness (Kent), Hinkley Point (Bridgwater, Somerset), Sizewell to Leiston, Wylfa to Valley, and from Torness (Scotland). Sometimes, spent fuel consignments from different nuclear power stations are collected together at a conveniently sited marshalling yard for the longer haul to Sellafield.[10]

In the past (up until about 2003) imported overseas fuel generally arrived at and was off-loaded at the BNG dedicated quay in the Port of Barrow-in-Furness

A SPENT FUEL FLASK OFFLOADED AT AN OFF-SITE RAILHEAD

EXAMPLE OF OFF-STATION RAILHEAD – BRIDGWATER SERVING HINKLEY POINT
NOTE CLOSE PROXIMITY OF HOUSES

TRANSFER OF AGR FLASK FROM ROAD VEHICLE TO TRAIN FLATROL
SLIDE BACK COVERS ON BOTH TRUCK AND FLATROL

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[9] Water conditions in the fuel storage ponds have to be maintained at a high quality because the spent fuel cladding is susceptible to degradation whilst under water in storage. This is particularly so for Magnox fuel where the cladding is susceptible to breakaway corrosion under slightly acid conditions and, if the cladding is breached, the elemental uranium metal fuel pin within may form hydrides which significantly lower the self-ignition temperature (from about 220°C to ambient). The design of the enriched fuels for the AGR and light water reactors did include considerable development effort to provide a durable fuel element containment for longer post-reactor service periods. Later oxide fuels do not present the same formidable corrosion and ignition problems as the Magnox fuel, although batches of AGR fuel stored for about 8 years are believed to have sustained considerable corrosion damage to the stainless steel cladding. Zirconium alloy clad light water reactor fuels are better suited to long term water immersion, although this fuel cladding is highly reagent in accident conditions involving steam at high temperature.

A small proportion of the fuel within the active core of the reactor sustains damage, usually in the form of failed fuel pin cladding which permits the release of fission 'products from the fuel within. Damaged irradiated fuel requires isolation from intact fuel assemblies in the fuel pond, since releasing fission products will contaminate the pond water, resulting in increased radiation dose exposure to employees and expensive decontamination procedures. Such damaged fuel is usually segregated and bottled (enclosed within a special container) prior to early dispatch from the nuclear power station for post-irradiation examination (PIE) - this fuel is often referred to as 'short-cooled' because it has not undergone a substantial decay period at the power station prior to dispatch.

[10] Spent fuel from three nuclear power stations in the South East of England (Dungeness A, Bradwell and Sizewell A) is transferred by rail to BNFL Sellafield through London. Bradwell is now shut down and may have by now transferred all of its spent fuel. The most direct route for transportation of this fuel is via London with around three shipments passing through London every week. Trains awaiting marshalling flasks from Dungeness and Sizewell to a single train for onward to Sellafield are normally held at Willesden Brent Rail sidings for several hours. The transport of spent fuel complies with general operational safety requirements for rail transport (speed restrictions, etc) – there are no specific rules for spent fuel transport.

wherefrom it was transported by rail directly to Sellafield. Although Barrow-in-Furness has been the preferred entry port from some years, there is nothing in law that prohibits overseas fuel being imported into any UK commercial port with sufficient handling facilities (crane or Ro-Ro ferry) or, indeed, fuel could be imported directly via rail through the Channel Tunnel. Because the nuclear safety case centres around the compliance of the transportation flask (with IAEA TS-R-1)[11] alone, the mode and route of transport and arrival location do not have to be considered other than on security and physical protection issues.

Fuel Transportation Flasks: The size and geometry, as well as the radioactivity shielding, heat emission and criticality control requirements of the fuel elements, determines the type of flask required for transportation.

There are a number of designs of flask available to transport these different types of fuel and fuel assemblies for which, in the United Kingdom, there are about twenty types of flask certified for the transportation of irradiated fuel including three main flask types for Magnox, AGR and LWR fuels.

Flask Characteristics: Both Magnox and AGR flasks comprise, essentially, a box-like or cuboid single-piece forged carbon steel container with a separate steel lid which is bolted on. The outer surfaces of both flasks are heavily finned to increase the effective heat transfer area of the flask. Typical design, construction and irradiated fuel load characteristics for Magnox and AGR flasks are as follows:

TABLE 2 IRRADIATED FUEL TRANSPORT FLASKS

	IRRADIATED FUEL LOAD							
TYPE	VOID FILL	GROSS WEIGHT tonnes	SHAPE	WALL THICKNESS mm	INTERNAL DIMENSIONS m	FUEL CARRIER	FUEL LOAD ELEMENTS No/tonnes	TYPICAL ACTIVITY PBq
Magnox	Water inert gas over	47	cuboid	370 steel	2.6x2.2x1.9	skip	200 2.5tU	35
AGR	Water inert gas over	53	cuboid	90 steel 180 lead	2.7x2.3x2.0	Segregated skip	20 modules (720 pins) ~1tU	63 - 90
LWR	Water/dry nitrogen	80 to 120	cylindrical	90 to 300	4.87 by 914 dia 5.05 by 1.22 dia	Sealed bottle (MEB)	5 to 12 3.23tU	74 - 120

LWR Flask Designs and Variants: Variation of the basic flask design is necessitated by the detailed geometry and burn-up rating of the fuel and, significantly, by the acceptance restrictions of the reprocessing plant. The preference at BNFL Sellafield is for irradiated fuel to be delivered immersed in water and for this uses a flask commonly referred as the Excellox ‘wet’ flask.

Typically, a LWR fuel transport flask comprises a hollow cylindrical carbon steel shell of ~2m overall diameter, with the outer surface of the shell finned to facilitate heat transfer — the structural wall thickness of the shell (excluding the depth of finning) is approximately 150mm. Certain types of LWR flasks are sealed with a metal gasket and within the outer shell fits a cylindrical lead liner which is contained within a stainless steel sheath of about 12mm wall thickness - this lead liner provides additional radiation shielding and is ported to provide for natural (therinosyphon) circulation of the water coolant between the two annuli formed with the flask cavity-liner-fuel bottle.

Within the flask, the irradiated fuel assemblies are arranged within a multi-element basket which serves to separate the individual fuel assemblies. The fuel basket fits within the inner cavity of the lead liner and occupies the entire cavity which is about 1m diameter and of ~5m length. For BNFL deliveries, the open basket is replaced with a sealed bottle (sometimes referred to as a multi-element bottle or MEB). The MEB is fitted with its own sealed lid and partially filled with water with a nitrogen, helium or air gas ullage space. The annular void formed between the bottle and the flask walls is filled with boronated water to absorb neutron activity within the fuel.

Magnox and AGR Flasks: Although similar in appearance, there are significant differences between Magnox and AGR flasks.

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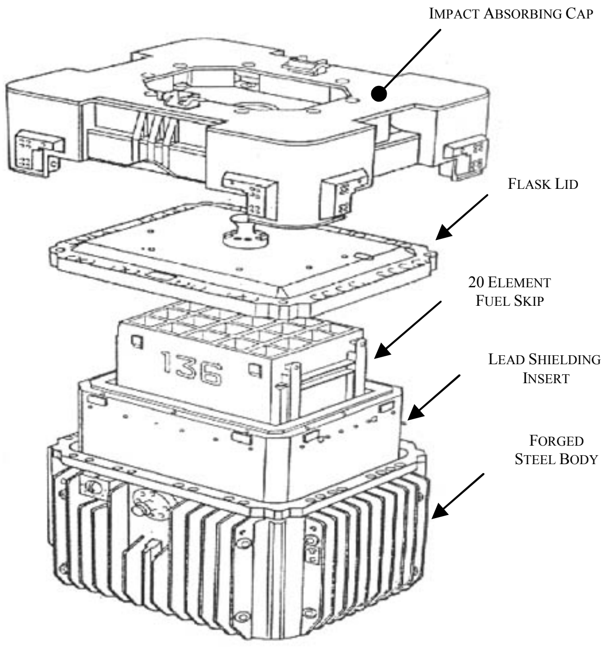
[11] IAEA 1996 Regulations, TS-R-1 – see also *Regulations for the Safe Transport of Radioactive Material, Safety Standards Series Nº ST-l* Requirements, Edition, Vienna (1996)

For transit the AGR flask is fitted with an aluminium alloy frame, provided to absorb energy during inadvertent impact - this requirement for additional shock absorption most probably arises from the thinner structural steel section thickness of the AGR flask.

Both Magnox and AGR irradiated fuel is placed within a steel skip which forms a snug fit within the body of the flask, the flask is filled with water, sealed within the pond. The final flask preparations prior to dispatch include decontamination of the outer surfaces and purging the small ullage space within the flask with an inert gas which is delivered via a valve coupling. AGR fuel modules are shipped complete with the radial fuel pin braces and graphite moderator shell, whereas Magnox fuel element lugs and splitterings (braces and graphite struts for certain of the Magnox reactors) are stripped from the fuel element to reduce the overall volume of each element ad retained at the dispatching power station. The Magnox fuel elements, each stripped down to a clad layer maintaining cover over the full rod, are placed in an unsegregated skip within the flask.

In the AGR flask the 20 fuel modules, each comprising 36 stainless steel clad fuel pins braced within a graphite moderator sleeve, are segregated by a griddage of boron alloy plates necessary to maintain spacing of the fuel modules and to thwart the onset of criticality in severely damaging accidents where the fuel elements may be damaged and/or displaced (ie crushed together).



AGR FLASK

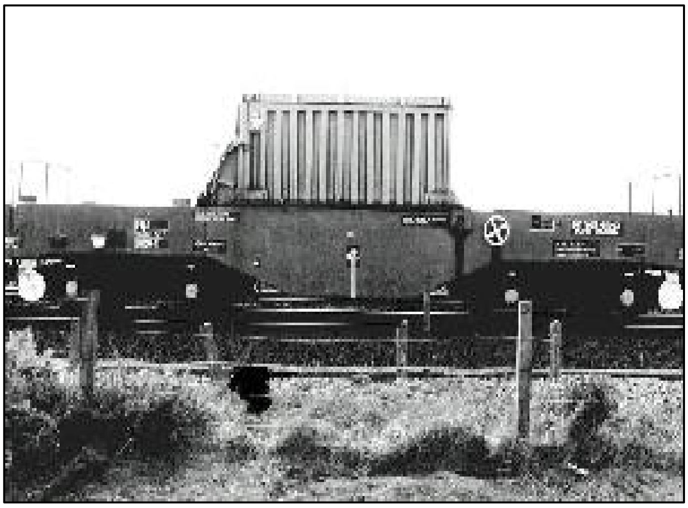
Flask Loading and Unloading: At the nuclear power station site the flask is loaded under water in the fuel pond. The individual fuel bundles or elements are inserted and the flask lid replaced. The final operation is to inject nitrogen gas through a penetration valve to establish a predetermined ullage space. Thereafter the penetration valve is closed and the flask lifted from the pond and external surfaces decontaminated and dried prior to transfer from the pond area.

For LWR flasks, the final operation in preparation for transportation is to fit the flask with shock absorbers. Two shock absorbers, each consisting a bulk of balsa wood or honeycomb aluminium contained within a stainless steel wrap, are positioned at each end of the flask and serve to protect the welded end cap and bolted lid - sometimes an all-steel fabrication is deployed as a shock absorber. The flask, complete with shock absorbers, is mounted on a low wagon in a prone position and bolted to the wagon bed via two sets of lugs that are welded to the main body of the flask.

Rail Movement: For rail transportation a flatrol wagon of about 21m length and standard gauge is used.

For Magnox and AGR spent fuel transportation, certain of these flatrols are fitted with roll-back covers that fully enclose the flask during transport. The flatrol wagons used for irradiated fuel transport each carry a single flask and weigh about 60 to 80 tonnes.

LWR fuel flasks total between 80 to 110 tonnes weight, The greater number of wet-filled flasks in service are each capable of carrying a maximum of seven fuel bundles or about 3.25 tonnes of irradiated uranium fuel within the fuel basket or, if fitted with a MEB, up to five fuel bundles. Irradiated fuel loads within a single flask are also limited by the heat generation of the fuel which, for example, for the NTL 11 flask is limited to 45kW



AGR FLASK ON A FLATROL WAGON UNDER SLIDE BACK COVERS

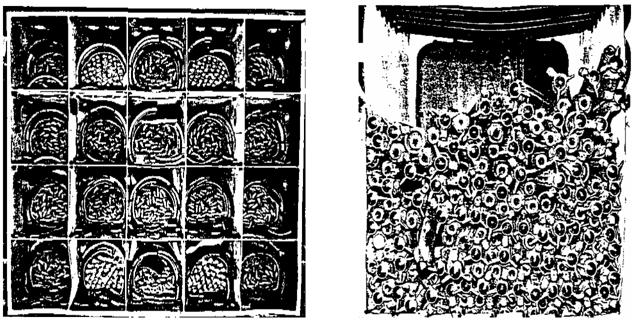
FLASK PERFORMANCE/COMPLIANCE

The United Kingdom adopts the recommendations of the International Atomic Energy Agency (IAEA) *Regulations for the Safe Transport of Radioactive Material* TS-R-1 as a means of performance of the spent fuel transportation flasks.

The ability of flask designs to meet these requirements is determined by a series of tests throughout which the flask contents shall remain sealed within the flask.[12, 13] Essentially, the tests impose conditions that are equivalent to an impact of about 30 mph (from 9m height or 13.2 ms^{-1} upon impact) onto an unyielding surface, followed by a drop onto a fixed penetrator (rod) from 1m, and then exposed to and engulfing fire with a flame temperature of 800°C for 30 minutes. The approval process and certification of IAEA compliance are issued by the country that undertakes the design and manufacture of the flask and, although such documentation is available to the consigning, transit and receiving states, such remain confidential and are not available in the public domain.

There is much criticism[14] of the entirely empirical approach of the IAEA flask compliance regime,[15] particularly in that for accident (or sabotage) scenarios the conditions encountered by the flask may be more severe and, indeed, substantially different from those applied in the IAEA tests. Indeed, the first of the drop tests (9m) solely determines the ability of the flask not to leak during and following the very specific impact conditions of the test (particularly, a linear descent with no tumbling).[16] Similarly, the punch test is aimed at demonstrating the ability of the flask containment to maintain a tolerable level of containment, although there is nothing requiring this test to be applied directly to the potentially weakest components of the flask.

Another very significant weakness is that the IAEA approach provides the opportunity for flasks to be designed to be test-specific, particularly now with very advanced computer-aided design techniques being available – see *Appendix I* for further details of the IAEA tests and requirements. Even extending the flask design beyond the requirements of the IAEA tests, there remains no compulsion and little incentive to carry out testing to a severity beyond what the standards require, particularly in that such tests are expensive and difficult.[17] Also, the IAEA tests include no specific provision or requirement for testing the resistance of the flask design to intentional actions to sabotage, damage or attempts to remove the radioactive contents. The assumption here seems to be that adequate safeguards will be in place to prevent the terrorist or saboteur gaining direct and unhindered access to the flask.



DUMMY AGR AND MAGNOX FUEL ELEMENTS FOLLOWING 20M FREE DROP

Some of these shortfalls are acknowledged by the IAEA and the radioactive materials carriers, although these, it is claimed, are by far more than offset by the flask design and construction being so conservative that such are able to withstand accidental forces and circumstances far more severe than the tests.

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[12] Small A1 and A2 quantities of radioactive material are allowed to release over a specified time period, although effectively the Type B(U) flask surety requirement is absolute.

[13] The UK *Competent Authority* approval for flasks (the IAEA 1999 Regulations) provides opportunity for the Carrier to demonstrate the adequacy of the flask design by extrapolation from other designs, calculation or by reasoned argument (IAEA 701) and where testing is undertaken much of this is on part or scale models of the flask design.

[14] *Import/Export of Irradiated Fuel and Radioactive Waste to and from the United Kingdom*, R1924-1, Large & Associates, 1994

[15] The IAEA tests also include plate, torch and immersions tests – the IAEA recommendations were first set down in 1964 and seem to have been based on then practice by the United States and the UK who when then virtually the only carriers of irradiated fuel: The 9m or ~30mph drop test is little more than the average speed of the rail and road modes of carriage then adopted in the US and UK respectively, the punch test represents and upturned rail, and the thermal or fire test derives from a British Standard for money safes with 30 minutes at 800°C being about the time the that temperature inside a safe or strongbox would have reached the self-ignition temperature of paper money.

[16] The nuclear industry argues that the 9m drop test is a very severe impact test because the flask is dropped onto a hard and unyielding target and, because the target absorbs little energy the 9m drop is representative of much greater drop heights that might occur in practice. However, some of the over-bridge and viaduct heights on UK network by far exceed any additional increment so deserved, with several bridges/viaducts being in excess of 25m and one at 40m height and the flask trains are permitted to travel at 50mph so a derailment and collision with a hard bridge abutment or tunnel portal would exceed the condition of the IAEA 9m drop test which is equivalent to a hard target impact at about 30mph..

[17] Lyman E, *Safety Aspects of Unirradiated MOX Fuel Transport, Comprehensive Assessment of MOX Use in Light Water Reactors*, IMA Project, Citizens' Nuclear Information Center, November 1997

SAFEGUARDING THE SPENT FUEL FLASK TRANSITS - SECURITY

There are separate IAEA recommendations[18] relating to the physical protection and security of nuclear materials which apply for both fixed nuclear installations and when the material is under transportation. The transport of nuclear material is recognized by the IAEA to be the operation most vulnerable to an attempted act of unauthorized removal of nuclear material, terrorist attack or sabotage.[19] The IAEA recommends[20] that full account be given to the *'design basis threats'* (DBTs), and that the physical protection provided should be *'in depth'*, and that emergency procedures should be prepared to counter effectively the identified DBTs.

That said, the IAEA recommendations[21] on security, physical protection systems and sabotage prevention are specified in general terms, the salient features of which are as follows[22]

- 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 of nuclear material and of sabotage of nuclear material is an essential element of the physical protection system.

In the UK the *Competent Authority* that approves radioactive material in transit is the *Radioactive Materials Transport Division* (RMTD) of the Department for Transport. More specifically, the RMTD generally Reviews the nuclear safety arrangements, although matters relating to security are undertaken by arrangement with the Department of Trade and Industry's *Office of Civil Nuclear Security* (OCNS).[23,24] OCNS regulates the security aspects of movement of all civil nuclear material by road and rail, classifying carriers so that IAEA Category II radioactive materials (such as spent fuel) may only be moved by a *Class A Approved Carrier*.

The OCNS publishes little detail of its security requirements and assessments, although OCNS should reflect in greater detail the IAEA recommendations relating to the physical security of nuclear materials, these being:

- Minimizing the total time during which the nuclear material remains in transport;
- Minimizing the number and duration of nuclear material transfers, ie transfer from one conveyance to another, transfer to and from temporary storage and temporary storage while awaiting the arrival of a vehicle, etc.;
- Protecting nuclear material during transport and in temporary storage in a manner consistent with the category of that material;
- Avoiding the use of regular movement schedules;
- Requiring predetermination of the trustworthiness of all individuals involved during transport of nuclear material; and
- Limiting advance knowledge of transport information to the minimum number of persons necessary[25]

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[18] International Atomic Energy Agency, *The Physical Protection of Nuclear Material and Nuclear Facilities*, IAEA INFCIRC/225 Rev b

[19] IAEA INFCIRC/225 *". . .the transport of nuclear material is probably the operation most vulnerable to an attempted act of unauthorized removal of nuclear material or sabotage. Therefore, taking into account the State's design basis threat, the physical protection provided should be "in depth" and particular attention should be given to the recovery of missing nuclear material. Emergency procedures should be prepared to counter effectively the State's design basis threat. . . . "*

[20] There is a plethora of regulations and statutes relating to the transportation of Category II materials in addition to the IAEA regulations (ST 1, TS-R-1 and INFCIRC/225) for the safe transport and physical protection of radioactive materials. Referring to the IAEA 1996 Regulations approvals and compliance is required for Multilateral Shipment Approval (IAEA 820) and fissile packages (IAEA 566), special use vessels (IAEA 566), details of the proposed route, controls and shipment period (IAEA 822), flooding (IAEA 671), etc.

[21] The IAEA recommendations are legally binding insofar that these are adopted into UK statute law by a series of regulations.

[22] The UK commitment to IAEA INFCIRC/225 is given in Note Verbale, dated 1 December 1997, communicating this to the Director General of the International Atomic Energy Agency (IAEA) – but see Large J H. Marignac Y, *Submission to the International Atomic Energy Agency - Convention on the Physical Protection of Nuclear Material (CPPNM)* – IAEA InfCirc/274 & InfCirc/225/Rev.4 - *IAEA Requirements on Design Basis Threat Assessment - Non Compliance of Eurofab LTA shipment from US to France on UK Vessel: Security and Physical Protection Issues*, IAEA 20 September 2004 - available on JointAssessmentIAEA.pdf

[23] These departmental responsibilities and jurisdictions extend throughout the British Isles and its territorial waters (and British registered vessels) so, in effect, the UK approves the nuclear and security safety aspects of imports of spent fuel carried from overseas destinations on British registered ships.

[24] OCNS dedicates 5% of its staff resource to security aspects of all classes of nuclear materials transport.

[25] Information on the movement of spent fuel is subject to restrictions under the *Nuclear Industries Security Regulations 2003*.

The OCNS recently expressed[26] some concern about security issues at Willesden sidings in London where spent fuel trains are marshalled, requiring improvements to the security regime and streamlining of procedures to reduce the times a DRS train was kept standing at the sidings. However, there is little other apparent security applied to the spent fuel trains with, for example, the train being unescorted other than with its driver and railway guardsman; the movements continue to be regular and generally limited to single route, particularly the section from the nuclear plant to the main line; and points of public access to the railway track (bridges, sidings, etc) do not seem to be patrolled or subject to any extra levels of security when a spent fuel train is in transit along a local section of track.

However no concern has been recorded by the OCNS at the lengthy periods that fuel flask trains are stationary whilst loading at the off-site railheads. For example, at Bridgewater which is the off-site railhead for the Hinkley Point power station, the train may be held in the track area of the loading compound for up to six hours whilst the road vehicle, carrying one flask per road journey, shuttles backwards and forth with fuel flasks from the power station. Throughout this time, the train is held in the centre of Bridgwater, in a residential area with a primary school about 100m away.[27]

It is not at all clear how the OCNS defines its Design Basis Threat (DBT) scenarios, although a Government Minister then (2002) considered the DBT to be based on *'intelligence about the motives, intentions and capabilities of potential adversaries',*[28,29] which seems to imply that there is sufficient confidence to detect the intent of terrorist act before such are carried through. This somewhat academic approach may have changed following the London underground and bus bombing of 2005.

EMERGENCY PLANNING AND THE PROVISION OF OFF-SITE PLANS

There are a number of schemes that would be expected to be implemented in the event of a radiological emergency developing in a spent fuel flask incident. These include the *National Arrangements for Incidents involving Radioactivity* (NAIR) and RADSAFE,[30] and in London (and probably other Fire and Civil Defence Authorities – LFCDAs) remnants of *The Public Information for Radiation Emergencies Regulations 1992* (PIRER) are continuing to be adopted, although much of PIRER has been revoked by the *Radiation (Emergency Preparedness & Public Information) Regulations 2001* (REPPIR).[31] However, spent fuel flasks are exempted from REPPIR on the basis that the Type B flask is designed not to release any radioactivity in any *foreseeable* circumstances.[32,33]

This somewhat odd reasoning of the Nuclear Installations Inspectorate (NII - H&SE) is quite contrary to its explanation as to why terrorist and other malevolent acts (ie terrorism) are not required to be taken into account for the operator and carrier's risk assessment reports required under REPPIR. The NII consider that it is unnecessary to include assessment of terrorist attack on the basis that

"...

> *that if a threat to the plant is judged by the operators, to fall below the limit of reasonable foreseeability then it does not need to be included in its submission to HSE. Given that there is no substantive evidence that a terrorist threat to a specific plant* (or transport mode) *and in a specific manner is reasonably foreseeable, HSE considers that it is quite correct that the reports of assessment do not need to consider this.".*[34, 35,36,37]

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[26] Office for Civil Nuclear Security, *The State of Security in the Civil Nuclear Industry and The Effectiveness of Security Regulation April 2004 to March 2005 A Report to the Minister of State for Energy*, Department of Trade and Industry by The Director of Civil Nuclear Security - http://www.dti.gov.uk/energy/nuclear/safety/dcns_report3.pdf

[27] http://www.sundaymirror.co.uk/archive/archive/tm_objectid=16311796%26method=full%26siteid=62484-name_page.html

[28] Letter, Sunil Parekh, APS to John Denham, Home Office Minister to Large & Associates, 10 May 2002

[29] Letter, Mike Smith, Manager Nuclear Security, Department of Trade and Industry to Large & Associates, 28 February 2003 – see also the Office of Civil Nuclear Security 1st Annual Report, October to March 2002

[30] The claim in the UK is that the emergency plans, such as RADSAFE prepared and operated by the carrier (here DRS-BNG) are sufficiently flexible to be extended to cover acts of terrorism, although nothing is available in the public domain to substantiate this

[31] *The Radiation (Emergency Preparedness and Public Information) Regulations* (REPPIR) are intended to implement articles 48 to 52 on intervention in cases of radiation emergency in an European Council Directive on the basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionising radiation (Euratom BSS96 Directive).

[32] REPPIR Regulation 3 gives Type B flasks exemption on the basis that *"Type B containers are exempt for the reason that they are designed to not release activity in any foreseeable circumstances"* – e-mail to Large & Associates from M Jennings, HMNII 13 March 2006.

[33] Department for Environment, Food and Rural Affairs, *Response to Radiological Emergencies,* October 1999 and Cabinet Office Civil Contingencies Secretariat, *Dealing with Disaster,* Revised 3rd edition, June 2003.

[34] E-mail Graham Holder, HSE to Large & Associates, 26 February 2003

[35] A past Greenpeace UK incursion into the nuclear power plant at Sizewell showed that the UK nuclear security systems may not be able unable to circumvent a terrorist attack Brown P, *The Threat that's Bigger than Ricin*, Guardian, 17 January 2003.

Following events of 11 September 2001 in New York and Washington, and in London in 2005, the potential vulnerabilities of nuclear facilities and transportation networks have attracted a great deal of attention[38,39] and some evaluation has been undertaken to assess the vulnerability and release of radioactivity from irradiated fuel transportation flasks[40] to terrorist attack and acts of sabotage, although nothing has been published by OCNS or the other involved parties (NII, RWTD etc).

In effect, because of the exemption of REPPIR and the fact that NAIR is resourced only to respond to minor radiation incidents, all that is in place for a spent fuel flask incident is RADSAFE. However, in comparison with plans for fixed installations, the RADSAFE[41] arrangements do not include provisions to protect the general public (eg evacuation or sheltering) because only a small area is considered likely to be affected in the event of a release and thus the probability of a transport accident having consequences for the public, is considered *'unforeseeable'*. For example, in the case of spent fuel transported by rail, emergency plans specify that all areas within 40 m of the incident would initially be cordoned off from the position of the flask and there is nothing in the publicly available RADSAFE arrangements for providing members of the public with information, either in advance of or following an actual incident.

Even if PIRER remains in place (by adoption by individual FCDAs, even though these regulations have been superseded by REPPIR), it defers to RADSAFE in the matter of informing the public in the aftermath of a spent fuel incident. In other words, contrary to the requirements of EC Directive 89/618[42,43] nothing seems to be in place to properly inform the public in the event of a release of radioactivity from a spent fuel flask in transit on the railway.

POTENTIAL WEAKNESSES IN SPENT FUEL FLASK SURETY

There are three weaknesses in the basis of the nuclear safety case as applied to transportation of spent nuclear fuel. These relate to the assumed limit of the severity of damage to the flask and the fuel contents; the frequency of accidents and incidents; and that relatively large numbers of public could be in close proximity to the accident/incident site:

i) Assumed Limit of Severity of Accidents and Incidents

In adopting the IAEA tests as the flask compliance criteria, the underlying assumption is that real accidents and situations will not result in forces and circumstances greater than those experienced in the tests.

Accidents: There are many examples where the forces and circumstances of accidental situations by far exceed the severity applied by the IAEA TS-R-1 compliance tests.

SUMMIT TUNNEL FIRE IN DECEMBER 1984 – N° 8 VENTILATION SHAFT

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[36] Large J H, *A Review of the Off-Site Emergency Plans under The Radiation (Emergency Preparedness & Public Information) Regulations, 2001* – see also *The Radiation (Emergency Preparedness & Public Information) Regulations, 2001*

[37] *List of 'Terror Targets' Revealed*, BBC News, 22 March 2006, http://news.bbc.co.uk/1/hi/uk/4832740.stm

[38] Nuclear Terrorism: How real is the Threat, IAEA-CB-86-1 – see also, Large J H, Schneider M, *The implications of 11 September of the Nuclear Industry*, Oxford Research Group, Rhodes House, Oxford November 2002, Large J H, *The Aftermath of the US Attacks: The End of Probabilistic Risk Analysis, Rethinking Nuclear Energy and Democracy after 09/11*, PSR/IPPNW Switzerland, Basel April 2002

[39] See article Daily Mirror 16 October 2005, report of nuclear details and potential found in abandoned car of member of the group involved with the unsuccessful London bombing of 21 July 2005 - Nuke Bomb Plot, Sunday Mirror, 16th October 2005 http://www.sundaymirror.co.uk/news/tm_objectid=16254342%26method=full%26siteid=62484%26headline=nuke%2dbomb%2d%2dplot%2d-name_page.html.

[40] Luna R, *Comparison of Results from Two Spent Fuel Sabotage Source Term Experiments*, Int. J. Radioact. Mat. Transp. 11(1-2), pp 81-84 (2000)

[41] The RADSAFE consortium is a group of organisations involved in the transport of radioactive material, who have agreed to offer each other mutual assistance (in the form of provision of advice and personnel) in the event of a transport incident involving radioactive material belonging to a member. RADSAFE provides members with services including a 24 hour national notification number, technical support and support in communicating with the emergency services and the media. http://www.radsafe.org.uk/about.htm.

[42] Council Directive *On Informing the Public about Health Protection Measures to be Applied and Steps to be Taken in the Event of a Radiological Emergency*, 89/618/Euratom November 1989.

[43] *Regulation 17* of *REPPIR* which requires local authorities to provide essential information to the public in advance of and in the aftermath of a radiological incident does not apply to spent fuel flasks (exempted under Regulation 3), so there is no requirement for public authorities to plan for the provision of essential information relating to a spent fuel incident.

Similarly, there have been a number of fires[44] in road and rail tunnels of such severity that emergency crews could do little more than to allow the fires to burn themselves out. Actual fires in confined spaces, such as ships and tunnels, give rise to temperatures and, particularly, durations that by far exceed the IAEA 800°C and 30-minute thermal test specification.

Terrorist Acts: Not only is the IAEA empirical approach flawed because it cannot conceivably cater for all severities of damage, it completely omits to account for any contrived situations. That is the IAEA test regime is drawn from accidental circumstances and, because accidents are accidental and unintelligent events, this approach cannot necessarily counter intentional and intelligent attacks on the system. An intelligent and intentional act, that is an act of terrorism, is likely to seek out the vulnerable parts of the flask and its transport system, tailoring the nature of the act to maximize damage and the radiological consequences.

Moreover, a terrorist attack might also be expected to include elements intended to hinder or harass the implementation of countermeasures to minimize either or both the magnitude of the release and radiation uptake in the immediate aftermath of the attack.

ii) Frequency of Accidents and Incidents

A second line of defence promulgated in the nuclear safety case is that severely damaging accidents and situations are acceptably infrequent so as not to be credible.

***A Priori* Accidents:** If it is accepted that real accidents could give rise to circumstance that would fail the flask containment (ie tunnel fires, terrorist explosive device, etc) then the frequency of occurrence of failure must be acceptable. This foundation is usually developed into the composite that untoward accidents and incidents must be of *acceptable risk* and result in *tolerable consequences*. This interprets to:

- Severely damaging events must be acceptably infrequent;
- the outcome (radioactive release) from all other events (ie credible events) must be tolerable (inconsequential); and
- if the radioactive release were to be significant then the emergency procedures and countermeasures would be effective in mitigating the consequences to a tolerable level.

Acts of Terrorism: Overall, the nuclear industry underpins nuclear safety against natural and accidentally occurring hazards on a basis of *'as chance would have it'*, and it provides protection against human error by designing the systems and equipment to be tolerant and/or independent of human action (or inaction). Much the same probabilistic approach applies to the transportation of radioactive materials, including spent nuclear fuel.

This combined approach of gauging the risk by probabilistic assessment and treating the human operators as inconsequential dummies may have some effect in safeguarding nuclear systems against accidents and unintentional human error, but it may prove to be woefully ineffective against intentional and intelligently driven acts of terrorism. Of course, the probability or chance of the occurrence of a malicious human act, such as the terrorist attacks of 11th September 2001 and 7 July 2005, cannot be determined by classical *a priori* probabilistic means.

This is particularly so for when, as with the spent fuel transport, the nuclear system moves out of the physically protective confines of the nuclear plant. For this situation, it is not possible to establish an impenetrable security boundary around the spent fuel train, like the security fencing around a nuclear power station; and the railway runs to strict timetable, so much so that patterns of flask movement have been firmly established over the years. Also, the surrounding terrain along the route is constantly changing, providing nooks and crannies where the terrorists may hide and under-track culverts and the like where explosives may be placed. Although the railway can be pre-checked before the convoy's arrival, because the route is so accessible it may be possible for terrorists to install themselves in the intervening period between route checking and the spent fuel train's passing.

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[44] 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 elV. D-40213 Dusseldorf. 1995.

iii) Proximity of Large Numbers of Public – Emergency Planning

The fundamental weakness in the nuclear safety case applied to the transportation of spent fuel is that the transport route passes through and nearby centres of population, thus placing at risk of radiation exposure relatively large numbers of people.

In summary: Movement of nuclear materials is inherently risky both in terms of severe accident and terrorist attack. Not all accident scenarios and accident severities can be foreseen; it is only possible to maintain a limited security cordon around the flask and its consignment; the transportation route will invariably pass through or nearby centres of population; terrorists are able to seek out and exploit vulnerabilities in the transport arrangements and localities on the route; and emergency planning is difficult to maintain over the entire route.

THE TERRORIST THREAT AND THE RESISTANCE OF FLASKS TO MALEVOLENT ACTS

Perhaps it would be imprudent here to present in any great detail possible means by which a terrorist group might stage a successful attack on a spent fuel flask. Instead, examine in outline the obvious means available which include either subjecting the flask to a persistent and high temperature fire, say in a rail tunnel, and by breaching the flask containment with explosive.

Release Source Term

The key assumption required in any analysis predicting the dispersion and consequences of a radiological incident is how much of the radioactivity in the flask is released – this fraction is referred to as the release source term. In arriving at an estimate of the source term account has to be taken of the various barriers of containment, the fuel element or pin cladding and, obviously, the flask (and for LWR fuel the MEB); the chemical failure of the cladding and the fuel itself, and any degree of retention or capture of radionuclides in the release path, that is with particles adhering (plating out) to the flask and nearby surfaces and materials. Once the fuel particles are available for dispersion and subsequent uptake by individual receptors (ie humans), it is the post release volatility at the dictate of the conditions of the fire and its products of combustion that determined the range of respirable-sized (<10μm) particles which dominate the immediate and early phases of dose uptake in the aftermath of a release.

The approach to arriving at a reliable source term has been extensively Reviewed and general issues relating to terrorist attack are summarised here (See APPENDIX III for greater detail):

Explosive Loading: There is now an emerging field of literature on the response of irradiated uranium dioxide fuel and fuel transport flasks when subject to explosion,[45,46,47,48,49] which relate generally to unirradiated with some irradiated uranium dioxide fuels across a variety of flask designs. These trials demonstrate that with both military ordnance and even relatively crude 'home made' shaped charges it is possible to breach a flask containment. Although all of the published work has been applied to the cylindrical LWR flasks and smaller plutonium dioxide flask designs, there is nothing superior about either the Magnox or AGR cuboid flasks that would present any extraordinary difficulty.

Fire Engulfment: All IAEA Type B flask designs are required to satisfy the thermal test of fire engulfment at 800^{o}C for 30 minutes. The thermal performance of all flask designs beyond these conditions, at higher temperature and longer fire duration lead to eventual failure of the flask containment.[14,75,76] The wet filled flasks used in the UK are more susceptible to failure as a result of raising the temperature of the water fill to saturation conditions.

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[45] *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

[46] 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.

[47] 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

[48] 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)

[49] *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

CHANNEL TUNNEL FIRE 1996 – EXTENSIVE CONCRETE LINER DAMAGE

For example, in a Magnox flask a rapid internal pressure rise is triggered from about 65 minutes into a 1,100°C temperature fire or at about 100 minutes, or thereabouts, for a fire at the IAEA specified temperature of 800°C. Increasing internal pressure raises compressive and tensile stresses in the flask walls with the carbon steel elastic limit being surpassed relatively early (~5 to 10 minutes for σ_c and 30 minutes for σ_t), pressure continues to rise asymptotically until failure, either by yielding of the lid bolts (whereby the internal pressure is relieved)[50] or by catastrophic rupturing of the flask structure (predicted at a corner feature), at about 115 minutes into a 800°C fire or about 65 minutes into an 1,100°C fire. At this point the internal temperature conditions would be about 190°C which is just below the air ignition temperature of the elemental uranium metal rod of Magnox fuel.[51]

Explosions and Fire Combinations

Another potential terrorist attack mode could include the spent fuel train being brought to a halt and entrapped within a rail tunnel, the rigging of explosive charges and the ignition of a source of fuel (such as the locomotive fuel) being left to burn; and so and so forth. An explosive disruption followed by fire provides the opportunity for increased radioactive release from the fuel: First, as a puff of aerosol of fuel particles aerosolised by the explosive force and second, as prolonged as the fire itself, as further particles of the damaged and likely oxidising fuel are entrapped and swept into the rising plume of the fire. Many of the works cited above were analyses or analytical extensions of measurements of surrogate spent (irradiated) fuel aerosols produced in sabotage-like configurations although these generally apply to ceramic dioxide fuels (UO_2) and little is published on the fire and particulate generation of Magnox elemental metal fuel.

For Oxide fuels, the correlation between various tests has been poor with a projection range of approximately 10 (0.7 to 12) between the lowest and highest estimates of the ratio of spent fuel respirable aerosol mass to surrogate respirable aerosol mass. Prolonged fires can result in fire conditions (temperature and duration) that will break down the matrix of the fuel and give rise to a significant release fraction of aerosol – actual fires in rail tunnels (Summit and Channel tunnels), have demonstrated that thermal conditions are sufficiently severe to degrade the fuel and result in a release of fuel particles.

For oxide fuels the release fractions of aerosols and particulate of respirable size might be summarised as follows:

TABLE 5 FLASK SOURCE TERM RESPIRABLE SIZED RELEASE FRACTIONS FROM PUBLISHED WORK[52,53,54,55]

CONDITION	RELEASE FRACTION	COMMENTS
Fire at 800°C	1.E-4	IAEA Conditions > 30 minutes
Impact at 0.1J/g	5.E-3	Containment of the fuel unknown
Explosive – Excellox	1.E-4 to 1.E-3	Probably extracted from Ref 79
ditto	6.E-5 to 8.E-4	Adapted from spent to surrogate fuel
Fire 2 hours	3.3.E-7	ditto
Explosion	1.E-1	Terrorist scenario on PuO_2 in FS47 flask shipment

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[50] If the flask remains upright then with yielding of the bolts the steam formed in the ullage space above the water level within the flask would vent until the pressure reduced for the lid to be pulled shut by the elastically extended lid bolts – this whole process of puff and shut, puff and shut, for a flask immersed in a hydrocarbon fire generating steam at 600kg/h would take about 100 minutes to completely expel all of the flask cooling water. If, however, the flask is upside down, the venting through the lid would be water and not steam so the entire water contents would be expelled in 30 seconds or so.

[51] The Magnox fuel is pyrophoric – the uranium metal will burn (flare) in air at temperatures above 220 - 275°C or lower at ambient if the cladding has been damaged and hydrides have formed on the fuel surface – the magnesium alloy cladding will also burn fiercely at about 700°C in air and the alloy will also violently react with steam via the exothermic reactions $Mg + H_2O \rightarrow MgO + H_2$ H = 360kJ and $Mg + 2H_2O \rightarrow Mg(OH)2 + H_2$ H = 440kJ.

[52] *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

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

[54] *Fuel Incident*, letter of 7 November 1983 Relating to the Haddom Neck PWR fuel oxidation Incident of 1983 at the Battelle Columbia Laboratory, Macdonald

[55] *Comparison of Results from Two Spent Fuel Sabotage Source Term Experiments* Luna, R.E. Int. J. Radioact. Mat. Transp. 11(1-2), pp 81-84 (2000)

Because of the pyrophoric properties of Magnox fuel once exposed to air, exothermic oxidation (burning) will result in a breakdown of the fuel body into particulate form available for release from the flask and dispersion in the atmosphere. Depending on the local conditions, the release fraction for a explosion-fire incident would be expected to be significantly higher than that determined by empirical trials for AGR and LWR dioxide fuels.

In summary: Given the recent and likely continuing climate of terrorist threat, it is not unreasonable to conclude that transportation of spent nuclear fuel is not and cannot be adequately defended against this threat:

- The claim of the UK authorities that the *'motives, intentions and capabilities of potential adversaries* can be identified before the attack is somewhat shallow in light of the second Greenpeace UK intrusion into the Sizewell B nuclear power station which was unchallenged until the activists were actually inside safety critical buildings.[56]
- There is the evidence to suggest that nuclear facilities have been considered by those known to have acted with malicious intent.
- There is no demonstration that the transport route can be absolutely safeguarded against terrorist attack.
- Past research and experimental programmes, involving shaped charges and propelled round attack on actual fuel flasks carried out in the United States and elsewhere, show that the heavily shielded CASTOR type flasks cannot maintain surety under such attack - there is no technical reason to suppose that, subject to similar explosive testing, the UK Magnox and AGR spent fuel transport flasks would survive any better.

ACCIDENT AND TERRORIST ATTACK CONDITIONS – THE RADIOLOGICAL CONSEQUENCES

There is considerable information and data published on the 1986 Chernobyl accident and how the radioactive release contaminated the nearby towns of Pripyat and Chernobyl. Although a postulated release from a flask or flasks severely damaged in an accident or terrorist incident cannot be directly compared in terms of the magnitude of the Chernobyl release, the third phase of the 10 day Chernobyl release provides a basis for conditions not that dissimilar to spent fuel subject to a fierce and prolonged fire. At Chernobyl later release phases include oxidised UO_{2+x} fuel particles a form of release not unexpected from spent fuel fire (AGR and PWR) engulfment release situation.[57]

Obviously, it is not possible to define or foresee exact scenarios but it is reasonable to include for both accidents and terrorist acts. These might range from, say, a terrorist attack directly targeting the flask(s) with an amour penetrating round whilst the flask is in the open, followed by fire; a bomb alongside the rail track; a derailment (accident) or an impounding (terrorism) of the flask in a rail tunnel followed by a fire; and, similarly an explosive event followed by a severe fire in the confines of a tunnel, and a host of other accident and terrorist attack scenarios.

Conditions for a selected range of accident and incident scenarios that result in severe damage of a single spent fuel flask and the outcome of the analyses are given in APPENDIX II.

LWR Spent Fuel Incidents

Work undertaken by the then National Radiological Protection Board (NRPB) in 1983 considered a LWR flask subject to four scenarios involving the flask in combinations of impact and fire and, separately, explosive events. The release fractions for these events were low (for Cs^{137} between 3.E-4 to1.E-3) and the location chosen was in the open at a railway siding in north west London (Willesden). Similar analysis for an urban situation was undertaken by the Sandia laboratory in the United States[58] were the percentage release fractions of respirable aerosolised solids were taken to range between 0.02.E+0 to 0.2.E+0.

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[56] Greenpeace UK activists entered the inner security compounds recently on two occasions – first in December 2002 when 150 individuals broke through the security fence and occupied the roof of the main control building and in January 2003 when a smaller group of 19 individuals broke in and occupied parts of the reactor control building and it roof, climbing onto the dome of the reactor secondary containment.

[57] Example of a specific release phase source term can be found in Chernobyl Case Study Increases Confidence Level in Radionuclide Transport Assessments in the Geosphere. Bugai, D.Dewière L, Kashparov V et al and Dynamics of Redistribution of Radionuclides in Soils and Plants in Chernobyl Exclusion Zone, Ivanov Yu National Academy of Science of Ukraine. Kyiv, 2001 and see also Dissolution Kinetics of Chernobyl Fuel Particles: I. Dissolution of Fuel Particles of Various Genesis in Model Experiments. Kashparov V. A et al 2000

[58] *Draft Environmental Assessment of Transportation of Radionuclides in Urban Emissions*, Finley N et al, Sandia National Laboratory, 1980

The results of these two studies may be summarised for a range of probabilities (which include for meteorological conditions) the number of fatalities in interim and longer terms:

TABLE 6 NRPB LWR PREDICTIONS[59]

			NUMBER OF FATAL HEALTH EFFECTS - PROBABILITY		
	SCENARIO	RELEASE FRACTION Cs^{137}	EXPECTATION VALUE E	P=1	P=99.9
T1	T1 Impact + 2 hour fire	3.E-4	1.6	0.11	18
T2	T2 Explosive 3 min release	1.E-3	45	4.4	670
T3	T3 Explosive 3 min release	1.E-4	4.5	0.44	68
T4	T4 Explosive 3 min Short-Cooled Fuel	1.E-3	99	9.5	1,300

Note: For an explanation of the table see footnote 2

TABLE 7 SANDIA LWR PREDICTIONS

		NUMBER OF FATAL HEALTH EFFECTS – PROBABILITY EARLY - LATE FATALITIES		
SCENARIO EXPLOSIVE SHORT-COOLED FUEL	RELEASE FRACTION Cs^{137}	EXPECTATION VALUE E		
Lower Release estimate	1.E-3	<<1 - 12		
Baseline Release estimate	7.E-4	<1 - 40		
Upper Release estimate	2.E-3	2.8 - 104		

The comparable results between NRPB and Sandia are highlighted in terms of the short-cooled fuel and assumed release fraction and, compared in this way, are consistent. That said, the release fractions assumed for the NRPB study might be considered somewhat conservative, particularly if applied to a well planned terrorist attack on the unstable Magnox fuel.

It should be noted that these NRPB average expectation of cancer fatalities, ranging from a few to about 100, decreases as the conditional probability decreases, with a probability of 1,000 fatalities occurring at a chance (conditional probability) of about 1 in 1,000 (not shown in TABLE 6). Of course, these cancer fatalities would not appear immediately in the exposed population but would occur over several decades and, in terms of individual risk that is low compared to the risk of any one individual contracting a ‘natural’ cancer in his/her lifetime.

The extent and health effect of the release from the incident site can be expressed in terms of the individual risk, here presented for the average (Expectation) value E:

TABLE 8 NRPB INDIVIDUAL RISK -V- DISTANCE

DISTANCE km	T1 $x10^{-3}$	T2 $x10^{-3}$	T3 $x10^{-3}$	T4 $x10^{-3}$
0.1	0.25	1.8	0.22	8.0
1.0	0.0062	0.13	0.013	0.4
10	0.00015	0.005	0.0005	0.05
20	0.00005	0.0018	0.00018	0.0032
50	0.0000012	0.000052	0.000005	0.000088

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[59] Of course, both the NRPB and Sandia studies predict the fatal cancers and other health detriment based on the ICRP 26 0.0125 per Sievert risk factor prior to the ICRP 60 in which the risk factor was increased 0.05 per Sievert, an increase of fourfold – the values given in Tables 6, 7 and 8 might be modified by this increase, albeit with some caution.

A more recent study[60] considered the hypothetical case of a single LWR dry flask subjected to the conditions of a fire that occurred in the Howerd Street Tunnel in Baltimore, Maryland in July 2001. The actual fire raged for three days unchecked, consuming an entire mixed goods freight train although no radioactive materials or spent fuel were involved in the real fire.

The modal analysis[61] adapted to forecast flask failure reckoned the flask seals to fail at 1.35 hours into the fire, the lead radiation shield inside the flask body melted at 1.8 hours, and the fuel pellet bursting temperature of 750°C would be reached at 6.32 hours into the fire.

For average wind and climatic conditions, at a release fraction of 9% of the flask content[62] but assuming that 50% of all releasing particulates adhere (plate out) to the tunnel lining and nearby surfaces, the radioactive release beyond the tunnel was predicted to have the following consequences:

TABLE 9 HOWERD TUNNEL SCENARIO 2001

AFFECTED POPULATION	345,493
POPULATION DOSE MAN-SV - RANGE	155 – 1,000
LATENT CANCER FATALITIES - RANGE	8 - 50
1-YEAR POPULATION DOSE MAN-SV	4,385 - 2806
LATENT CANCER FATALITIES 1-YEAR DOSE MAN-SV	219 - 1,403
50 YEAR POPULATION DOSE MAN-SV	88,013 – 563,280
50 YEAR LATENT CANCER FATALITIES DOSE - RANGE	4,401 - 28,164

The work also forecast the decontamination costs for the hypothetical Baltimore accident (2001 values):[63,64,65,66]

TABLE 10 PROJECTED COST OF CLEAN-UP – 2001 US $ VALUES

AREA HEAVILY CONTAMINATED)	9.9 km^2
AREA MODERATELY CONTAMINATED	62.4 km^2
COST/ km^2, HEAVY CONTAMINATION	$394,604,748
COST/ km^2, MODERATE CONTAMINATION	$182,592,165
COST/ km^2, LIGHT CONTAMINATION	$128,263,609
TOTAL CLEAN-UP COST	**$13.7 B**

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[60] *Radiological Consequences Of Severe Rail Accidents Involving Spent Nuclear Fuel Shipments To Yucca Mountain: Hypothetical Baltimore Rail Tunnel Fire Involving SNF* Lamb M & Resnikoff M, Radioactive Waste Management Associates September 2001

[61] *Shipping Container Response to Severe Highway and Rail Accident Conditions: Main Report (Technical Report)*, Fischer, L E, et al, Lawrence Livermore National Laboratory, NUREG/CR-4829-v1,-v2, February 1987

[62] *Spent Fuel Dissolution Studies, FY1994 to 1994*. Gray & Wilson, Pacific Northwest Laboratories. PNL-10540, 1995.

[63] Site Restoration: Estimation of Attributable Costs from Plutonium-Dispersal Accidents, Chanin, D I & W B Murfin, SAND96-0957, May 1996.

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

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

[66] Barclays Bank Environment Director Phil Case comments on real-world valuations of environmental liabilities (including some case studies on radioactively contaminated land) in *Environmental risk management and corporate lending - a global perspective* CRC Press, Woodhead publishing, 1999. In C6 - *Land as Security - The Valuation Process* - suggests that any level of elevated of contamination, such as HPA 3mSv dose criteria similar technical clean-up levels are inappropriate because radioactively contaminated land is virtually worthless; and the prospect of contaminating valuable business properties in London (from a terrorist dirty bomb attack or fuel flask attack for example) would be economically disastrous as far as the property market was concerned.

Magnox Spent Fuel Incident

Now consider the case of a train hauling Magnox spent fuel targeted by terrorists to maximise the radiological consequences.

In broad outline, the scenario includes both explosive intrusion and subsequent fire in a confined space such as a railway tunnel. An explosive device is deployed to open or penetrate the lid of each of 2 flasks, either by shearing banks of lid bolts, or with a shaped charge to breach the lid. A fire is then set to boil off the water fill and ignite the fuel element cladding and inner uranium rod of each of the 200 or so Magnox elements contained within each flask, and then to provide energy to loft the radioactive release plume for effective dispersion via the natural chimney flues formed by the tunnel air ventilation shafts. The analysis is based on an urban locality a uniform population density of 8,000 persons/km^2 which may distort the numbers upwards in terms of lower population densities at the further distances covered by the model.

TABLE 10 2 MAGNOX FLASKS - COSYMA PREDICTION TO ICRP 60 - LATE HEALTH EFFECTS

			NUMBER OF LATE FATAL HEALTH EFFECTS - PROBABILITY		
	SCENARIO	RELEASE FRACTION Cs^{137}	EXPECTATION VALUE E	P=50	P=99.9
Magnox	Explosion + 6 hour fire	3.E-2	2,815	2,344	8,491

TABLE 11 MAGNOX INDIVIDUAL RISK -v- DISTANCE

DISTANCE km	MAGNOX xE-3
0.1	0.36
1.0	0.163
10	0.0327
20	0.019
50	0.0078

TABLE 11 summarises the risk carried by any one individual to developing a fatal cancer related to the distance of that individual downwind from the site of the incident. For example and individual at 1km downwind from the incident is at risk of (1000/0.163 =) 1 in 6,135 over his or her lifetime.

TABLE 12 2 AGR FLASKS - COSYMA PREDICTION TO ICRP 60 - LATE HEALTH EFFECTS

			NUMBER OF LATE FATAL HEALTH EFFECTS - PROBABILITY		
	SCENARIO	RELEASE FRACTION Cs^{137}	EXPECTATION VALUE E	P=50	P=99.9
AGR	Explosion + 6 hour fire	1.E-3	1,511	1,514	3,022

Numbers of population involved in early countermeasures for the Magnox and AGR scenarios, again for a densely populated urban environment, are automatically calculated and inserted into the COSYMA model at 260,000 and 350,000 individuals for AGR and Magnox cases respectively.

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.

The primary uptake route for spent fuel aerosol 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. The relative contribution of this secondary, longer term uptake, diminished rapidly with time, being at one year virtually negligible if the exposure time is minimized to no more than about one month. The exposure from inhalation of radioactive 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. 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.[67]

The UK's system of emergency preparedness centres around a release dominated by β-γ emitters where the principal dose uptake pathway is external exposure. 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 for vehicles (ie shielding factor = 0), and a 6 hour lapse before any activity is removed from contaminated individuals. Similarly, for sheltering there is a 3 hour delay before sheltering, sheltering is commenced within the area extending out to 18km and/or where the exposure is predicted at 5mSv, and sheltering is limited to 4 hours, with a shielding factor of 50%. For an urban situation, 90% of the population are assumed to be indoors at the time of the incident. Relocation of individuals at a short term exposure greater that 50mSv is assumed to occur at 5 days. The model assumes there to be effective controls, in the longer term, in foodstuffs and potable water rendering the ingestion, etc., uptake to a minimum.

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

Finally, it should be noted that the results generated by computer based models, such as COSYMA, have to be considered with caution. Accurately modelling radioactive release, the subsequent dispersion, deposition and human dose uptake is fraught with difficulty and uncertainty. This includes fundamental assumptions on how much radioactivity is released, its chemical form and volatility, the particle size distribution, how this will disperse and deposit over a complex urban terrain and, perhaps most of all, how the individuals of the population caught up in the aftermath will react. Each of these factors can introduce elements of not insignificant uncertainty and error, so much so that the results produced in this Review should be regarded only to illustrate trends of how a radioactive release from a spent fuel flask might be expected to develop.

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[67] Of the emergency services personnel, firefighters, police and medics, if is only the firefighters who have a nationally agreed radiation dose limitation system in place.

APPENDIX I

IAEA TS-R-1 COMPLIANCE TESTS AND REQUIREMENTS

Leaktightness: The IAEA Regulations do not prescribe any content limit in terms of radioactivity for the TYPE B flasks but, instead, superimposed limits on the radioactivity loss or dispersal by leakage during normal transport and for (and following) the mechanical, thermal and immersion tests. In other words, an acceptable rate of activity loss is cited rather than specifying an absolute or relative 'leaktightness' for the package.

Drop Impact Test: First consider the IAEA TS-R-1 drop or impact tests: For the irradiated fuel TYPE B transport flasks this should be interpreted to mean that the structural performance of the flask is only important in the specific role of continuing containment during and following an accident. This meanest of interpretations suggests that the TYPE B flasks are not required to withstand moderate to severe accidents in such a way that the flask could be re-used. In these terms, the first of the drop tests (from 9m) simply determines the ability of the flask not to leak upon or following impact. Similarly, the punch and plate drop tests are aimed at demonstrating the ability of the flask to maintain a tolerable level of containment. The punch drop test simulates potential penetration by an upturned rail, or similar, into the wall of the flask, whereas the plate drop test is aimed, it seems, at proving the integrity of external valves and fillers, although neither of these tests are specific with respect to isolating the potentially weakest components of the flask, nor do such include for a secondary event within the flask if penetrated. For example, the punch test does not include for the detonation of any explosive introduced into the flask by a missile and the performance of the flask with respect to this.

Fire Incidents - Test Specification: In the IAEA thermal (fire) test, the flask must not leak at an accumulated rate in a period of one week greater than the appropriate pre-specified value. Separately, the radiation emissions from the surface of the flask following these tests shall be maintained at a tolerable level, although and as previously noted, a substantial 100-fold reduction is permitted in radiation shielding following a severely damaging incident.

The self-heating characteristic of the fuel and dissipation of this heat to the flask is not specifically covered for by an IAEA test, although the regulations do specify a maximum surface temperature of the flask of 50°C in normal use. Accordingly, consideration needs to be given to the thermal performance of the flask in both accident and normal operational conditions.

Incident Conditions Resulting in Temperature Increase: A number of conditions will result in abnormal temperature increase within, the flask and for this the IAEA thermal test is presented as being representative of the most severe of all credible accidents.

The IAEA thermal test assumes fire engulfment of the flask to be the primary means of heat input, thus the onus is on the flask designer to provide sufficient thermal insulation or, as is reality, greater thermal mass to enable the flask to 'ride out' a relatively short duration (and moderate temperature) engulfing fire scenario. However, the irradiated fuel generates heat by virtue of its (radio)activity alone which, dependent on the pre-decay cooling period whilst the fuel is stored in the power station ponds, will decline from about 27kW at 90 days to 10kW at one year pond storage.

Loss of Coolant Water - Irradiated Fuel: Normally and for a water filled flask, such as an AGR flask, fuel decay heat generation is transferred from the fuel to the inner surfaces of the lead liner and thence to body of the flask by the water. If, however, the water fill is lost as a result of some flask damaging incident or, say, earlier incorrect sealing of the flask at time of dispatch, then the efficacy of heat transfer from the fuel is very much impaired.

Complete loss of coolant would result in fuel clad temperatures in excess of 1,000°C, at about which a violently exothermic reaction could occur between the zirconium alloy fuel cladding (LWR fuel) and residual steam within the flask cavity. Similarly, partial loss of coolant would result in melting of the lead liner (AGR and some LWR flasks), increased gamma radiation emission from the flask and, eventually, complete loss of coolant.

Incident Involving Fire Engulfment: The generally more demanding thermal condition for an irradiated fuel flask is when the flask is fully engulfed in fire. This is represented by the IAEA thermal test, which has been subject to criticism.

When the external temperature, particularly resulting from a fire engulfing the outer surfaces of the flask, is higher than the flask internal temperature there is a net flow into the flask. If the fire is completely engulfing then the modes of heat transfer into the flask will be direct, but if the fire is remote, that is shielded directly from the flask, the modes of heat transfer will be radiation (thermal), convection and conduction. For both these cases the IAEA regulations stipulate appropriate surface emissivity and heat absorption coefficients. Many observers consider the maximum temperature limits and the fire duration to be minimal and not at all representative of realistic fire conditions. This lack of realism of the IAEA thermal test is particularly so for tunnel fires where the tunnel enclosure provides a significant thermal radiation input to the flask(s), and in which temperatures may be sustained and exceed the IAEA reference temperature of 800°C, reaching in excess of 1,000°C.

For the irradiated fuel flasks the possibility of melting of part of the internal gamma radiation shielding is particularly important, since the wet-fill LWR flasks include substantial lead liners to provide gamma shielding and, for the very high burn-up fuels, there is other shielding (cadmium and/or boron-silicate) for absorption of neutrons emitted by the fuel. A typical LWR irradiated fuel flask will survive a fire of 30 minutes or so duration without loss of integrity. For a fire lasting an hour or more the vents (if fitted) would open (by failure and not in their intended role for filling and purging the flask at dispatch) releasing contaminated cooling water, thereafter 4 hours of sustained fire would promote failure of fuel elements, and after nine hours all of the fuel elements would be likely to fail. Some LWR flask designs when subjected to fire will rupture at about 2 hours into the fire.

Similar analysis for Magnox and AGR fuel flasks yields a more complex mode of failure in which fuel element failure triggers in 2 to 3 hours, particularly if the coolant venting was rapid. In certain conditions for the Magnox/AGR flask design, complete coolant venting occurs at about 110 minutes (flask upright) in a 1100°C engulfing fire and the coolant is completely expelled from the flask within 30 to 40 seconds (flask upside down).

Radioactive Package Types: The IAEA Safety Series TS-R-1 provides the important distinction between the types of packages related to the toxic-weighted magnitude of the radioactivity being carried. The distinction between types of packages, based on the total weighted radioactive contents of the package, comprises TYPE A, B and C[68] system of containers and the so-called Transport Index.

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[68] TYPE C packages are for air freighting physically small packages of high radioactivity.

Essentially, the activity contents permitted in a TYPE A package are determined by the assumption that a proportion of the contents could be released and that the exposure to any individual from this fraction would be tolerable.

Since the TYPE A package is specified in terms of defined limits of radioactive contents, a second category of transportation package is required for radioactive consignments, such as irradiated fuel, that could not possibly satisfy the TYPE A limits in the event of a severely damaging accident. For this the TYPE B package enables consignors to transport very large radioactive source terms (such as irradiated fuel). Since there is no effective limitation of the size of the radioactive source term carried within a TYPE B package, there can be no reliance upon the part release assumption of the TYPE A package uptake rule. In other words the containment of TYPE B packages has to be virtually absolute in all foreseeable accident scenarios.

Irradiated Fuel and Criticality: Irradiated fuel, which is intensely radioactive, must be contained for transport within a TYPE B package or flask. For each specific type of fuel the IAEA Regulations require modification of the flask design to cater for the prerequisites of the mass of the fissile material, the radionuclide contents, and the physical form, chemical state and spatial arrangement of the fuel assemblies.

The mass of fissile material and spatial arrangement of the fuel assemblies relate to restrictions on the criticality potential of the fuel. The IAEA defines critical (fissile) material to include both plutonium and uranium components.[69] This effectively means that the flask contents must not interact within any other individual flask. In other words, each flask must possess a net neutron absorption characteristic. This requirement is generally achieved by providing each flask (usually in the form of a removal skip or fuel bottle) with a neutron absorbing racking system of boron alloy steel, thus maintaining spatial geometry and neutron absorption.

For enriched AGR and LWR fuels criticality is at risk within the flask. Although reactor in-core irradiation (burn-up) of the fuel depletes the U^{235} fissile content, the IAEA require the criticality assessment to be undertaken as if the enriched fuel was unirradiated.

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[69] Totally natural uranium based fuels (Magnox) are considered to be fissile exempt for the purposes of the IAEA regulations – for Magnox, natural uranium fuels and fuels below 0.9% enrichment, criticality of the irradiated fuel cannot occur.

APPENDIX II

ACCIDENT/INCIDENT CONDITIONS FOR SEVERELY DAMAGING SCENARIOS

There are a number of computer software program available for forecasting the dispersion and deposition of a radioactive release. For these examples, the European Commission COSYMA program gives dispersion and deposition under specified climatic conditions using cyclic sampling of data previously acquired for specific locations in Europe – for these models the population data for a densely populated urban environment (London).

The interaction of the released radioactivity with humans with these factors determining the human health detriment in the short, interim and long terms and such that might be carried across generations. These determinates include the route and efficacy of human uptake, the length of exposure within the contaminated area, the susceptibility of that individual to disease from the particular source, and the effectiveness of countermeasures introduced in the aftermath of the incident.

COSYMA includes a data base of point by point populations and agricultural produce (base on 100 km^2 comprising segments of constant 15^o longitude with a variable latitude to maintain equal areas) so a sample number of locations have been included in the analysis as example of the health detriment numbers for urban populations, although the population data has not been refined down below the 100km^2 cell size held by COSYMA. The local population refinement could be incorporated providing that the population distribution data is available for both of these sample and any other location nominated for analysis.

Sheltering and evacuation countermeasures are invoked on a dose basis applied over a single region and at an effective dose of 0.05Sv[70] for evacuation but countermeasures based on purely geometric locations (ie automatic emergency planning zones) are not assumed because these generally automatic arrangements can only apply to a fixed nuclear installation. An initial delay of 3 hours from the onset of the incident is assumed before any countermeasures are effectively implemented and prior to evacuation 3 hours of sheltering is assumed. The time taken to move evacuees out of the area is 60 minutes and a further period of 6 hours is assumed before skin contamination can be removed from evacuees. For extreme releases and based on inhalation and resuspension dose allocation, relocation from the area is assumed to be completed within 5 days. For all periods of exposure (sheltering and transport out) normally accepted shielding factors are adopted.

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. 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.[71] The risk to any individual (the individual risk) is also a function of the distance and direction for the site of the release

This approach is applicable to *a priori* accidents (ie road traffic accidents) and the occurrence of natural hazards (ie earthquakes) with the probability of the accident occurring included in the overall probability train. Since the flask and transport system can be designed to withstand reasonably foreseeable accident circumstances and severities (so far as the IAEA testing regime applies), it follows that the probability of a flask damaging accident occurring will be low. This probabilistic approach can also be applied for radioactive releases that stem from terrorist attack, although the probabilistic train of reasoning excludes the terrorist event itself so.

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[70] In the UK a system of Emergency Reference Levels (ERLs) are deployed. For sheltering these are arranged in Lower (3mSv) and Upper (30mSv) levels and for evacuation 30mSv Lower and 300mSv upper – the countermeasure should not be undertaken before the Lower exposure level but should be implemented to prevent the individual reaching or exceeding the Upper level.

[71] 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.

APPENDIX III

TERRORIST ACTIONS – EXPLOSIVES AND FIRE

Terrorist attack against any nuclear consignment in transit cannot be discounted and, in recent months, the threat has heightened in the UK. 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.[72] 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 a few individuals in urban environments.[73]

In the early 1990s the West German Federal Ministry of Environment, Nature Protection and Reactor Safety (BMU) required physical testing of transportation flasks against shaped explosive charge. 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.[74] In 1996 the French also conducted firing trials on another type of Type B flask containing plutonium dioxide, not releasing the information until 2004, with the work showing the uncertainties of the assessment of how much (the release fraction) would be released in a real terrorist incident.[75]

Similar trials simulating sabotage on irradiated fuel flasks were undertaken in the early 1980s and 1990s in the United States.[76] In the United Kingdom, the National Radiological Protection Board undertook the analysis of a radioactive release from an irradiated PWR fuel flask that had be hypothetically subject to terrorist attack by an armoured piercing round, thus setting the parameters for a radioactive release initiated by explosive conditions[77] - the release fractions adopted in this NRPB study ranged 1.E-4 to 1.E-3.

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[72] Current portable anti-tank weapons are:

WEAPON	COUNTRY	WEIGHT	RANGE	WARHEAD Ø/KG	ARMOUR PENETRATION
Milan Anti-Tank Missile	France	32 kg	2000 m	133 mm/3.12 kg	>1000 mm
Eryx Anti-Tank Missile	France	21 kg	600 m	160 mm/ 3.8 kg	900 mm
Panzerfaust 3 Anti-Tank Launcher	Germany	13 kg	300 m	110 mm/NA	>700 mm
Folgore Anti-Tank System	Italy	21 kg	4500 m	80 mm/3 kg	>450 mm
Apilas	South Africa	9 kg	330 m	112 mm/NA	>720 mm
RPG-7 Anti-Tank Launcher	Soviet Union	11 kg	300 m	85 mm/NA	330 mm
C-90-C Weapon System	Spain	5 kg	200 m	90 mm/NA	500 mm
AT-4 Anti-Tank Launcher	Sweden	7 kg	300 m	84 mm/NA	>400 mm
Carl Gustav M2 Recoilless Gun	Sweden	15 kg	700 m	84 mm/NA	>400 mm
LAW 80 Anti-tank Launcher	U.K.	9 kg	500 m	94 mm/NA	700 mm
M72 66mm Anti-tank Launcher	USA	4 kg	220 m	66 mm/NA	350 mm
SMAW	USA	14 kg	500 m	83 mm/NA	>600 mm
AT-8 Bunker Buster	USA	8 kg	250 m	84 mm/NA	NA
Superdragon Anti-tank Missile	USA	17 kg	1500 m	140 mm/10.07 kg	>500 mm
TOW 2 Anti-tank Missile	USA	116 kg	3750 m	127 mm/28 kg	>700 mm
Javelin AAWS/M	USA	16 kg	2000 m	127 mm/NA	>400 mm

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

[74] 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.

[75] *Plutonium Transports in France Safety and Security Concerns over the FS47 Transportation Cask*, Yves Marignac, Xavier Coeytaux, John H. Large, 21 September 2004

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

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

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,[78] 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.E-5 to 8.E-4 grams weight (per gram of surrogate fuel matrix) of respirable surrogate spent fuel aerosol released from the flask under attack. For this test the explosive charge was not in physical contact with the fuel assemblies so the aerosol/particulates given off primarily derive from the shock and blast loading with the release fractions relating 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.

The size distribution of the surrogate fuel (U-238) particles released was:

TABLE B AEROSOL/PARTICLE SIZE DISTRIBUTION FOLLOWING EXPLOSIVE PENETRATION

	POST-DETONATION PRESSURE INSIDE FLASK	
EQUIV AERODYNAMIC Ø [μm]	**RELEASE NORMAL** g	**RELEASE AT 0.8 BAR** g
< 12.5	1.0	0.4
12.5 - 25	0.7	0.1
25 - 50	1.0	0.1
50 - 100	0.9	0.1

Analysis of the dispersion following an explosive attack on a flask of irradiated fuel utilized data from a source that is no longer in publication.[79] However, others referring to this work give the release of respirable-sized particles from the flask to range from 1 x 10^{-6} to 1 x 10^{-3} for actinides in oxide form (which is generally the level assumed for other fission and activation products).

These experimental trials were conducted on the robust CASTOR design of irradiated fuel transport flask with side walls of 150 to 200mm solid carbon steel and of about 100 tonnes weight - 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 outer shell of the flask.

The resulting aerosol formed, particularly the range and dominance of a particle size, is dependent upon the amount of particles present at the time of fuel pin cladding failure, the dispersion of these particles within the fuel pellets, the inherent size of the particles in the matrix of the fuel, along with any retention or 'plating out' and retention of fuel particles on the surfaces of the fuel assembly, flask walls and breach through the vehicle container.

The ejection of the aerosol is via those particles caught up in the highly turbulent jet stream that puffs out of the flask internals during the short spell when external and internal pressures are equalizing. In the reported trials the aerosol release was very short term, with less than 1% of the <12.5μm particles being released after 30 seconds. However, this period of release extends considerably if the flask sustains greater damage and/or if fire breaks out in or about the vehicle trailer unit.

Another very significant factor that determines the health consequences of the radioactive release is the particle size. In the reported trials, the surrogate fuel gave off a range of particle sizes of which about 25 to 50% (depending on the flask pressure) were of respirable size (say <12.5).[80,81]

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[78] *Comparison of Results from Two Spent Fuel Sabotage Source Term Experiments* Luna, R.E. Int. J. Radioact. Mat. Transp. 11(1-2), pp 81-84 (2000)

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

[80] Only particles with aerodynamic equivalent diameters AED < 10 mm are considered to be respirable and to contribute to radiation exposure via inhalation. For other exposure pathways such as ground shine the deposition velocity which depends on the aerodynamic diameter influences the level of ground contamination from dry or wet deposition.

[81] Eastmen R J, Tod S, *The Microstructure of Unirradiated SBR Mox Fuel,* IAEA-SM-358/9 British Nuclear Fuels plc

Appendix IV

Irradiated (Spent) Fuel

Irradiation: The nuclear processes underway within the fuel core of a nuclear reactor bombard the atomic structure of the uranium fuel with neutrons. The collision and absorption of a neutron within a whole uranium atom, splits the uranium and creates a number of fission products and frees more neutrons which enable the nuclear chain reaction to prosper.

The isotope of uranium that is principally responsible for fission is uranium-235 which is present in naturally abundant uranium to the extent of 0.715%, with the remaining uranium being U-238 which is less fissionable. The fission process with U-235, which is also possible with another four different isotopic elements, commences with the absorption of a neutron in U^{235} forming U^{236} at an excited and unstable state. In some instances the U^{236} emits gamma radiation and returns to a stable state but the majority of absorptions result in the U^{236} nuclear splitting or fissioning, yielding two fission fragments whose mass numbers varies between about 70 and 160, giving a range of (radioactively) unstable elements (caesium, ruthenium, etc), together with a number of neutrons, beta particles and gamma radiation, neutrinos and energy. It is the majority of these fission fragments or products that are eventually separated out as high-level radioactive waste.

Increasing the amount of U^{235} present in the fuel increases the number of fissions available before the fuel becomes too depleted to function. The Magnox reactor fuel is not enriched and comprises just U^{235} at the natural level of ~0.7%, whereas the advanced gas-cooled reactor AGR and light water reactor fuels (LWR pressurised water reactor PWR and BWR boiling water reactor) utilise enriched uranium where the content of U^{235} is increased to 2 to 3.5% with the level of enrichment differing in various regions of the reactor core. Some types of research reactor utilise moderately and highly enriched uranium fuel, and to achieve compactness of design and longevity of in-core service, submarine propulsion reactors (both United States and Royal Navy) are fuelled with fuel enriched in excess of 93% U^{235}. Generally, the higher the degree of U^{235} enrichment then the longer the fuel remains in the reactor, so the greater irradiation and, hence, the larger the proportion of fission products and overall radioactivity.

Almost all of the species of fission fragments are unstable, losing energy by emitting from the unstable nuclei some combination of alpha, beta and gamma rays, and by internal conversion which emits X-rays. This process eventually leads to a stable or grounded isotope by a random process which characterises the individual radioisotope by half-life[82] which, according to the particular fission fragment or radioisotope ranges from a few seconds (Radon Rn^{220} 55 seconds), to hours (Technetium Tc^{99m} 6 hours), days (Iodine I^{131} 8.05 days), years (Caesium Cs^{137} 30 years) and some actinides yield by the absorption of a neutron in U^{238} tens of thousands of years (Plutonium Pu^{239} 24,400 years). The half-life indicates for how long the initial (radio)activity of each radioisotope will take to halve, and thereafter to reduce to one quarter, one eighth and so on.

In summary, each fission product species is characterised by its elemental chemistry, its (radio)activity and its natural decay half-life. At any one time, the activities of any number of fission products can be summed together on the basis of their respective quantities, and the way in which any mix of fission products will decay over future time can be determine by account of the individual half-lives.

Fuel Inventory: Fission products are retained in the fuel whilst it is in the reactor core by the cladding or sheathing around the individual fuel rod or pellets. The longer the fuel stays in the core the greater the amount of energy in the form of heat liberated to the reactor cooling system, and the greater the amount of fission products held in the fuel pins.

The crude measure of this is fuel *burn-up* which essentially relates to the extent of irradiation (nuclear absorption), that is a product of the neutron flux in the reactor core and the total time that the fuel has been subject to irradiation. The extent of irradiation also depends on where the fuel is positioned in the reactor core, to offset the peripheral areas of the core where the irradiating neutron flux is lower, enriched fuels may be of a lower level or uranium enrichment to offset the lower rate of burn-up, and/or some reactors such as the Magnox and AGR, have the capability of shuffling the fuel to different locations in the core to achieve an even fuel burn-up.

The unit of fuel burn-up is conventionally related to the electrical energy produced, being expressed as MWd/tU (MegaWatt.day per tonne of uranium) and which is usually given as an average burn-up for the whole fuel core. Typical fuel burn-ups for the present generation of (thermal) nuclear reactors are:

Table 1 Commercial Reactor and Fuel Characteristics

Reactor Type	Units	Magnox	AGR	LWR
Fuel	U^{235} %	U^{nat}	2.25 - 3	3.05 – 3.5
Burn-Up	MWd/tU	3,600 – 7,300	10,000 – 40,000	33,000 – 55,000
U^{nat} per GW_eyear	tU/GW_eyear	400	180	200
Reprocessing Delay	year	2 - 3	5	5
Fuel Throughput 1 GW_eyear	tU	400	50	35

The burn-up and fuel utilisation figures given in Table 1 will vary from reactor to reactor and fuel performance generally increases with the fuel development programme (time).

Currently under Review by government is the decision whether to proceed with a new programme nuclear power stations. If the Energy Review favours new nuclear build then the UK reactor programme is likely to feature the Generation III light water reactors, either or

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[82] The radioactive decay is the measure of the number of nuclei decaying over a set time, taken as per second. This is measured in units of the Becquerel (Bq), or in the past, the Curie (Ci), with 1 Bq being one decay per second and a Ci being equal to 3.7E+10 Bq (3,7000 million Bq). The original Curie unit was set by the number of nuclei disintegrations occurring in 1 gram of radium, so 2 grams of radium will have 2 Ci of activity, and so on.

both AP 600/1000 and EPR,[83] These reactors aim to achieve fuel burn-ups in excess of 65,000MWd/tU so it follows that the transportation of spent fuel from these reactors will carry with it a greater unit quantity of radioactivity (Bq per unit of Bq/tonne) and, hence, a greater the radiotoxic potential in the event of a release over the projected 60 year operating life (compared to 40 years for Sizewell B PWR) of these Generation III nuclear power plants.

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[83] AP or Advanced Passive reactor is a Westinghouse design and the EPR or European Pressurised Reactor is an Arriva design – an EPR unit is presently under construction at Olkiluoto, Finland, see *European Pressurised Reactor at Olkiluoto 3, Finland - Review of the Finnish Radiation & Nuclear Safety Authority (STUK) Assessment*, Large & Associates, R3123-A2, July 2005