Assessment of the Radiological Impact of the Transport and Disposal of Light Bulbs Containing Tritium, Krypton-85 and Radioisotopes of Thorium

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ABSTRACT

The European Lamp Companies Federation commissioned HPA to carry out a study to assess the radiological consequences arising from the transport and disposal of lamps containing low levels of radioactive material. An assessment was carried out of doses received by workers and members of the public representative of the individuals most exposed during transport and disposal to landfill of these lamps. For transport, doses from both routine and accident scenarios were considered and compared with dose criteria for exemption of 10 μSv y^{-1} (routine operations) and 1 mSv y^{-1} (accidents) retrospectively. All doses calculated in this study were below these dose criteria for exemption even when the activity assumed in the consignment were well above the activity limits for exemption. The highest dose from routine transport of lamps was 7 μSv y^{-1}; the highest estimated dose from an accident in a warehouse was 2.5 10^{-3} mSv y^{-1}.

The study also estimated activities for lighting products as consumer goods in transport up to the end-users, which would give rise to doses equal to the dose criteria for exemption. The minimum activities thus calculated were 1.9 10^{9} Bq for ^{3}H, 5.0 10^{8} Bq for ^{85}Kr and 2.9 10^{6} Bq for thorium, respectively a factor of about 2, 50000 and 300 higher than the current activity limits for exempt consignments given in the IAEA Transport Regulations. For ^{85}Kr and thorium, activities which would give rise to dose equal to the dose criteria for exemption were also calculated for transport of disused, unpackaged lamps to a recycling plant or a landfill site. The minimum activities thus calculated were 4.0 10^{7} Bq for ^{85}Kr and 6.3 10^{4} Bq for thorium, respectively a factor of about 4000 and 60 higher than the current activity limits for exempt consignments given in the IAEA Transport Regulations.

This study has shown that the radiological consequences from the transport of lamps to the end-user and transport in bulk of disused lamps to landfill are not significant. On the basis of the outcome of this assessment the exemption limits for consignments recommended by the IAEA in its Regulations for the Safe Transport of Radioactive Material appear to be restrictive when applied to the transport of lamps containing low levels of radioactive material.

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In the second part of this study doses from disposal to landfill of disused lamps containing small quantities of radioactivity were also estimated. In Europe most of these disused lamps are recycled; only a small fraction is sent to municipal landfill sites. The objective of the assessment was to carry out scoping calculations of doses using cautious assumptions for comparison with dose criteria relevant to disposal to landfill currently applied in the United Kingdom in order to determine maximum activities of ^{3}H, ^{85}Kr and thorium. The lowest values of these activities can be taken as general upper limits on the activities that can be disposed of to landfill in order to meet all dose criteria. These activities were 6 10^{12} Bq for ^{3}H, 4 10^{15} Bq for ^{85}Kr and 3 10^{11} Bq for thorium. The maximum number of lamps that can be disposed of without exceeding the dose criteria were also calculated. These numbers vastly exceed the numbers of lamps containing low levels of radioactivity which are currently disposed of to landfill each year (about 1 10^{6} for each type of lamps). This study has therefore shown that the radiological consequences from the disposal of disused lamps to landfill are not significant.

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The following amendments have been made to this report since its first publication (November 2010).

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Page number 47. Heading of third and fourth columns of Table A2 have been amended. Units of dose rate for external exposure per unit activity concentration given in Table A2 are Sv h^{-1} Bq^{-1} g, not Sv y^{-1} Bq^{-1} g as stated in column headings of original version of the report.

CONTENTS

1 INTRODUCTION

A small fraction - about 2% - of the lamps sold on the European markets contains low levels of radioactive material. The radionuclides found in these lamps are ^{3}H, ^{85}Kr and isotopes of thorium (^{232}Th and ^{228}Th). The manufacturing, transport and disposal of these lamps is covered by national and international legislation aimed at minimising the hazard that the radioactivity may potentially pose to human health.

The European Lamp Companies (ELC) federation was established in 1985 to provide a forum for the lamp industry in Europe. It represents the leading European lamp manufacturers, which employ 50,000 people, and account for 95 percent of total European production, with an annual turnover in Europe of €5 billion. One of the objectives of the federation is to monitor, advise and co-operate with legislative bodies in developing European Directives and Regulations of relevance to the European lamp industry.

The European Lamp Companies Federation commissioned HPA to carry out a study to assess the radiological consequences arising from the transport and disposal to landfill of lamps containing low levels of radioactive material. The study considered a range of exposure scenarios in order to estimate the highest doses* that might be received by different individuals (eg, workers in the lamp manufacturing industry, other transport workers, workers at a landfill facility involved with disposal operations and members of the public) in different situations. The doses were then compared with relevant dose criteria which have been adopted in international regulations and in United Kingdom. The assessment draws upon similar studies undertaken in the past (USNRC 2001, Gelder et al, 2001; Harvey, 2008) and makes use of scenarios that reflect realistically common practices adopted by the lamp industry based on information provided by ELC.

This document describes in detail the assessment carried out by HPA. The remainder of this section provide information on the regulatory requirements and dose criteria currently recommended at international level and in the United Kingdom relevant to the transport and disposal to landfill of lamps containing small quantities of radioactive material and on the types of lamp considered in this study. Sections 2 and 3 describe the methodology used in the calculation of doses during transport and disposal to landfill of the lamps. Sections 4 and 5 provide the results of the assessment and Section 6 discusses the results and provides some conclusions.

1.1 Types of lamps containing low levels of radioactivity

A number of lamps are available that may contain low levels of radioactivity. The lamps fall into three broad categories: high-intensity discharge (HID) lamps; one type of electrodeless induction lamp and starters or glow switches for fluorescent lamp systems,

* In this report the term dose is taken to mean the sum of the committed effective dose from intakes in a period (usually 1 year) and the effective dose from external exposure received during the same period (ICRP, 1991).

used as starting aid for fluorescent tubes and compact fluorescent lamps. All these lamps are used predominantly in professional lighting.

Tritium (^{3}H) is used in the glow-switch starter in fluorescent lamp systems, either as a separately provided unit, such as those for linear fluorescent tubes, or as a unit permanently mounted in the base of a compact fluorescent lamp. Tritium is applied as elemental gas and is contained in a soft glass canister with walls at least 1 mm thick. Although tritium-based starters are being phased out in the EU in favour of electronic gear, current annual global production is of the order of 10^9 of the separate canisters and 10^8 of the compact fluorescent lamps containing integral tritium-based starters.

Krypton gas containing ^{85}Kr is used as a starting aid in HID and electrodeless induction lamps and is generally mixed with argon. The argon-krypton noble-gas mixture is contained in the arc tube of a lamp, which has a ceramic or quartz glass wall at least 1 mm thick. For most lamps containing ^{85}Kr, the arc tube is housed in an outer envelope made of soft glass, hard glass or quartz; the exceptions are ‘burner only’ quartz glass lamps which include the electrodeless induction lamps as well as some special HID lamps.

Naturally occurring thorium containing ^{232}Th and ^{228}Th is used in HID lamps as ThO_2 in the electrodes to improve metallurgical properties, either in thoriated tungsten electrodes or as a coating on the electrodes. ThI_4 can also be added to the salt mix in to improve the lamp’s spectral characteristics or as a starting aid. Although the lamps are manufactured with chemically separated thorium, over the lamp’s lifetime, which is conservatively estimated to be 15 years (US Nuclear Regulatory Commission, 2001) the activity of the progeny in the decay chain of ^{232}Th reaches 75% of the activity of ^{232}Th. For the purposes of this study, it was therefore conservatively assumed that secular equilibrium was reached at the time of disposal. Information on the lamps considered in this study is given in Table 1. The first column gives the codes used to identify different types of lamps.

Table 1. Types of lamps considered in the assessment

Lamp code	Lamp type and description	Radionuclide	Activity in lamp (Bq)	Maximum activity concentration (Bq g^{-1})
LH3	Starter for fluorescent light. Radioactive material surrounded by 1 mm glass	^{3}H (gas)	1 10^{3}	1 10^{7}
LKR85_1	Short arc lamp/ metal halide. Radioactive material surrounded by 1 mm quartz glass. Filling gas assumed to be argon	^{85}Kr (gas)	2 10^{3}	6.7 10^{6}
LKR85_2	Short arc lamp/ metal halide. Radioactive material surrounded by 1 mm quartz glass. Filling gas assumed to be argon	^{85}Kr (gas)	1 10^{3}	6.7 10^{6}
LKR85_3	Short arc lamp/ metal halide. Radioactive material surrounded by 1 mm quartz glass. Filling gas assumed to be argon	^{85}Kr (gas)	1 10^{2}	6.7 10^{6}
LTH232_1	Mercury short arc lamp. Cathode containing thorium oxide in tungsten matrix surrounded by 1 mm quartz glass. Fill gas assumed to be argon	^{232}Th (solid as ThO_2)	1 10^{3}	7.4 10^{1}
LTH232_2	Metal halide lamp. Cathode containing thorium oxide in tungsten matrix surrounded by 1 mm quartz glass. Fill gas assumed to be argon	^{232}Th (solid as ThO_2)	1 10^{2}	7.4 10^{1}
LTH232_3	Metal halide lamp. Cathode containing thorium oxide in tungsten matrix surrounded by 1 mm quartz glass. Fill gas assumed to be argon	^{232}Th (solid as ThO_2)	2.5 10^{1}	7.4 10^{1}
LTH232_4	Metal halide lamp. Thorium iodide as a dose material in a matrix surrounded by 1 mm quartz glass	^{232}Th (solid as ThI_4)	1 10^{0}	5.0 10^{1}

Disused lamps containing low levels of radionuclides are generally collected and either recycled or disposed of directly to a municipal landfill. Information provided by ELC suggests that the recycling companies only collect the type of lamps under the Waste Electrical and Electronic Equipment Directive, known as WEEE directive (European Commission, 2003), which are mostly fluorescent lamps, and that 30% of lamps regulated under the WEEE directive are collected (ELC, 2010). About 90% of these lamps are recycled and the remaining 10% disposed of to landfill. It is estimated that out of all the lamps collected to be recycled under the WEEE directive only 2% contain radioactive material (ELC, 2010). Table 2 gives a summary of the number of lamps in packages and pallets normally transported and those collected for recycling (ELC, 2010). The numbers of lamps containing low levels of radioactivity that are disposed of to landfill in Europe each year were provided by ELC (ELC, 2010) and are also given in Table 2.

Table 2. Number of lamps transported and disposed of to landfill annually

		Number of lamps			
Lamp code	Lamp mass (min – max) (g)	Package	Pallet	Recycling bag[#]	Disposed of to landfill annually
LH3		$1\ 10^{0}$	$1\ 10^{2}$	$1\ 10^{1}$	$1\ 10^{6}$
LKR85_1	10 – 175	$6\ 10^{1}$	$9\ 10^{3}$	$9\ 10^{2}$	$5\ 10^{4}$
LKR85_2	10 – 175	$6\ 10^{1}$	$9\ 10^{3}$	$9\ 10^{2}$	$1\ 10^{5}$
LKR85_3	10 – 175	$6\ 10^{1}$	$6.3\ 10^{1}$*	$9\ 10^{2}$	$8.5\ 10^{5}$
LTH232_1	450 – 3000	$1\ 10^{0}$	$1\ 10^{2}$	$1\ 10^{1}$	$1\ 10^{5}$
LTH232_2	30 – 650	$1\ 10^{1}$	$1\ 10^{3}$	$1\ 10^{2}$	$1\ 10^{5}$
LTH232_3	25 – 250	$1\ 10^{1}$	$1\ 10^{3}$	$1\ 10^{2}$	$4\ 10^{5}$
LTH232_4	19.5 – 64	$1\ 10^{1}$	$1\ 10^{3}$	$1\ 10^{2}$	$4\ 10^{5}$

Notes:

*: For pallets these lamps are assumed to be mixed with lamps containing no radioactive material at a ratio of 0.7%.

#: Only 2% of the lamps in a recycling bag is assumed to contain radioactive material.

1.2 Regulatory framework for the transport of lamps containing low levels of radioactive material

Legislation currently in force in European countries regulating the transport of lamps containing low levels of radioactive material is largely based on the Regulations for the Safe Transport of Radioactive Material, published by the International Atomic Energy Agency (IAEA) (IAEA, 2009). The IAEA transport regulations include limits on activity concentration and activity for consignments which may be used to exempt materials and consignments from the requirements of the regulations. The IAEA Transport Regulations do not apply to a material which contains radionuclides where either the activity concentrations or the activity for the consignment is less than these limits, which are generally referred to as exemption values.

Exemption values were derived on the basis of the general principle that a justified practice or source can be exempted if the health hazard to people caused by the practice or source is sufficiently low and that the practice or source in question is inherently safe. IAEA reviewed the radiological basis for exemption (IAEA, 1988) and concluded that an individual effective dose of a few tens of microsieverts a year provided a basis for exemption. In order to take into account exposures of individuals from more than one exempted practice, IAEA also recommended that exposure from each exempted practice should be of the order of 10 μSv y^{-1}. IAEA also required the collective effective dose to be ALARA and suggested that it may be assumed to be so if it is below 1 man Sv y^{-1} of practice.

Exemption values were first included in the IAEA Basic Safety Standards (BSS) (IAEA, 1996) and were derived using a methodology described in the report from the European Commission RP-65 (European Commission, 1993), which used the dose criteria recommended by the IAEA. RP-65 adopted two additional dose criteria. The first was to protect against events with a low probability of occurrence but relatively high consequence. The approach taken for probabilistic events was to consider the 'probability weighted dose' and then to compare it with the 10 μSv y^{-1} dose criterion. A dose criterion of 1 mSv y^{-1} was used for accident scenarios with a nominal probability of not higher than 1 in 100 for such events to occur. This approach was taken because it was considered inappropriate to exempt a source from the reporting requirement in the BSS if it could give rise to doses above the dose limit for members of the public. In addition, in some circumstances it is possible for selective localised exposure of the skin to occur, from, say, handling a radioactive source. In order to exclude the possibility of any deterministic effects, a limit on the annual dose to skin of 50 mSv was adopted in RP-65 (European Commission, 1993).

The exemption values given in the IAEA BSS (IAEA, 1996) were calculated for exposure scenarios and pathways that did not explicitly address the transport of radioactive material. Calculations for transport specific scenarios (Carey et al, 1995) showed that the incorporation into the Transport Regulations of a set of exemption values different from that in the BSS was not justified, given that the use of different exemption values in various practices may give rise to problems at interfaces and may cause legal and procedural complications (IAEA, 2002).

Table 3 gives exemption values for the radionuclides included in this study. For the purpose of the assessment only limits on activity for consignments were considered. For lamps containing thorium two activity limits given in the IAEA Transport Regulations are relevant: one applies when only some of the radionuclides in the decay chain of ^{232}Th are present, while the second one applies to thorium when all the progeny in the decay chain of ^{232}Th are in secular equilibrium. The first limit is a combination of the activity limits of ^{232}Th and ^{228}Th which takes account of the fraction of the two radionuclides in the mixture according to the formula:

$$\frac{1}{A_L} = \sum_i \frac{f(i)}{A_L(i)} \qquad 1$$

where $A_L(i)$ is the activity limit for radionuclide i and $f(i)$ is the fraction of that radionuclide in the mixture. In this case the appropriate activity limit for an exempt consignment is 1 10^4 Bq. When all the progeny in the decay chain of ^{232}Th are in secular equilibrium with the parent radionuclide the value of 1 10^3 Bq applies.

Table 3. Exemption values for radionuclides contained in lamps applicable to transport (IAEA, 2009)

Radionuclide	Activity concentration for exempt material (Bq g^{-1})	Activity limit for an exempt consignment (Bq)
^{3}H	1 10^6	1 10^9
^{85}Kr	1 10^5	1 10^4
^{232}Th	1 10^0	1 10^4
^{228}Th	1 10^1	1 10^4
Th (nat)	1 10^0	1 10^3

1.2.1 Dose criteria applicable to the disposal of lamps to landfill

The system of radiological protection elaborated by the International Commission on Radiological Protection defines three groups of exposed individuals: workers, members of the public and patients (ICRP, 2007). In this system a worker is considered to be someone whose employer “has recognised rights and duties in relation to occupational radiological protection”. In the case of a worker at a landfill site it may be argued that the operator of the facility does not have these rights and duties, and therefore the dose limit for a member of the public (ie, 1 mSv y^{-1} (ICRP, 2007)) applies to both workers and members of the public during the operational phase of the landfill site. The dose limit of 1 mSv y^{-1} does not generally apply for exposures incurred during accidents, such as a fire. However for assessments of doses from disposal to landfill, such a dose criterion is generally recommended for long-term exposures of members of the public from the contamination of the landfill site caused by an accident, while a dose criterion of 1 mSv is used as a reference for acute exposures of both landfill workers and members of the public due to a single event.

In the post-closure phase of a landfill facility a number of different dose criteria apply. As with the operational phase, the most appropriate criterion for inhalation of gases released from a landfill facility during the normal evolution of the site is the limit for members of the public, 1 mSv y^{-1}. This is also the appropriate criterion to apply if a 'bathtubbing' occurs, where the drainage system of the landfill facility fails and the leachate containing radioactive waste overflows the sides of the landfill.

The criterion for migration with groundwater is a risk-based one. HPA has recommended a risk constraint of 1 in 100 000 per year (HPA, 2009) for migration of radionuclides with groundwater from a disposal facility, which corresponds approximately to 150 µSv y^{-1} using ICRP’s recommended detriment-adjusted risk coefficient of 0.06 per Sv (ICRP, 2007). HPA has also recommended an annual dose criterion of 3 mSv for designation of land as radioactively contaminated (HPA, 2006) and this is therefore an appropriate criterion for post-closure, inadvertent intrusion into a landfill facility. The dose criteria discussed above are summarised in Table 4.

Table 4 Dose criteria for disposal used in this study

Phase	Scenario	Dose criterion
Operational phase	Normal operation (landfill worker)	1 mSv y^{-1}
	Fire, acute (landfill worker, members of the public)	1 mSv
	Fire, long term (members of the public)	1 mSv y^{-1}
Post-closure phase	Normal evolution (member of the public, inhalation of landfill gases)	1 mSv y^{-1}
	Migration (member of the public)	150 µSv y^{-1}
	Intrusion (member of the public)	3 mSv y^{-1}
	Bathtubbing (member of the public)	1 mSv y^{-1}

2 METHODOLOGY FOR THE ASSESSMENT OF DOSES DURING TRANSPORT OF LAMPS CONTAINING LOW LEVELS OF RADIOACTIVITY

The assessment of doses from the exposure to the radiation emitted by ^{3}H, ^{85}Kr and isotopes of thorium in lamps during transport was carried out using a number of representative exposure scenarios. The exposure situations considered include scenarios which simulate practices adopted by the lamp industry to transport the lamps under routine conditions (including shipment and storage at warehouses), as well as ad hoc scenarios which simulate exposure as a result of accidents occurring during transport. It should be noted that the likelihood of such accidents to occur is very low, but no attempt was made to estimate this probability. Doses were calculated for adult individuals representative of people receiving the highest dose, including transport and logistic employees and members of the public and compared with doses criterion of 10 µSv y^{-1} for scenarios under routine conditions and 1 mSv y^{-1} for scenarios under accident conditions.

A review of work on this topic carried out in the past was conducted in order to develop methodologies that were used in the assessment. Key information required for the assessments were identified and data provided by the customer to tailor the assessment to the needs of the customer. Information required include data on activity transported per consignment or disposed of, geometry of the consignment, information on the vehicles used, hours spent by drivers transporting these consignments or by other workers loading and unloading packages and other information.

Five scenarios were considered for routine situations from the manufacturing stage to the disposal of lamps and three scenarios were considered for accidental situations. The scenarios for transport under routine conditions considered in this assessment were:

- Transport from manufacturing plant to distribution centre by road (Scenario T1);
- Transport from distribution centre to retail centre by plane (Scenario T2);
- Transport from distribution centre to retail centre by sea (Scenario T3);
- Transport of disused lamps to a landfill site (Scenario T4);
- Transport of disused lamps to a recycling centre (Scenario T5);

It should be noted that scenarios T1, T2 and T3 deal with new lighting products containing low levels of radioactive materials in their packages shipped to the end-users, while scenarios T4 and T5 deal with disused lighting products without their packing collected from the end-users or other places and transported to a recycling plant or a landfill facility .

The accident scenarios considered in the assessment were:

- Road accident (Scenario A1);
- Package damaged in a cargo handling bay (Scenario A2);
- Fire in a warehouse loading bay (Scenario A3).

These scenarios include exposure pathways which are considered in the IAEA Q system developed to determine A_1 and A_2 values, which define the activities of a radionuclide that is allowed in Type A packages (IAEA, 2002).

Detailed information on the equations used and the assumptions made for each scenario are given in the remainder of this section. The exposure times for each transport operation were taken from previous work (USNRC, 2001), and information provided by ELC (ELC, 2010). Since the actual number of consignments is unknown annual exposure times used in scenarios for transport under routine conditions were determined assuming each transport operation occurs once a week for 50 weeks during the year. For accident scenarios it was assumed that only one event occurs in a year. Table 5 summarises exposure times used in the assessment for each scenario; activities used for each scenario are given in Table 6.

For lamps containing thorium, the activity of radionuclides in the decay chain of ^{232}Th has increased by the time the lamps are disposed of. The age of the lamps involved in an accident and the resulting extent of in-growth are generally unknown. For the purposes of this study it was therefore conservatively assumed that all the radionuclides in the decay of ^{232}Th are in secular equilibrium with the parent in the scenarios under routine conditions transport to a landfill site (Scenario T4) and to a recycling centre (Scenario T5), and in all the accident scenarios. For the other scenarios it was assumed that the activity of ^{228}Th was half of that of ^{232}Th and that all other radionuclides in the decay chain are in secular equilibrium with ^{228}Th (ELC, 2010). Branching ratios used in the calculations are given in Table A1 of Appendix A.

2.1 Scenarios for transport under routine conditions

2.1.1 General assumptions

These scenarios consider exposure from the radioactive material in intact lamps during transport under routine conditions. Only doses from external exposure to radiation emitted by the lamps were calculated for these scenarios. Since ^{3}H emits only beta radiation doses for lamps containing this radionuclide were not calculated for these scenarios. Potential doses from inhalation due to natural leakage of tritium were considered negligible compared to the doses received in accident scenarios where the lamps break and therefore were not included in the assessment. Similarly it was considered that doses to the skin from exposure to beta radiation emitted by the lamps were not significant since beta radiation is attenuated by the glass enclosing the source.

The general equation used in the study for the calculation of doses from external exposure is:

$$D_{ext} = A_{load}\, T_{exp}\, DR_{load} \qquad 2$$

A_{load} is the activity of the total load (Bq); T_{exp} is the exposure time in a year (h y^{-1}) and DR_{load} is the effective dose rate per unit activity (Sv h^{-1} per Bq).

Unit effective dose rates were calculated using Microshield v 7.02 (Negin, 1986), with posterior/anterior geometry, for the specific geometry of the load adopted in each scenario. It was generally assumed that shielding was provided by the glass of the lamps, assumed to be 1 mm thick and with a density of 2.2 g cm^{-3}. For the lamps containing krypton and thorium it was assumed that the gas filling the lamp was argon since the concentration of the krypton gas is too low to be used in the calculations. The density of argon is assumed to be 1.4 10^{-3} g cm^{-3} (Tennent, 1971). For lamps containing thorium it was assumed that thorium oxide is an alloy fixed in the tungsten matrix in the electrode in mercury arc lamps, while thorium iodide is imbedded in the filling material of metal halide lamps; therefore this radionuclide is released into the atmosphere only as a result of fire.

2.1.1.1 *Bremsstrahlung contribution to doses from beta radiation emitted by ^{85}Kr*

Although beta radiation emitted by the lamps is attenuated by the glass of the lamp, bremsstrahlung radiation is generated when the beta radiation is slowed down as it passes through the glass. The contribution of bremsstrahlung radiation to the effective dose rate per unit activity was only determined for lamps containing ^{85}Kr (LKR85_1, LKR85_2 and LKR85_3, see Table 1), for which the effect of this radiation is thought to be of similar magnitude to the contribution from gamma radiation (Handbook of Radiological Protection 1971).

To determine the possible contribution of bremsstrahlung radiation, dose rates from gamma radiation emitted by a source containing ^{85}Kr were calculated using a Monte Carlo method. In this simulation a source of ^{85}Kr, with an activity of 2000 Bq, was assumed to be contained within a small ‘burner’ lamp made of quartz glass 1 mm thick. The lamp was 12 mm long and 7 mm in diameter. The gas filling the lamp was assumed to be argon, because of the small amount of ^{85}Kr, at standard atmospheric pressure. The fibreboard packaging was assumed to offer minimal shielding to the gamma and bremsstrahlung radiations.

The gamma dose rate at a distance of 0.5 mm was calculated to be 6.6 10^{-12} Gy s^{-1}, the dose rate from bremsstrahlung radiation was calculated to be 4.4 10^{-12} Gy s^{-1}, giving a ratio of bremsstrahlung dose rate to gamma dose rate of about 0.7. At 1 m away from the lamp the ratio between the bremsstrahlung and the gamma dose rate was reduced to about 0.6. For the purpose of this study it was assumed that the contribution from bremsstrahlung radiation to the dose rates for external exposure for lamps containing ^{85}Kr was 0.7 that from gamma radiation.

2.1.2 Transport from manufacturer to distribution centre by road (Scenario T1)

For this scenario doses were calculated to a driver of a lorry transporting lamps by road from the factory, where lamps are manufactured, to a distribution centre, and to a warehouse worker, who is exposed to radioactivity in the lamps whilst loading and unloading the lamps from a lorry and during general warehouse work. Exposures to members of the public were also considered when a lorry travels through a populated area.

2.1.2.1 Doses to driver of vehicles transporting lamps

In this scenario the lorry is assumed to be large, as this is likely to carry the largest quantity of lamps the longest distance and hence give the most cautious dose estimate. The lorry was assumed to be 16 m long divided into two sections each 7.8 m long, 2.48 m wide and 3 m high, giving a total storage volume of 116 m^3. It was assumed that 20 pallets of lamps were transported in the lorry, each about 1 m^3 in volume, (IAEA, 2010) and that this load is stacked separately in the front section of the lorry in an arrangement of five pallets long, two pallets high and two pallets wide. The distance from the front of the load to the lorry driver was assumed to be 1.5 m. The driver is assumed to be exposed for 400 h y^{-1}, see Table 5. Activities of the loads for each type of lamps are given in Table 6. The annual dose to the driver was calculated using Equation 2.

2.1.2.2 Doses to a warehouse worker

The NUREG study (USNRC, 2001) included exposures to a number of warehouse workers: primary loaders, other loaders, forklift truck drivers and store room clerks; the highest doses were received by storeroom clerks as they have the longest exposure time at the shortest distance. For this study, doses were calculated to a warehouse worker assumed to be exposed when loading or unloading lighting products to and from a lorry into a warehouse and also when he carries out other duties within the warehouse in the vicinity of where the lamps are stored.

It was assumed that it takes 75 minutes (ELC, 2010) for a warehouse worker to unload all the pallets in a large lorry using a fork lift truck at a distance of 1 m. It is assumed that over a year the individual unloads/offloads lamps for 50 weeks of the year resulting in an exposure time of about 60 hours. The annual dose to a warehouse worker from external exposure whilst loading or unloading was calculated using Equation 2. For this calculation A_{load} was taken to be the total activity in a pallet. Effective dose rates for unit activity, DR_{load} were calculated at 1 m from a pallet of lamps with a volume of 1 m^3.

Doses to warehouse workers from external exposure to radioactivity in the lamps whilst carrying out duties other than loading these lamps were calculated assuming that a warehouse worker is employed in the warehouse for 250 days per year and is exposed for 4 hours per day to a consignment of lamps (20 pallets) of size 5 m × 2 m × 2 m at a distance of 5 m. The annual dose to a warehouse worker was calculated using Equation 2. Exposure times and activities of the loads for each type of lamps are given in Table 5 and Table 6.

2.1.2.3 Exposure to a member of the public during road transport

It was assumed that members of the general population are exposed to radiation from the lamps while a lorry transporting the lamps pass through an urban area. The NUREG study suggested that a large percentage of the population of a town (125,000 people) could be exposed for 3 minutes a year at 18 m from a single consignment (USNRC, 2001). In this study doses were calculated assuming that a car driver is exposed while driving at a distance of 3 m from the vehicle transporting the lamps for two hours. Similar doses could be received by the driver of a vehicle close to the lorry either in a car park or on a passenger ferry. This is quite an uncommon event and is unlikely to occur to the same individual more than once a year. The annual dose to a member of the public was calculated using Equation 2. A_{load} is the activity in a lorry, see Table 6.

2.1.3 Transport from distribution centre to retail centre by plane (Scenario T2)

In this scenario individual doses from exposure to radioactive materials in lamps transported in a plane and during loading and unloading operations from a plane were calculated. This scenario may not be appropriate for all lamp types, because not all lamp types are transported by air. Most consignments of lamps are likely to be transported by a freight aircraft with only three crew members and no passengers. These planes have a large capacity and are able to transport a full consignment of 20 pallets. However to include exposure to passengers, the scenario chosen for this study assumes that the lamps are transported in the cargo hold of a passenger plane. In the calculation it was assumed that the size of the load is smaller than the load that could be carried by a freight aircraft and equivalent to a consignment of 10 pallets (5 m × 2 m × 1 m). A flight time of 12 hours was assumed.

2.1.3.1 Doses to air crew from external exposure during flight

Crew members and flight attendants were assumed to be exposed to the radioactivity in the load in the baggage hold for the duration of the flight. The NUREG study suggested that flight attendants were more likely to spend longer times closer to the baggage hold than the flight crew. For this assessment, therefore, doses were calculated to flight attendants who were assumed to be exposed at 1 m from the load for 2.5 hours (ie, 20% of the flight time), (USNRC 2001; Gelder et al, 2001). It was also assumed that flight attendants are on the same flights as the lamp consignments 50 times a year, which gives a total annual exposure time of 125 hours. The annual dose to the plane crew was calculated using Equation 2. Exposure times and activities of the loads for each type of lamp are given in Table 5 and Table 6.

2.1.3.2 Doses to passengers from external exposure during flight

This scenario assumed that a passenger was exposed to external irradiation from the load in the baggage hold for the duration of the flight (12 hours). The passenger was assumed to be seated at 1 m from the load. Unlike the air crew, passengers were assumed to be flying on the same plane as the load of lamps only once a year. Even if one person may board more than one flight carrying a consignment of lamps in a year, it is unlikely that this person occupies the same seat each time. Annual doses to the passengers were calculated using Equation 2. Unit effective dose rates were the same as those calculated for flight attendants. Exposure times and activities of the loads for each type of lamps are given in Table 5 and Table 6.

2.1.3.3 Doses to workers loading lighting products on and off planes

This exposure is assumed to occur when loading and unloading lamps to or from a plane into the air freight terminal. The NUREG study considered exposures to a number of categories of workers: primary loaders, other loaders, forklift truck drivers, sorters, freight clerks and plane loaders. The scenario adopted for this study is similar to that used above for the warehouse worker in Section 2.1.2.2. It was assumed that the workers at the air freight terminal spend 30 minutes loading and unloading a pallet to and from the hold of the aircraft. Assuming 50 working weeks per year the annual exposure time assumed was 25 hours. It is unlikely that these individuals would be exposed to large consignments over the year, as the lamps are likely to be mixed with other consignments of non-radioactive material. The annual dose to the workers loading lighting products on and off planes was calculated using Equation 2. A_{load} is the activity in a pallet, see Table 6; the unit effective dose rate, DR_{load} were calculated at 1 m from a pallet of lamps with a volume of 1 m^3.

2.1.4 Transport from distribution centre by sea (Scenario T3)

A large number of consignments of lamps are also transported by sea, as well as being transported by road and air. Consignments may be transported for short distances (ie, across the English Channel or the North Sea) by ferry and longer distances by container ship. A recent study carried out by the UK Health Protection Agency (Hughes and Harvey, 2009) has shown that the highest doses from exposure to transport of radioactive materials by sea are received by the crew who secure a vehicle carrying radioactive material on ferries or containers on ships. The containers on large cargo vessels are normally loaded by crane at some distance from the load. During the voyage the containers are located at some distance from the ships crew.

On the basis of the findings of the HPA study, for this scenario doses were calculated for a member of the crew securing a lorry containing a consignment of lamps to a ferry. It was assumed that this person stands 1 m from the lorry for about 5 minutes during this operation. It was also assumed that transport of lamps on a particularly ferry occurs once a week for 50 weeks in a year, giving an annual exposure time of 4 hours.

The annual dose to crew members was calculated using Equation 2. Effective dose rates for unit activity, DR_{load}, were calculated at 1 m from a consignment of lamps of 20 pallets of size 5 m × 2 m × 2 m.

2.2 Transport from retail centres to waste disposal

Disused lamps containing low levels of radionuclides are generally collected and either recycled or disposed of directly to a municipal landfill. About 90% of these lamps are recycled and the remaining 10% disposed of to landfill.

2.2.1 Transport to landfill site (Scenario T4)

This scenario accounts for the transfer of disused lamps from the consumer's premises to a municipal landfill. In 2007 in the United Kingdom there were about 1500 landfill sites (Surrey county council, 2010) to which 23 million tonnes of waste are disposed of per year, according to data for 2004 and 2005 (BBC News, 2007). The waste disposed of to landfill in the EU countries apart from the United Kingdom amounted to about 70 million tonnes of waste per year in 2004 and 2005. Assuming that the same amount of waste is disposed of at each landfill site in Europe is the same as the amount disposed of in the

United Kingdom, it can be estimated that the number of landfill sites Europe is about 6000 (BBC News, 2007). In the NUREG report (USNRC, 2001) it was assumed that all the activity to a landfill from lamps was disposed in a single waste collection.

The NUREG study (USNRC, 2001) showed that doses to the waste collectors are much higher than those to drivers and workers at the transfer stations. For this study, therefore doses were calculated only for waste collectors, who are exposed to external irradiation from handling the waste material. The waste collectors are assumed to collect lamps once a week (50 collections in a year). It is assumed that at this stage all the lamps are structurally intact (USNRC, 2001).

This scenario assumes that a waste collector handles or is close to a cylindrical container of radius 0.38 m × 0.9 m high (USNRC, 2001). Since the packing density of the lamps and waste was assumed to be high, water was chosen for the source to allow for self shielding within the container (USNRC, 2001). It was assumed that the waste collector is at a distance of 0.3 m for 4 hours for each collection. The annual dose to a waste collector was calculated using Equation 2. Unit effective dose rates, DR_{waste}, were calculated assuming a density for the waste of 1 g cm^{-3} to take account of self shielding provided by the lamps.

A_{load} in Equation 2 was calculated using the equation:

$$A_{load} = \frac{A_{lamp}\, N_{lamp}}{N_{LF}\, N_d} \qquad 3$$

A_{lamp} is the activity of 1 lamp (Bq), see Table 6; N_{lamp} is the number of lamps disposed to landfill in a year in Europe, see Table 2; N_{LF} is the number of landfill sites in which lamps are disposal of in Europe and N_d is the number of collections of disused lamp to be transported to a landfill in a year.

2.2.2 Transport to recycling plant (Scenario T5)

For this scenario it was assumed that lamps destined to be recycled are collected directly from large premises by the waste recycling facility using medium sized vans. Lamps are collected four days per week for 50 weeks of the year. The lamps are then moved to larger lorries, capable of carrying about 16 times the load of the smaller vans and delivered weekly to the recycling plant.

Only a small proportion of the lamps sent for recycling contain low levels of radioactivity. Information provided by ELC suggests only 5-7% of the lamps collected are high-intensity discharge lamps and that 35% of them contain low levels of radioactivity (ELC, 2010). For the purpose of this assessment, therefore, it was assumed that only 2% of the lamps collected and sent to be recycled contain radioactive material.

Doses were calculated to a waste collector driving a small van, from external exposure while driving the van and while loading and unloading the van using Equation 2. Doses to the driver of the large lorry were not considered since the doses are likely to be lower than the driver transporting the load of new lamps in scenario T1.

In the calculations it was assumed that the van carries about 10 bags containing crushed or non crushed lamps. The size of each bag lamps is approximately 0.06 m^3 (Balcan Engineering, 2010); for the purpose of the calculations it was assumed that it can be represented by a cylinder about 30 cm in diameter and 80 cm high. The bags were assumed to be stacked in the front section of the van separated from the other contents, in an arrangement of five bags along the width of the van by two bags. The dimension of the load in the van is, therefore, about 1.5 m × 0.6 m × 0.8 m high. The number of lamps in each bag is given in Table 2; total activities carried in a bag are given in Table 6. Since the lamps are packed closely in the bags it was assumed that the density is similar to water, ie, about 1 g cm^{-3} to allow for self shielding, as for scenario T4.

The driver of the van is assumed to spend 2 hours collecting bags at a distance of 0.3 m from the load. The same driver is assumed to unload the lamps from the van and load them into the lorry. It was assumed that it takes about 5 to 6 minutes to carry out this operation. It was assumed that during this operation the van driver is in close proximity to the bags at an average distance of 0.1 m. Annual exposure times are given in Table 5.

2.3 Scenarios for accidents during transport

Scenarios for accidents during transport assume that an accident occurs during the transport of lamps by road from the factory to the distribution or retail centre and that such an event only occurs for a single consignment from each type of lamp in a year. In previous studies different accident scenarios were assumed to occur from spillages, breaking of lamps and fires. A crash and burn scenario was used in a European study (Gelder et al, 2001) involving a vehicle carrying a load of lamps which crashed in an accident and subsequently caught fire. Doses were estimated to the public from the release of material from the fire and to workers involved in the clean-up operations at the site after the fire. The NUREG study (USNRC, 2001) considered different accident scenarios: a breakage of lamps at a warehouse or storeroom and a fire at a warehouse. In this study it was decided to include both breakage and fire scenarios. The exposure pathways considered were similar to previous studies: inhalation of radioactive material released during the accident, external exposure to radionuclides in the air; external exposure to the radioactive material on the ground and for lamps containing thorium only (LTH232_1, LTH232_2, LTH232_3, LTH232_4, see Table 1) doses to the skin from handling some of the lamps containing thorium during repackaging of the damaged packages following an accident.

Doses from inhalation were calculated using the equation:

$$D_{inh} = C_{air}\, T_{exp}\, R_{inh}\, DC_{inh} \qquad 4$$

C_{air} is the activity concentration in the air inhaled during the accident (Bq m^{-3}); T_{exp} is the exposure time (h); R_{Inh} is the inhalation rate for an adult worker (1.2 m^3 h^{-1}) and DC_{inh} is the dose coefficient for inhalation for adult members of the public (Sv Bq^{-1}) (ICRP, 1996). Doses from inhalation were not calculated for ^{85}Kr, since it is a noble gas and its dose coefficient for inhalation is 0. For ^{232}Th and ^{228}Th, two different sets of dose coefficients were used, see Table A3 of Appendix A)

Doses from external exposure from radionuclides in the air during the accident were calculated using the equation:

$$D_{ext,cloud} = C_{air}\, T_{exp}\, DR_{cloud} \quad 5$$

DR_{cloud} is the dose rate for gamma and beta radiation for external exposure to radionuclides in the air per unit activity concentration (Sv h^{-1} per Bq m^{-3} (Ekermann and Ryman, 1993), see Table A2 of Appendix A).

Doses from external exposure from material deposited on the ground following a fire assumed that external exposure occurs from gamma radiation emitted by debris scattered over the area of the fire. The equation used to calculate doses for this exposure pathway was:

$$D_{ext,dep} = A_{dep}\, T_{exp}\, DR_{dep} \quad 6$$

A_{dep} is the activity deposited on the ground after the fire (Bq); T_{exp} is the exposure time; DR_{dep} is the dose coefficient for gamma irradiation (Sv h^{-1} per Bq). These dose coefficients were calculated using Microshield for a plane source for posterior/anterior external geometry. The calculation assumed that the individual is exposed in the centre of a circle of radius of 1 m. The material deposited was assumed to be quartz glass with a thickness of 1 mm and density of 2.2 g cm^{-3}.

The equivalent dose to the skin, H_{skin}, was calculated using the equation:

$$H_{skin} = A_s\, T_{exp}\, (DR_{skin,\gamma(7)} + DR_{skin,\beta(40)}\, SF) \quad 7$$

A_s is the activity per unit area of the skin (Bq cm^{-2}); T_{exp} is the exposure time (h); $DR_{skin,\ \gamma(7)}$ is the skin equivalent dose rate to the basal layer of skin epidermis per unit contamination (Sv h^{-1} Bq^{-1} cm^2) for gamma irradiation (7 mg cm^{-2}) (Chaptinel et al, 1985) and $DR_{skin,\ \beta(40)}$ is the skin equivalent dose rate to the basal layer of skin epidermis per unit contamination (Sv h^{-1} Bq^{-1} cm^2) for beta irradiation (40 mg cm^{-2}) (Cross et al, 1992). *SF* is the shielding factor for beta radiation provided by wearing gloves (IAEA, 1987), calculated using the equation:

$$SF = e^{-\mu d}, \quad \mu = 0.017\,(E_{\beta max})^{-1.14} \quad 8$$

$E_{\beta max}$ is the maximum beta energy for radionuclides in the decay chain of ^{232}Th (2.25 MeV for ^{212}Bi); *d* is the mass per unit area of clothing, given by the product of the thickness of the gloves (0.2 cm) and the density of gloves (760 mg cm^{-3}) (Tennent, 1971). Therefore the value of *SF* used in the calculation was 0.36.

The effective dose to the skin, D_{skin}, was calculated using the equation:

$$D_{skin} = H_{skin}\, w_{skin}\, \frac{S_{contact}}{S_{body}} \qquad 9$$

w_{skin} is the tissue weighting factor for skin (0.01) (ICRP, 1990); S_{body} is the surface area of the body exposed to UV radiation (3 10^3 cm^2) (ICRP, 1991) and $S_{contact}$ is the area in contact with the package, calculated using the equation:

$$S_{contact} = \frac{M_{lamp}}{\rho_{lamp}\, d_{1/2}} \qquad 10$$

M_{lamp} is the mass of a lamp (6 g, assuming a metal halide lamp 5 cm long and 12 cm in diameter (ELC, 2010)); ρ_{lamp} is the average density of the broken lamps, including glass and metal, assumed to be the same as that of iron (5 g cm^{-3}) (Tennent, 1971) and $d_{1/2}$ is the half thickness of the source to take account for the activity distributed over two halves of the source (0.5 cm).

2.3.1 Doses for ^3H

A different approach than that described in the previous section was adopted to calculate doses from ^3H following an accident, as Equation 5 cannot be used. For ^3H doses were calculated for inhalation and absorption through the skin of radionuclides in the air. It was assumed that the dose from absorption through the skin of radionuclides in the air, D_{abs}, is half that from inhalation, D_{inh}, and proportional to the sedentary inhalation rate, $R_{inh,\, sed}$, of the individual exposed (Osborne, 1966; ICRP, 1993). The total dose can, therefore, be written as:

$$D_{tot} = D_{inh} + D_{abs} = F\, D_{inh} \qquad 11$$

Rearranging Equation 11, given that D_{inh} is proportional to the normal inhalation rate, R_{inh}, F can be calculated as:

$$F = 1 + \frac{D_{abs}}{D_{inh}} = 1 + 0.5\, \frac{R_{inh,sed}}{R_{inh}} \qquad 12$$

The sedentary inhalation rate assumed in the calculation was 0.54 m^3 h^{-1} (Smith and Jones, 2003). Inhalation rates used in the calculations for different pathways are given in the relevant sections.

2.3.2 Road accident (Scenario A1)

This scenario assumes that a consignment of lamps is completely broken in an accident and subsequent fire. Doses were estimated for the driver of the lorry, workers involved in the clean-up operations and nearby members of the public. Doses to fire fighters were not calculated for this scenario since the fire is outside and the dispersion of the smoke is likely to be greater than if the fire was in a building. As a result doses received by fire-fighters in this scenario are likely to be much lower than those received by fire-fighters in scenario A3.

2.3.2.1 Doses to the lorry driver

The total dose to the lorry driver involved in a roadside accident is the sum of the dose from inhalation and external exposure to radionuclides in the air. It was assumed that the driver only inhaled gases released from the broken lamps when fleeing the vehicle and not from the fire. Doses were therefore calculated only for lamps containing ^{3}H and ^{85}Kr, since thorium in the lamps is in solid form and would only be released in the fire.

Doses from inhalation of ^{3}H were calculated using Equation 4, assuming an exposure time of 0.25 hours and a inhalation rate for an adult worker (1.2 m^3 h^{-1}). It was assumed that 100% of the lamps were broken in the accident.

The activity concentration in air, C_{air}, was calculated assuming that the accident involves a van rather than a lorry as in a lorry the driver's cabin is separated from the load transported. The equation used to calculate C_{air} was:

$$C_{air} = \frac{A_{load}\, RF}{V\, k_{af}\, T_{exp}} (1 - e^{-k_{af}\, T_{exp}}) \qquad 13$$

A_{load} is the activity released in the accident, see Table 6; RF is the release fraction from fire (Asselineau et al, 1995), see Table A1 of Appendix A; V is the volume of the van, assumed to be 3 m × 1.8 m × 1.3 m = 7 m^3, k_{af} is the rate of air changes in a lorry (5 h^{-1} (USNRC, 2001)) and T_{exp} is the exposure time, assumed to the same as that used to calculate doses from inhalation, see Table 5.

The dose from external exposure to radionuclides in the air was calculated using Equation 5 for ^{85}Kr. The dose for ^{3}H was calculated using Equation 11 and 12.

2.3.2.2 Doses to clean-up workers

In this scenario it was assumed that, after the fire was extinguished, debris and wreckage from the road were removed from the site of the accident. Dose were calculated for workers involved in the clean-up of the site These workers were assumed not to be wearing breathing apparatus and to be exposed to the radioactivity in the material for 4 hours (Gelder et al, 2001). It was assumed that gas from lamps had already been released before clean-up started; doses were therefore only calculated for lamps containing thorium isotopes. It was also assumed that the broken lamps were collected mechanically and sent to a recycling facility or landfill site; clean-up workers therefore were assumed to have no contact with the waste material. They received doses from external irradiation from material deposited on the ground and from inhalation and external exposure to the resuspended material.

Doses from external exposure from material deposited on the ground after the fire were calculated using Equation 6, assuming that external exposure occurs from debris containing radioactivity scattered over a circular area of 5 m in radius. The activity deposited on the ground after fire A_{dep} is given by the equation:

$$A_{dep} = A_{load}\,(1 - RF) \qquad 14$$

A_{load} is the activity transported by the lorry (Bq), see Table 6, and RF is the release fraction from fire for radionuclides in the decay chain of ^{232}Th (Asselineau et al, 1995), see Table A1 of Appendix A;

Doses from inhalation of resuspended material were calculated using Equation 4. The activity concentration in the air resuspended from the fire, C_{air} was calculated using the equation:

$$C_{air} = \frac{A_{dep}}{S}\, f_{res}\, R_{res} \qquad 15$$

S is the surface area of the contamination (78.5 m^2), f_{res} is the fraction of material which is available for resuspension (0.01 (UNRSC, 2001)) and R_{res} is the resuspension rate (10^{-5} m^{-1} (Gelder et al, 2001)). Doses from external exposure to resuspended radionuclides were calculated using Equation 5, using the activity concentration calculated for doses from inhalation (Equation 15).

2.3.2.3 Doses to members of the public from road accident and fire

In this scenario it was assumed that members of the public stood at 100 m from the site of the accident while the fire was extinguished. These people were assumed to be exposed to both the gases (^{3}H and ^{85}Kr) released at the time of the accident and to the thorium released during the fire. An exposure time of 30 minutes was assumed for both situations, see Table 5.

Members of the public receive doses from inhalation and external exposure to radionuclides in the air. Doses from inhalation of ^{3}H and ^{232}Th were calculated using Equation 4, assuming a inhalation rate of 0.92 m^3 h^{-1}. C_{air} was calculated using the equation:

$$C_{air} = \frac{A_{lorry}\, RF}{T_{exp}}\, TIAC \qquad 16$$

A_{lorry} is the activity of lamp type transported by lorry (Bq); RF is the release fraction from fire, see Table A1 of Appendix A; $TIAC$ is the time integrated air concentration for 30 minute release at ground level at a distance of 100 m for category F (6 10^{-3} Bq s m^{-3} (Clarke, 1979).

Doses from external exposure to radionuclides in the air were calculated using Equation 5 for ^{85}Kr and ^{232}Th. Doses for ^{3}H were calculated using Equation 11 and 12.

2.3.3 Package damaged in a cargo handling bay (Scenario A2)

In this scenario a fork lift truck drives over a package containing lamps and crushes all the lamps in the package. It is assumed that all the activity in gas form is released. Since there is no release of gas from the thorium lamps doses for thorium isotopes were not calculated. The package was assumed to be a box of medium size (15 cm × 30 cm × 15 cm) containing about 60 ^{85}Kr lamps or a larger box (50 cm × 20 cm × 10 cm) containing a single lamp of tritium. The loading bay was assumed to be 20 m long, 5 m wide and 3 m high.

The fork lift truck driver receives doses from inhalation of gases and external exposure to radionuclides in the air. It was assumed that the driver is exposed to the gases released from the broken lamps for a period of 1 hour. Doses to a fork lift truck driver from inhalation were calculated using Equation 4, assuming an inhalation rate for an adult worker (1.2 m^3 h^{-1}). The activity concentration in the air inhaled by the driver, C_{air}, was calculated using Equation 13. A_{load} is the activity of ^3H and ^{85}Kr in a single package (Bq); V is the volume of the loading bay (300 m^3); k_{af} is the rate of air changes in a loading bay (4 h^{-1} (USNRC, 2001)). Doses from external exposure radionuclides in the air were calculated using Equation 5.

For this scenario doses were also calculated to a warehouse worker who is given the task to repackage the damaged packages. The person carrying out this task was assumed to be exposed to beta and gamma radiation emitted from the broken lamps containing thorium, since the ^3H and ^{85}Kr would have dispersed. It was assumed that the individual may handle or be close to the broken lamps during repackaging for a period of half an hour and receive a dose to the skin.

Doses to the skin from repackaging were calculated using Equation 7, 8, 9 and 10. A_s was calculated using the equation:

$$A_s = \frac{A_{lamp}}{A_{contact}} \qquad 17$$

A_{lamp} is the activity in a lamp containing thorium and $A_{contact}$ is given by Equation 10.

2.3.4 Fire in a warehouse loading bay (Scenario A3)

In this scenario it was assumed that a consignment of lamps is completely destroyed by fire in a warehouse loading bay. Doses were calculated for fire-fighters who put out the fire and general workers involved in clearing debris from the area once the fire has been extinguished. The NUREG study (USNRC, 2001) showed that doses to other workers or members of the public who are in the vicinity of the fire would be much lower than those to the fire-fighters. It was assumed that the fire-fighters are wearing breathing apparatus when dealing with the fire, but that the apparatus is not effective in protecting against inhalation of tritium.

2.3.4.1 Dose to fire-fighters

Fire-fighters were assumed to receive doses from inhalation and from external exposure to radionuclides in the air. Doses from external exposure to radionuclides in the air were calculated using Equation 5. Doses from inhalation were calculated using Equation 4. The exposure time for a fire-fighter was assumed to be 30 minutes. For doses from inhalation of thorium it was assumed that the breathing apparatus provides a protection factor of 0.001 (USNRC, 2001). The activity concentration in the air inhaled by the fire-fighter, C_{air}, was calculated using Equation 13. in this case V is the volume of the loading bay, assumed to be 300 m^3 and k_{af} is the air changes in the loading bay (4 h^{-1} (USNRC, 2001).

2.3.4.2 Doses to clean-up workers

This scenario assumed that workers removed the debris, after the fire was extinguished. Unlike the fire fighters, these workers were assumed not to be wearing breathing apparatus and receive doses from inhalation and external exposure to resuspended material and external exposure to radioactivity in the material deposited on the ground. They were assumed to be exposed from the material for 8 hours while clean up occurs.

Doses from external exposure to material deposited on the ground were calculated using Equation 6, assuming that debris was scattered over an area of 5 m in radius. The activity deposited on the ground after fire A_{dep} is given by Equation 14. Doses from external exposure to the radionuclides in the air were calculated using Equation 5.

Doses from inhalation of resuspended material were calculated using Equation 4. The activity concentration in the air resuspended from the fire, C_{air}, was calculated using Equation 16.

Table 5. Exposure pathways and exposure times assumed in the study for each scenario

Exposure scenario	Exposed individual	Exposure pathways	No. of events	Exposure time (h) Per event	Exposure time (h) Per year
Routine scenarios					
Transport from factory to distribution centre by road (Scenario T1)	Lorry driver	External irradiation	50	8	400
	Warehouse worker	External irradiation whilst loading	50	1.25	62.5
		External irradiation during other duties	250	4	1000
	Member of public	External irradiation	1	2	2
Transport from distribution to retail centre by plane (Scenario T2)	Flight crew	External irradiation	50	2.5	125
	Passengers	External irradiation	1	12	12
	Loading operators	External irradiation	50	0.5	25
Transport from distribution to retail centre by sea (Scenario T3)	Ferry crew members	External irradiation	50	0.08	4
Transport of disused lamps to landfill site (Scenario T4)	Waste collector	External irradiation	50	4	200
Transport of disused lamps to recycling plant (Scenario T5)	Waste collector	External irradiation whilst driving	200	2	400
		External irradiation whilst unloading	200	0.1	20
Accident scenarios					
Road accident (Scenario A1)	Lorry driver	Inhalation, external (cloud)	1	0.25	0.25
	Clean-up worker	External (dep.), inhalation, external	1	4	4

Table 5. Exposure pathways and exposure times assumed in the study for each scenario

Exposure scenario	Exposed individual	Exposure pathways	No. of events	Exposure time (h) Per event	Exposure time (h) Per year
		(air)			
	Member of public	Inhalation, external (air)	1	0.5	0.5
Package breakage at distribution centre/warehouse (Scenario A2)	Fork lift truck driver	Inhalation, external (air)	1	1	1
	Warehouse worker	Skin dose from repackaging	1	0.5	0.5
Fire at distribution centre/warehouse (Scenario A3)	Fire fighter	Inhalation, external (air)	1	0.5	0.5
	Clean-up worker	External (dep.), inhalation, external (air)	1	8	8

Table 6. Sizes and activities of various loads assumed in the assessment of doses from transport of lamps containing low levels of radioactivity

Exposure scenario	Exposed individual	Size of load	Activity of load (Bq)							
			LH3	LKR85_1	LKR85_2	LKR85_3	LTH232_1	LTH232_2	LTH232_3	LTH232_4
Routine scenarios										
Transport from factory to distribution centre by road (Scenario T1)	Lorry driver	20 pallets		$3.6\ 10^{8}$	$1.8\ 10^{8}$	$1.26\ 10^{5}$	$2\ 10^{6}$	$2\ 10^{6}$	$5\ 10^{5}$	$2\ 10^{4}$
	Warehouse worker (loading)	1 pallet		$1.8\ 10^{7}$	$9\ 10^{6}$	$6.3\ 10^{3}$	$1\ 10^{5}$	$1\ 10^{5}$	$2.5\ 10^{4}$	$1\ 10^{3}$
	Warehouse worker (other duties)	20 pallets		$3.6\ 10^{8}$	$1.8\ 10^{8}$	$1.26\ 10^{5}$	$2\ 10^{6}$	$2\ 10^{6}$	$5\ 10^{5}$	$2\ 10^{4}$
	Member of the public	20 pallets		$3.6\ 10^{8}$	$1.8\ 10^{8}$	$1.26\ 10^{5}$	$2\ 10^{6}$	$2\ 10^{6}$	$5\ 10^{5}$	$2\ 10^{4}$
Transport from distribution to retail centre by plane (Scenario T2)	Flight crew	10 pallets		$1.8\ 10^{8}$	$9\ 10^{7}$	$6.3\ 10^{4}$	$1\ 10^{6}$	$1\ 10^{6}$	$2.5\ 10^{5}$	$1\ 10^{4}$
	Passenger	10 pallets		$1.8\ 10^{8}$	$9\ 10^{7}$	$6.3\ 10^{4}$	$1\ 10^{6}$	$1\ 10^{6}$	$2.5\ 10^{5}$	$1\ 10^{4}$
	Loading operator	1 pallet		$1.8\ 10^{7}$	$9\ 10^{6}$	$6.3\ 10^{3}$	$1\ 10^{5}$	$1\ 10^{5}$	$2.5\ 10^{4}$	$1\ 10^{3}$
Transport from distribution to retail centre by sea (Scenario T3)	Ferry crew member	20 pallets		$3.6\ 10^{8}$	$1.8\ 10^{8}$	$1.26\ 10^{5}$	$2\ 10^{6}$	$2\ 10^{6}$	$5\ 10^{5}$	$2\ 10^{4}$
Transport of disused lamps to landfill site (Scenario T4)	Waste collector	See Table 2		$3.33\ 10^{2}$	$3.33\ 10^{2}$	$2.83\ 10^{2}$	$3.33\ 10^{2}$	$3.33\ 10^{1}$	$3.33\ 10^{1}$	$1.33\ 10^{0}$
Transport of disused lamps to recycling plant (Scenario T5)	Waste collector (driving)	10 bags*		$3.6\ 10^{5}$	$1.8\ 10^{5}$	$1.8\ 10^{4}$	$2.0\ 10^{3}$	$2.0\ 10^{3}$	$5.0\ 10^{2}$	$2.0\ 10^{1}$
	Waste collector (loading)	1 bag*		$3.6\ 10^{4}$	$1.8\ 10^{4}$	$1.8\ 10^{3}$	$2.0\ 10^{2}$	$2.0\ 10^{2}$	$5.0\ 10^{1}$	$2.0\ 10^{0}$
Accident scenarios										
Road accident (Scenario A1)	Lorry driver	1 pallet	$1\ 10^{5}$	$1.8\ 10^{7}$	$9\ 10^{6}$	$6.3\ 10^{3}$				
	Clean-up operator	1 pallet					$1\ 10^{5}$	$1\ 10^{5}$	$2.5\ 10^{4}$	$1.0\ 10^{3}$
	Member of public	1 pallet	$1\ 10^{5}$	$1.8\ 10^{7}$	$9\ 10^{6}$	$6.3\ 10^{3}$	$1\ 10^{5}$	$1\ 10^{5}$	$2.5\ 10^{4}$	$1.0\ 10^{3}$
Package breakage at distribution centre/warehouse (Scenario A2)	Fork lift truck driver	1 package	$1\ 10^{3}$	$1.2\ 10^{5}$	$6\ 10^{4}$	$6\ 10^{3}$				
	Warehouse worker (repackaging)	1 lamp					$1\ 10^{3}$	$1\ 10^{2}$	$2.5\ 10^{1}$	$1\ 10^{0}$
Fire at distribution centre/warehouse (Scenario A3)	Doses to fire fighter	20 pallets	$2\ 10^{6}$	$3.6\ 10^{8}$	$1.8\ 10^{8}$	$1.26\ 10^{5}$	$2\ 10^{6}$	$2\ 10^{6}$	$5\ 10^{5}$	$2\ 10^{4}$
	Clean up operator	20 pallets					$2\ 10^{6}$	$2\ 10^{6}$	$5\ 10^{5}$	$2\ 10^{4}$

Notes:

*: Number of lamps in a bag is given in Table 2; only 2% of the content of the bag is assumed to be radioactive

3 METHODOLOGY FOR THE ASSESSMENT OF DOSES FROM DISPOSAL TO LANDFILL OF LAMPS CONTAINING LOW LEVELS OF RADIOACTIVITY

Doses were calculated using a number of scenarios which simulate typical exposure situations likely to occur at a landfill site. Two separate phases were considered: an operational phase and a post-closure phase. For the operational phase the scenarios considered were exposure of landfill workers during normal operations and exposure of landfill workers and members of the public during a fire. For members of the public doses in the long-term from exposure to radioactivity released during the fire and deposited on the ground were also calculated. Earlier work (Anderson and Mobbs, 2010; Chen et al, 2007; Crawford and Wilmot, 2005) suggests that these scenarios result in relatively significant doses during the operational phase. For the post closure phase the scenarios considered were exposure of residents, that is people living on the landfill site after it has closed, to landfill gases during normal evolution of the facility, migration, intrusion (ie, residence on the site after excavation) and bathtubbing, that is failure of the drainage system of the landfill facility followed by the overflowing of the leachate containing radioactive waste. For normal evolution in the post-closure phase, exposures of nearby residents through inhalation of landfill gases and exposures of members of the public in the distant future through migration with groundwater give significant doses (Anderson and Mobbs, 2010; Chen et al, 2007). In the latter case, only ^{232}Th and its progeny were considered since the relatively short half lives of ^{3}H and ^{85}Kr mean that these radionuclides decay almost entirely before appearing in the environment through migration with groundwater. Intrusions and bathtubbing were included because these are accident scenarios which give rise to relatively significant doses (Anderson and Mobbs, 2010; Chen et al, 2007; Crawford and Wilmot, 2005). Exposed groups and exposure pathways assumed for each scenario are summarised in Table 7.

In each scenario, doses were calculated for a nominal activity concentration in the waste of 1 Bq g^{-1} for each of the radionuclides included in this study; no differentiation was made between different types of lamps as was the case for the assessment of doses from transport, see Section 2. The waste was assumed to be a mixture of normal landfill waste and non-incandescent lamps including lamps containing low levels of radioactivity. The activity concentration of 1 Bq g^{-1} is below the limit for very low level waste (VLLW) of 4 Bq g^{-1} (Department of the Environment et al, 1995). For a landfill facility such as the one assumed in this study (see Table 8), this equates to an inventory of 2.2 TBq, which is below the disposal limit for NORMs of 3 TBq for ^{232}Th in secular equilibrium with its progeny (Anderson and Mobbs, 2010). The inventory is not indicative of the activity actually disposed of to landfill in the form of lamps containing low levels of radioactivity. This was a scoping assessment and the results of the dose calculations were scaled to determine the maximum activity that can be disposed of to landfill in compliance with the dose criteria discussed in Section 1.2.1.

It should be noted that the calculations were intended to be scoping only and the scenarios were not exhaustive and only applied to adults. The assumptions made in the calculations were cautious in nature in order to ensure that doses calculated were not underestimated. The assumptions for each scenario are discussed in detail in the relevant sections.

Table 7. Exposure pathways by exposed group

Phase	Scenario	Exposed group	Exposure pathways
Operational	Normal operation	Landfill worker	External exposure to contamination on skin Inhalation of resuspended dust/material Ingestion of dust/material External exposure from waste
	Fire	Landfill workers	Inhalation of particles from a fire External exposure from smoke plume
		Members of the public	Inhalation of particles from a fire External exposure from smoke plume External exposure from ground deposition Ingestion of vegetables grown on affected land
Post-closure	Normal evolution	Residents	Inhalation of landfill gases
	Migration	Members of the public	External exposure from land Inhalation of airborne dust from pasture/arable land Ingestion of water abstracted from river Ingestion of freshwater fish & terrestrial food
	Intrusion	Residents	External exposure from waste Inhalation of dust Ingestion of dust Ingestion of garden-grown vegetables
	Bathtubbing	Residents	External exposure from waste Inhalation of dust Ingestion of dust Ingestion of garden-grown vegetables

3.1 Parameters for the conceptual landfill facility

The calculation of doses associated with the disposal of lamps to a landfill site was carried out using a conceptual landfill facility, which is not based on any actual landfill site but is representative of typical municipal facilities in operation throughout Europe. Under EU legislation landfill facilities fall into three categories: inert, non-hazardous and hazardous (European Commission, 1999). The legislation sets minimum conditions in each category for the permeability of the base and sides of the facility, leachate collection, surface sealing and control of landfill gas. Previous studies have found that doses due to migration with groundwater of radionuclides disposed to landfill are greater for inert facilities than for non-hazardous or hazardous facilities (Chen et al, 2007). Doses from landfill gases or intrusion are also likely to be higher for inert facilities since surface sealing is not required for this type of facility. Conservatively, therefore, this study assumed that the theoretical landfill facility to which lamps are disposed of falls into the inert category. It was assumed that it covers an area of 8 10^4 m^2 and allows for 15 m depth of waste. The base and sides were assumed to have a permeability of 10^{-7} m s^{-1} and be at least 1 m thick in line with European legislation. It was also assumed that the liner is unsaturated and sits directly on a saturated aquifer. Surface sealing after closure is not required for inert landfills under EU legislation, but it is reasonable to expect that restoration will include re-landscaping by covering with a layer of clean soil at least 1 m thick. The landfill site was assumed to have an operational lifetime of 15 years, during which 2.2 10^6 t of waste are disposed of.

After closure it was assumed that the site remains under institutional control for 30 years, after which time inadvertent intrusion may occur. It was also assumed that rain water infiltrates the landfill over time and that the waste is readily soluble and therefore activity is leached out of the waste and migrates through the liner into the groundwater system. Table 8 gives a summary of the parameter values used for the conceptual landfill site used in this study.

Table 8. Parameters for conceptual inert landfill used in this study

Parameter	Unit	Value
Liner permeability	m s^{-1}	1 10^{-7}
Liner thickness	m	1
Depth of clean soil cover post-closure	m	1
Operational lifetime	y	15
Mass capacity	t	2.2 10^6
Area	m^2	8 10^4
Waste depth	m	15
Waste bulk density	g cm^{-3}	1.8
Institutional control period	y	30

3.2 Scenarios for operational phase

The highest doses received during the operational phase of a landfill facility arise at the very end of its life, when the landfill site is full. In the calculations it was therefore assumed that the full inventory had been disposed of and no allowance was made for radioactive decay during the operational phase.

3.2.1 Doses to landfill workers for normal operations

Landfill workers were considered to spend their entire working time distributing and moving waste around the site using a mechanical excavator. It was assumed that they spend 90% of their time in the closed cab of the excavator with air-conditioning and a dust filtration system and the remaining 10% outdoors standing on or next to contaminated waste (Anderson and Mobbs, 2010). The exposure pathways considered in the calculations were external irradiation from radioactive material on skin, inhalation of gases and particulates or dust, inadvertent ingestion of dust and external exposure to the radioactivity in the waste.

3.2.1.1 Doses to the skin

For this exposure pathway annual effective doses to the skin arising from beta radiation emitted by the radioactive material in contact with the skin of the hands of a landfill worker were calculated. Doses from gamma radiation were not considered since they give a small contribution to the overall skin dose on unshielded hands. It was conservatively assumed that the workers do not wear gloves (ie, there was no shielding from beta radiation) and that only the palms of their hands and one side of the fingers/thumb are contaminated. The radioactive material on the hands is assumed to have the same activity concentration as the waste and to be on the hands for the entire working day but to be removed at the end of the shift. The annual effective dose to the skin, D_{skin} was calculated using Equation 9; $S_{contact}$ is the area of the palms of the hands (400 cm^2, (ICRP, 1975)). The equivalent dose to the skin H_{skin} is given by:

$$H_{skin} = C_{waste}\, T_{exp}\, \tau_{skin}\, \rho_{skin}\, DR_{skin,\beta(40)} \qquad 18$$

where C_{waste} is the activity concentration in the waste (1 Bq g^{-1}), T_{exp} is the time spent with contamination on skin (2000 h y^{-1}), τ_{skin} is the thickness of the radioactive material on the skin (0.01 cm (Harvey et al, 1995)), ρ_{skin} is the density of the waste on the skin (0.5 g cm^{-3} (Harvey et al, 1995)) and $DR_{skin,\ \beta(40)}$ is the skin equivalent beta dose rate to the basal layer of epidermis (40 mg cm^{-2} for palms of the hands) for a plane isotropic source, uniformly distributed over 100 cm^2 (Sv h^{-1} Bq^{-1} cm^2 (Cross et al, 1992), see Table A2 of Appendix A).

In this scenario it was assumed that the waste containing thorium is in a form that can adhere to skin. This is a cautious assumption because, unless the lamps are crushed and ground prior to disposal, the lamp parts - mostly electrodes - that contain thorium are of the order of a few centimetres in size and do not adhere to the skin for a working day, although a worker might handle electrodes for part of a day.

3.2.1.2 Doses from inhalation

For this assessment, it was conservatively assumed that the resuspended dust has the same activity concentration as the waste from which it is raised. The committed effective dose from inhalation of resuspended material D_{inh} is given by the equation:

$$D_{inh} = C_{waste}\, R_{inh}\,(T_{exp,in}\, DL_{in} + T_{exp,out}\, DL_{out})\, DC_{inh} \qquad 19$$

where C_{waste} is the activity concentration in the waste (1 Bq g^{-1}), R_{inh} is the inhalation rate for heavy work (1.69 m^3 h^{-1} (Smith KR and Jones AL, 2003)), $T_{exp,\ in}$ and $T_{exp,\ out}$ are the times spent inside and outside the excavator cab respectively (1800 h y^{-1} and 200 h y^{-1}), DL_{in} is the dust loading inside the cab (1 10^{-5}, g m^{-3} (Dockery and Sprengler, 1988)) and DL_{out} is the dust loading outside the cab (1 10^{-3}, g m^{-3} (Gilbert et al, 1983)) and DC_{inh} is the inhalation dose coefficient for members of the public (Sv Bq^{-1}, see Table A3 of appendix A), (ICRP, 1996).

3.2.1.3 Doses from ingestion

A worker may inadvertently ingest contaminated material that has adhered to his hands while working at the landfill facility. As with the calculation of doses for skin contamination, it was assumed that the worker does not wear gloves and that the material containing radioactivity is removed at the end of a working day. The annual committed effective dose due to ingestion D_{ing} is given by the equation:

$$D_{ing} = C_{waste}\, T_{exp}\, R_{ing}\, DC_{ing} \qquad 20$$

where C_{waste} is the activity concentration in the waste (1 Bq g^{-1}), T_{exp} is the time spent at work (2000 h y^{-1}), R_{ing} is the inadvertent ingestion rate for adults (5 10^{-3} g h^{-1} (Smith KR and Jones AL, 2003) and DC_{ing} is the ingestion dose coefficient for members of the public (ICRP, 1996), see Table A3 of Appendix A).

3.2.1.4 External exposure to radioactivity in the waste

In this scenario landfill workers were assumed to be in close proximity to the waste for their entire day. The exposure is to both beta and gamma radiation whilst outside, but only gamma radiation in the excavator cab since it was assumed that the cab walls and floor effectively shield all the beta radiation. It was also assumed that the gamma dose rate inside the cab is half that outside (ie, a shielding factor of 2 was applied to the inside dose rate) (European Commission, 1993). The external dose due to the waste D_{ext} is therefore given by the equation:

$$D_{ext} = C_{waste}\left(T_{exp,in}\,\frac{R_{\gamma,slab}}{2} + T_{exp,out}\,R_{\gamma,slab} + T_{exp,out}\,R_{\beta,slab}\right) \qquad 21$$

where C_{waste} is the concentration of activity on the waste (1 Bq g^{-1}), $T_{exp,\ in}$ and $T_{exp,\ out}$ are the times spent inside and outside inside and outside the cab respectively (1800 and 200 h y^{-1}) and $R_{\gamma,\ slab}$ and $R_{\beta,\ slab}$ are the dose rates for gamma and beta radiation for external exposure to the waste per unit activity respectively (Sv h^{-1} per Bq g^{-1}). The bremsstrahlung contribution to doses from beta radiation emitted by ^{85}Kr was not taken into account for this scenario as the lamps were assumed to be broken up once they reach the landfill facility.

Dose rates for gamma radiation were calculated using Microshield version 7.02 (Negin, 1986), modelling the waste as an infinite slab of soil 5 m thick with a bulk density of 1.5 g cm^{-3}; photons with energy below 0.015 MeV were excluded. The gamma dose rate is taken as the effective dose equivalent rate for rotational geometry and includes contribution from build-up, where the build-up material reference is the air gap.

Dose rates for beta radiation were calculated using mean beta energies, J_{β} (MeV) (ICRP, 1983) and assuming that the exposure geometry is 1 m above a semi-infinite slab. The equation used to calculate beta dose rates was (European Commission, 1993):

$$
\begin{array}{ll}
J_\beta < 0.1\,MeV & R_{\gamma,slab} = 0 \\
0.1\,MeV \le J_\beta < 0.4\,MeV & Ln(R_{\gamma,slab}) = 6\,Ln(J_\beta) - 16.4 \\
J_\beta \ge 0.4\,MeV & Ln(R_{\gamma,slab}) = 2.86\,Ln(J_\beta) - 19.7
\end{array}
\tag{22}
$$

Values for J_β used in the assessment are given in Table A1 of Appendix A. Values for $R_{\gamma,\,slab}$ and $R_{\beta,\,slab}$ are given in Table A2 of Appendix A.

3.2.2 Doses from fire scenario

In this scenario it was assumed that material containing radioactivity was lifted into the air by a fire at the landfill site and was inhaled by both landfill workers and people residing in the vicinity of the facility. These people were also assumed to receive doses from external exposure to radionuclides in the air and deposited on the ground or from eating foods grown in soil contaminated by deposition from a fire. It is unlikely that a clean-up operation would be initiated after a fire at a landfill site and therefore doses from material resuspended by a clean-up operation were not considered.

For this assessment it was assumed that the fire occurred at the surface level for the duration of 1 hour (Crawford and Wilmot, 2005). The radionuclides were assumed to be well mixed with the other waste and no allowance was made for decay during the fire. It was conservatively assumed that there was no plume rise and the effective release height was 0 m. A simple Gaussian plume model was applied to the dispersion of material, assuming that the plume was neutrally buoyant and non-depleting and the AMAD of the particles was 1 μm. Doses were calculated for landfill workers, assumed to be standing on the plume centre line 100 m from the fire and residents, assumed to live 250 m from the fire.

The total dose to landfill workers from the fire is the sum of the dose from inhalation, D_{inh}, and external exposure from radionuclides in the air, D_{cloud}. The dose from inhalation was calculated using Equation 4. T_{exp} is the time spent in the plume of smoke (1 h), R_{inh} is the inhalation rate (1.69, $m^3\ h^{-1}$ (Smith KR and Jones AL, 2003)) and DC_{inh} is the dose coefficient for inhalation ($Sv\ Bq^{-1}$, see Table A3 of Appendix A). Doses from external exposure to radionuclides in the air were calculated using Equation 5. Activity concentrations in air, C_{air}, were calculated using the equation:

$$C_{air} = \frac{A_{landfill}\, f_{waste}\, RF}{T_{exp}} TIAC \tag{23}$$

where $TIAC$ is the time-integrated air concentration at 100 m from the fire for a 30 minute release in Pasquill category F atmospheric conditions for an effective release height of 0 m ($5.8\ 10^{-3}\ Bq\ h\ m^{-3}\ Bq^{-1}$ (Clarke, 1979)), f_{waste} is the fraction of waste in the landfill which is consumed in the fire (0.01), $A_{landfill}$ is the total activity in the landfill ($2\ 10^{12}$ Bq), RF is the release fraction for the radionuclide (dimensionless). A correction factor of 0.7, (Clarke, 1979) was applied to adjust the time-integrated air concentration from a 30 minute release to a 1 hour release.

The equations used to calculate acute doses from exposures to radionuclides in the fire to nearby residents are the same as those used for landfill workers, albeit with different parameter values. Doses from inhalation and external exposure to radionuclides in the air were calculated using Equation 4 and 5. assuming the same time spent in the plume of smoke as for landfill workers (1 h), and a inhalation rate, R_{inh}, of 0.92 $m^3\ h^{-1}$ (Smith KR and Jones AL, 2003)) and dose coefficients for inhalation for members of the public, see Table A3 of Appendix A. Activity concentrations in air, C_{air}, were calculated using Equation 23, using a time-integrated air concentration at 250 m from the fire for a 30 minute release in Pasquill category F atmospheric conditions, effective release height 0 m (1.2 10^{-3} Bq s m^{-3} Bq^{-1} (Clarke, 1979)), adjusted using a correction factor of 0.7 to account for the longer duration of release of 1 hour.

Residents were also assumed to be exposed to material deposited from the plume on a longer timescale, via both external exposure and ingestion of food grown on contaminated soil. The annual effective dose due to deposited contamination was calculated using the contaminated land methodology (Oatway and Mobbs, 2003). The concentration of contamination in the soil required by this methodology (C_{soil}, Bq g^{-1}) is given by:

$$C_{soil} = \frac{C_{ground}}{d_{soil}\ \rho_{soil}} \qquad 24$$

where C_{ground} is the activity deposited on the ground per unit area (Bq m^{-2}), d_{soil} is the depth of soil that is contaminated (0.25 m (IAEA, 2003)) and ρ_{soil} is the density of the soil (1.5 10^6 g m^{-3} (Kowe, Carey, et al. 2007)). The contamination on the ground is given by (Crawford and Wilmot, 2005)

$$C_{ground} = C_{air}\ T_{dep}\,(v_{dry} + \Lambda h) \qquad 25$$

where T_{dep} is the time over which deposition occurs, assumed to be the same as duration of fire (1 h), v_{dry} is the dry deposition velocity for 1 μm particle (0 for ^{85}Kr; 1 10^{-3} m s^{-1} for the other radionuclides (Simmonds et al, 1995)), Λ is the washout coefficient (0 for ^{85}Kr; 1 10^{-4} s^{-1} for other radionuclides (Simmonds et al, 1995)) and h is the height of the plume (0 m).

3.3 Post-closure phase

Once the landfill has been closed and knowledge of the existence of the landfill has been lost, there is an increasing probability that the site will be redeveloped. For this assessment, it was assumed that 30 years elapse between closure (including site restoration) and redevelopment of the site. Radioactive decay during the operational phase was not considered.

3.3.1 Inhalation of landfill gases by residents

In this assessment, since the waste is inert, no gases were assumed to be generated by the decay of the waste and the only gases that may escape the landfill are those in the lamps. Conservatively, this assessment assumed that all the ^3H is in the form of tritiated water, and that it is all available to evaporate out of the landfill as tritiated water vapour. Other gases that may escape are ^{85}Kr and ^{220}Rn from the ^{232}Th decay chain. The half-life of ^{220}Rn is sufficiently short that very little of it can escape from the landfill into a house before decaying and this radionuclide was therefore excluded from the calculations. No doses result from inhalation of ^{85}Kr, and this radionuclide was therefore also excluded from the calculation of doses for this scenario.

The committed effective dose D_{inh} (Sv y^{-1}) due to inhalation of ^{3}H released from lamps into a house built over a closed landfill is given by (Crawford and Wilmot, 2005):

$$D_{inh} = R_{inh}\, O_{in}\, Rel(t) \frac{a_h}{a_l\, k V_h} DC_{inh} \qquad 26$$

where DC_{inh} is the inhalation dose coefficient for members of the public (Sv Bq^{-1}, see Table A3 of appendix A), R_{inh} is the inhalation rate (0.92 m^3 h^{-1} (ICRP, 1994)), O_{in} is the fraction of the time spent indoor (0.9 (Smith KR and Jones AL, 2003)), *Rel(t)* is the release rate of ^{3}H from the landfill site (Bq y^{-1}), a_h is the typical area of a house (50 m^2 (Crawford and Wilmot, 2005)), a_l is the surface area of the landfill (8 10^4 m^2, see Table 8), k is the turnover rate of air in a house (8766 y^{-1} (UNSCEAR, 1977)) and V_h is the representative volume of a house (125 m^3).

The release rate of ^{3}H was calculated assuming that this radionuclide was in the form of tritiated water (HTO) and that it was all released from the lamps and mixed with water infiltrating the landfill site. The activity release rate of ^{3}H from the whole surface of the landfill is given by the equation:

$$Rel(t) = C_{water}\, E\, a_l\, \rho_{water}\, e^{-\lambda t} \qquad 27$$

where C_{water} is the initial activity concentration (Bq g^{-1}) in landfill water E is the evapotranspiration rate (ie, evaporation directly from restored landfill and transpiration from plants growing on the landfill) (45 m y^{-1} (Crawford and Wilmot, 2005), ρ_{water} is the density of water (1 10^6 g m^{-3}) and λ is the decay constant (y^{-1}, see Table A1 of Appendix A) In the calculations t was taken to be 30 years.

The only loss of activity considered was due to radioactive decay; no loss due to earlier evapotranspiration or migration of ^{3}H was taken into account. The landfill water was assumed to be a mixture of tritiated water from the lamps and clean water that infiltrated, hence:

$$C_{water} = \frac{A}{M_{HTO} + M_{clean}} \qquad 28$$

where A is the total tritium activity in the waste (2 10^{12} Bq), M_{HTO} is the mass of tritiated water in the waste (g) and M_{clean} is the mass of clean, infiltrated water (g). Since $M_{HTO} << M_{clean}$:

$$C_{water} \approx \frac{A}{M_{clean}} \qquad 29$$

The mass of clean water that has infiltrated the landfill is given by:

$$M_{clean} = \varepsilon \phi V_{landfill} \rho_{water} \qquad 30$$

where ε is the porosity of waste in the landfill (0.5 (Crawford and Wilmot, 2005)), ϕ is the saturation of the landfill (0.5 (Crawford and Wilmot, 2005)) and $V_{landfill}$ is the volume of the landfill (1.2 10^6 m^3).

3.3.2 Dose to members of the public from migration with groundwater

Rainwater is expected to infiltrate a closed landfill and leach activity out of the waste, eventually passing through the barrier and into groundwater. Because the liner has very low permeability, this process is very slow and therefore most of the ^{85}Kr and ^{3}H will have decayed a number of half-lives by the time it appears in the biosphere and were excluded from the calculation of doses for this scenario.

The dose from migration of ^{232}Th and its progeny was modelled using the HPA's Landfill Modelling System (Anderson and Mobbs, 2010). The key assumptions of this model are that the waste and liner are unsaturated and the liner sits directly above a saturated aquifer from which drinking water is abstracted 250 m downstream from the landfill site. The annual dose initially increases, rising to a peak over decades and then decreases. The model was allowed to run past the peak dose, and although peak doses for different radionuclides in the decay chain were not coincident in time, the peak doses were summed to obtain a cautious estimate.

3.3.3 Doses to residents from inadvertent intrusion

In redeveloping the restored landfill site, it was assumed that waste is disturbed and brought to the surface. Although uncapped, the landfill restoration process was assumed to have covered the waste with at least 1 m of clean soil mixed with the contaminated waste thus diluting the activity concentration of the radionuclides in the waste. Residents were assumed to move into the housing 30 years after the landfill is closed and to grow root vegetables and fruit in their garden for their own consumption. The contaminated waste was assumed to have been brought up from 2 m down into the landfill and mixed evenly with the clean soil, thus a dilution factor of 0.67 was applied to the activity concentration at the surface. The activity concentration at time *t* after closure is therefore given by:

$$C(t) = \eta C_{waste} e^{-\lambda t} \qquad 31$$

where η is the dilution factor due to mixing contaminated waste with clean soil (dimensionless), C_{waste} is the concentration of activity in the waste at closure (1 Bq g^{-1}) and λ is the decay constant (y^{-1}, see Table A1 of appendix A). The value of *t* was taken to be 30 years.

Doses were calculated using the HPA methodology for contaminated land (Oatway and Mobbs, 2003) assuming that the contamination is evenly distributed on the surface of the site and to a depth of 1 m, with an activity concentration calculated using Equation 31.

3.3.4 Doses to residents from bathtubbing

For inert landfills, with only a soil covering and no impermeable cap, rainwater infiltrates and gathers in the landfill after closure. The water mixes with the waste and contaminants leach into the rainwater, forming a leachate solution. Landfills generally have a drainage system that limits the accumulation of leachate to prevent overflow and contamination of the surrounding land. In this scenario, it was assumed that the drainage system has failed and the leachate that overflows the sides of the landfill contains activity from the discarded lamps. ^{85}Kr is not very soluble and diffuses out of the landfill before the bathtubbing event, and was therefore excluded from the calculation. The bathtubbing event is assumed to be one-off and short term rather than ongoing, and no allowance was made for leaching of the contamination away from the site after it occurs. The residents were assumed to live in houses built on the affected land and consume vegetables grown on the land. Doses were calculated using the contaminated land methodology (Oatway and Mobbs, 2003), where the concentration of radionuclides in the soil (Bq g^{-1}) is given by (Crawford and Wilmot, 2005):

$$C_{soil}(t) = \frac{C_{leachate}(t)V_{leachate}}{G\,d_{soil}\;\rho_{soil}} \qquad 32$$

where $C_{leachate}(t)$ is the activity concentration in the leachate (Bq cm^{-3}) at time t after closure (30 y), $V_{leachate}$ is the volume of contaminated leachate that has overflowed (10^{3} m^{3}), G is the growing area for crops (10^{5} m^{2}), d_{soil} is the depth of soil affected by the leachate (0.25 m (IAEA, 2003)) and ρ_{soil} is the density of soil (1.5 g cm^{-3} (Kowe, Carey, et al. 2007). The leachate activity concentration is calculated as (Chen et al, 2007)

$$C_{leachate}(t) = \frac{\lambda_L\,A}{Q_{inf}}e^{-(\lambda_L+\lambda)t} \qquad 33$$

where λ_L is the leach rate (y^{-1}), A is the activity disposed of to the landfill (2 10^{12} Bq), λ is the radioactive decay constant (y^{-1}, see Table A1 of Appendix A) and Q_{inf} is the volumetric infiltration rate of rainwater into the landfill (cm^{3} y^{-1}), given by:

$$Q_{inf} = I_{inf}\;a_L \qquad 34$$

where I_{inf} is the annual infiltration rate, assumed to be 15 cm y^{-1} and a_L is the area of the landfill (8 10^{4} m^{2} (Chen et al, 2007)).

The leach rate, λ_L, is a first-order removal constant (Baes and Sharp, 1983), similar to the radioactive decay constant, calculated using the equation:

$$\lambda_L = \frac{Q_{inf}}{V_{landfil} \, R \, \varepsilon \, \phi} \tag{35}$$

where $V_{landfill}$ is the volume of the landfill site (1.2 10^6 m^3 (Chen et al, 2007)), R is the retardation coefficient (dimensionless), ε is the porosity of waste in the landfill (0.5 (Crawford and Wilmot, 2005)) and ϕ is the saturation of the landfill (0.5 (Crawford and Wilmot, 2005)). The retardation coefficient is element dependent, and is calculated from the distribution coefficient K_d of the elements in the waste (cm^3 g^{-1}):

$$R = 1 + \rho_{waste} \frac{K_d}{\varepsilon \, \phi} \tag{36}$$

where ρ_{waste} is the bulk density of the waste (1.8 g cm^{-3} (Crawford and Wilmot, 2005)). For this assessment the distribution coefficient for all radionuclides in waste was conservatively set to 0 cm^3 g^{-1} and therefore the retardation coefficient was assumed to be 1 for all radionuclides.

4 RESULTS OF THE ASSESSMENT OF DOSES DURING TRANSPORT OF LAMPS CONTAINING LOW LEVELS OF RADIOACTIVITY

4.1 Doses from transport of lamps containing tritium

Doses for lamps containing small quantities of ^3H were only calculated for accidental scenarios and are reported in Table 9. Doses were not calculated for clean-up workers and for workers involved in the repackaging of damaged packages. Doses ranged between 3.6 10^{-9} mSv y^{-1} and 5.4 10^{-5} mSv y^{-1}, well below the dose criterion of 1 mSv adopted in the calculation of exemption values for accident scenarios for the IAEA Basic Safety Standards (IAEA, 1996). This is to be expected as the activities in a consignment assumed for this study are below the activity limit for an exempt consignment recommended by the IAEA, see Table 3.

Table 9 also provides activities in a consignment which would give rise to doses of 1 mSv y^{-1} for the scenarios considered in this study. These activities are between 1.9 10^9 Bq and 2.8 10^{13} Bq, at least about 2 times the activity limit for an exempt consignment recommended by the IAEA.

Table 9. Doses from transport of lamps containing ^{3}H (LH3) for accident scenarios

Scenario		Dose ($mSv\ y^{-1}$)	Activity corresponding to exemption dose criterion (Bq)*
Road accident (Scenario A1)			
Lorry driver		$5.4\ 10^{-5}$	$1.9\ 10^{9}$
Clean-up worker		-	-
Member of the public		$3.6\ 10^{-9}$	$2.8\ 10^{13}$
Package damaged at cargo handling bay (Scenario A2)			
Fork lift truck driver		$2.2\ 10^{-8}$	$4.6\ 10^{10}$
Repackaging	Skin dose	-	-
	Effective dose	-	-
Fire at a cargo handling bay (Scenario A3)			
Fire-fighter		$3.8\ 10^{-5}$	$5.2\ 10^{10}$
Clean-up worker		-	-

Notes:

*: The dose criterion for exemption is 1 $mSv\ y^{-1}$ for effective dose and 50 $mSv\ y^{-1}$ for dose to the skin

4.2 Doses from transport of lamps containing krypton-85

Doses for lamps containing low levels of ^{85}Kr were calculated for scenarios for both routine and accident transport scenarios and are given in Table 10 and Table 11. For routine transport scenarios the activity in the consignment assumed in the calculations are above the activity limit for an exempt consignment recommended by the IAEA with the exception of Scenario T4. The highest doses were estimated for LKR85_1 lamps, each assumed to have an activity of 2000 Bq; doses for this type of lamps range between $4.1\ 10^{-5}$ $\mu Sv\ y^{-1}$ (waste collector for scenario T4) and 7.2 $\mu Sv\ y^{-1}$. The highest dose was calculated for a lorry driver transporting a consignment of LKR85_1 lamps from the factory to a distribution centre (7.2 $\mu Sv\ y^{-1}$).

Table 10 also provides activities in a consignment which would give rise to doses equal to the criterion for exemption of 10 $\mu Sv\ y^{-1}$ for the routine transport scenarios considered in this study. For scenarios T1, T2 and T3, involving new, packaged lamps, these activities were between $5.0\ 10^{8}$ Bq and $1.6\ 10^{11}$ Bq, at least $5\ 10^{4}$ times the activity limit for an exempt consignment recommended by the IAEA (see Table 3). Lower activities were estimated for scenarios T4 and T5, which include disused, unpackaged lamps; activities in a consignment that give rise to doses of 10 $\mu Sv\ y^{-1}$ were estimated to be $8.2\ 10^{7}$ Bq for scenario T4 (transport to a landfill site) and $4.0\ 10^{7}$ Bq for scenario T5 (transport to a recycling facility) at least $4\ 10^{3}$ times the activity limit for an exempt consignment recommended by the IAEA (see Table 3).

Table 10. Doses from transport of lamps containing ^{85}Kr for routine scenarios

Scenario		Dose ($\mu Sv\ y^{-1}$) LKR85_1	LKR85_2	LKR85_3	Activity corresponding to exemption dose criterion (Bq)*
Transport from manufacturing to distribution centre by road (Scenario T1)					
Lorry driver		$7.2\ 10^{0}$	$3.6\ 10^{0}$	$2.5\ 10^{-3}$	$5.0\ 10^{8}$
Warehouse worker	Loading lamps	$2.8\ 10^{-1}$	$1.4\ 10^{-1}$	$1.8\ 10^{-3}$	
	Other duties	$5.2\ 10^{0}$	$2.6\ 10^{0}$	$9.8\ 10^{-5}$	
	Total	$5.5\ 10^{0}$	$2.7\ 10^{0}$	$1.9\ 10^{-3}$	$6.6\ 10^{8}$
Member of the public		$2.2\ 10^{-2}$	$1.1\ 10^{-2}$	$7.8\ 10^{-6}$	$1.6\ 10^{11}$
Transport from distribution centre to retail centre by plane (Scenario T2)					
Flight crew		$2.5\ 10^{0}$	$1.3\ 10^{0}$	$8.8\ 10^{-4}$	$7.2\ 10^{8}$
Passengers		$2.4\ 10^{-1}$	$1.2\ 10^{-1}$	$8.4\ 10^{-5}$	$7.5\ 10^{9}$
Workers loading lamps on planes		$1.1\ 10^{-1}$	$5.6\ 10^{-2}$	$3.9\ 10^{-5}$	$1.6\ 10^{9}$
Transport from distribution centre by sea (Scenario T3)					
Crew members on ferry		$1.5\ 10^{-1}$	$7.5\ 10^{-2}$	$5.3\ 10^{-5}$	$2.4\ 10^{10}$
Transport to landfill site (Scenario T4)					
Waste collector		$4.1\ 10^{-5}$	$4.1\ 10^{-5}$	$3.5\ 10^{-5}$	$8.2\ 10^{7}$
Transport to recycling plant (Scenario T5)					
Waste collector	Driving	$8.6\ 10^{-2}$	$4.3\ 10^{-2}$	$4.3\ 10^{-3}$	
	Loading	$3.4\ 10^{-3}$	$1.7\ 10^{-3}$	$1.7\ 10^{-4}$	
	Total	$8.9\ 10^{-2}$	$4.5\ 10^{-2}$	$4.5\ 10^{-3}$	$4.0\ 10^{7}$

Notes:

*: For routine transport scenarios the dose criterion is 10 $\mu Sv\ y^{-1}$.

The highest doses for accident scenarios were estimated for LKR85_1 lamps and ranged between $2.6\ 10^{-8}$ mSv y^{-1} and $3.2\ 10^{-4}$ mSv y^{-1}. The highest dose was calculated for the driver of a lorry carrying a consignment of LKR85_1 lamps involved in a road accident (Scenario A1). Table 11 also provides activities in a consignment which would give rise to doses equal to the criterion for exemption of 1 mSv y^{-1} (50 mSv y^{-1} for skin) for the accident transport scenarios considered in this study. These activities are between $5.7\ 10^{10}$ Bq (Scenario A1) and $1.6\ 10^{12}$ Bq (Scenario A3). These activities are much higher than those determined for routine transport scenarios.

Table 11. Doses from transport of lamps containing ^{85}Kr for accident scenarios

Scenario		Dose (mSv y^{-1}) LKR85_1	LKR85_2	LKR85_3	Activity corresponding to exemption dose criterion (Bq)*
Road accident (Scenario A1)					
Lorry driver		$3.2\ 10^{-4}$	$1.6\ 10^{-4}$	$1.1\ 10^{-7}$	$5.7\ 10^{10}$
Clean-up worker		-	-	-	-
Members of the public		$2.6\ 10^{-8}$	$1.3\ 10^{-8}$	$9.1\ 10^{-9}$	$6.9\ 10^{14}$
Package damaged at cargo handling bay (Scenario A2)					
Fork lift truck driver		$8.5\ 10^{-8}$	$4.2\ 10^{-8}$	$4.2\ 10^{-12}$	$1.4\ 10^{12}$
Repackaging	Skin dose	-	-	-	-
	Effective dose	-	-	-	-
Fire at a cargo handling bay (Scenario A3)					
Fire-fighter		$2.2\ 10^{-4}$	$1.1\ 10^{-4}$	$7.8\ 10^{-8}$	$1.6\ 10^{12}$
Clean-up worker		-	-	-	-

Notes:

*: For accident scenarios the dose criterion for exemption is 1 mSv for effective dose and 50 mSv y^{-1} for dose to the skin.

4.3 Doses from transport of lamps containing thorium-232

Doses for lamps containing low levels of ^{232}Th were estimated for scenarios for both routine and accident transport scenarios and are given in Table 12 and Table 13. For routine transport scenarios activities in the consignments assumed in the calculations were generally above the activity limits for an exempt consignment recommended by the IAEA (IAEA, 2009), with the exception of Scenario T4 and Scenario T5 for lamps LTH232_3 and LTH232_4. The highest doses were estimated for LTH232_1 and LTH232_2 lamps. Doses for these two types of lamps were the same for all routine scenarios, except scenario T4, since the activities of the load assumed in the assessments were the same. Doses for LTH232_1 lamps ranged between $2.6\ 10^{-2}$ μSv y^{-1} (dose to a waste collector for scenario T4) and 7.0 μSv y^{-1} (dose to a lorry driver transporting a consignment of LTH232_1 lamps from the factory to a distribution centre). Table 12 also provides activities in a consignment which would give rise to doses equal to the criterion for exemption of 10 μSv y^{-1} for the routine transport scenarios considered in this study. For scenarios T1, T2 and T3, involving new, packaged lamps, these activities were between $2.9\ 10^{6}$ Bq and $9.1\ 10^{8}$ Bq, at least about $3\ 10^{2}$ times the activity limit for an exempt consignment recommended by the IAEA (see Table 3). Lower activities were estimated for scenarios T4 and T5, which include disused, unpackaged lamps; activities in a consignment that give rise to doses of 10 μSv y^{-1} were estimated to be $1.3\ 10^{5}$ Bq for scenario T4 (transport to a landfill site) and $6.3\ 10^{4}$ Bq for scenario T5 (transport to a recycling facility), at least 60 times the activity limit for an exempt consignment recommended by the IAEA (see Table 3).

Table 12. Doses from transport of lamps containing ^{232}Th for routine scenarios

Scenario		Dose (μSv y^{-1}) LTH232_1	LTH232_2	LTH232_3	LTH232_4	Activity corresponding to exemption dose criterion (Bq)*
Transport from manufacture to distribution centre by road (Scenario T1)						
Lorry driver		$7.0\ 10^{0}$	$7.0\ 10^{0}$	$1.7\ 10^{0}$	$7.0\ 10^{-2}$	$2.9\ 10^{6}$
Warehouse worker	Loading lamps	$2.7\ 10^{-1}$	$2.7\ 10^{-1}$	$6.8\ 10^{-2}$	$2.7\ 10^{-3}$	
	Other duties	$5.0\ 10^{0}$	$5.0\ 10^{0}$	$1.3\ 10^{0}$	$5.0\ 10^{-2}$	
	Total	$5.3\ 10^{0}$	$5.3\ 10^{0}$	$1.3\ 10^{0}$	$5.3\ 10^{-2}$	$3.8\ 10^{6}$
Member of the public		$2.2\ 10^{-2}$	$2.2\ 10^{-2}$	$5.5\ 10^{-3}$	$2.2\ 10^{-4}$	$9.1\ 10^{8}$
Transport from distribution centre to retail centre by plane (Scenario T2)						
Flight crew		$2.4\ 10^{0}$	$2.4\ 10^{0}$	$6.1\ 10^{-1}$	$2.4\ 10^{-2}$	$4.1\ 10^{6}$
Passengers		$2.3\ 10^{-1}$	$2.3\ 10^{-1}$	$5.8\ 10^{-2}$	$2.3\ 10^{-3}$	$4.3\ 10^{7}$
Workers loading lamps on planes		$1.1\ 10^{-1}$	$1.1\ 10^{-1}$	$2.7\ 10^{-2}$	$1.1\ 10^{-3}$	$9.3\ 10^{6}$
Transport from distribution centre by sea (Scenario T3)						
Crew members on ferry		$1.5\ 10^{-1}$	$1.5\ 10^{-1}$	$3.6\ 10^{-2}$	$1.5\ 10^{-3}$	$1.4\ 10^{8}$
Transport to landfill site (Scenario T4)						
Waste collector		$2.6\ 10^{-2}$	$2.6\ 10^{-3}$	$2.6\ 10^{-3}$	$1.0\ 10^{-4}$	$1.3\ 10^{5}$
Transport to recycling plant (Scenario T5)						
Waste collector	Driving	$3.0\ 10^{-1}$	$3.0\ 10^{-1}$	$7.6\ 10^{-2}$	$3.0\ 10^{-3}$	
	Loading	$1.1\ 10^{-2}$	$1.1\ 10^{-2}$	$2.8\ 10^{-3}$	$1.1\ 10^{-4}$	
	Total	$3.2\ 10^{-1}$	$3.2\ 10^{-1}$	$7.9\ 10^{-2}$	$3.2\ 10^{-3}$	$6.3\ 10^{4}$

Notes:

*: For routine transport scenarios the dose criterion for exemption is 10 μSv y^{-1}

The highest effective doses for accident scenarios were calculated for LTH232_1 lamps and ranged between 1.2 10^{-6} mSv y^{-1} and 2.4 10^{-3} mSv y^{-1}. The highest dose was calculated for a worker involved in the clean-up operations at a warehouse following a fire of LTH232_1 or LTH232_2 lamps (scenario A3). Doses to the skin from repackaging of damaged lamps were also calculated for these lamps; they were between 1.5 10^{-4} mSv y^{-1} (LTH232_4 lamps) and 1.5 10^{-1} mSv y^{-1} (LTH232_1 lamps). Table 13 also provides activities in a consignment which would give rise to doses equal to the dose criterion for exemption of 1 mSv y^{-1} (50 mSv y^{-1} for skin) for the accident transport scenarios considered in this study. Separate values were calculated for LTH232_4, as different dose coefficients for inhalation were used to calculate doses from inhalation for these lamps, to take account of the different chemical form of thorium in these lamps. For all types of thorium lamps the lowest activity which would give rise to doses equal to the exemption dose criterion were calculated for repackaging of damaged lamps for scenario A2 (3.4 10^{5} Bq, 340 times the activity limit for an exempt consignment). Activities determined for the comparison with the dose criterion for effective dose of 1 mSv y^{-1} were between 8.4 10^{8} Bq (Scenario A3, clean-up workers) and 7.4 10^{9} Bq (Scenario A3, fire-fighters) for lamps LTH232_1, LTH232_2 and LTH232_3, and between 7.5 10^{8} Bq (Scenario A3, clean-up workers) and 6.5 10^{9} Bq (Scenario A3, fire-fighters) for LTH232_4 lamps. These activities were much higher than those determined for routine transport scenarios.

Table 13. Doses from transport of lamps containing ^{232}Th for accident scenarios

Scenario		Dose (mSv y^{-1}) LTH232_1	LTH232_2	LTH232_3	LTH232_4	Activity corresponding to exemption dose criterion (Bq)*, #
Road accident (Scenario A1)						
Lorry driver		-	-	-	-	-
Clean-up worker		$5.9\ 10^{-5}$	$5.9\ 10^{-5}$	$1.5\ 10^{-5}$	$6.7\ 10^{-7}$	$1.5\ 10^{9} – 1.7\ 10^{9}$
Members of the public		$2.4\ 10^{-5}$	$2.4\ 10^{-5}$	$6.0\ 10^{-6}$	$2.7\ 10^{-7}$	$3.7\ 10^{9} – 4.2\ 10^{9}$
Package damaged at cargo handling bay (Scenario A2)						
Fork lift truck driver		-	-	-	-	-
Repackaging	Skin dose	$1.5\ 10^{-1}$	$1.5\ 10^{-2}$	$3.7\ 10^{-3}$	$1.5\ 10^{-4}$	$3.4\ 10^{5}$
	Effective dose	$1.2\ 10^{-6}$	$1.2\ 10^{-7}$	$2.9\ 10^{-8}$	$1.2\ 10^{-9}$	$8.6\ 10^{8}$
Fire at a cargo handling bay (Scenario A3)						
Fire-fighter		$2.7\ 10^{-4}$	$2.7\ 10^{-4}$	$6.7\ 10^{-5}$	$3.1\ 10^{-6}$	$6.5\ 10^{9} – 7.4\ 10^{9}$
Clean-up worker		$2.4\ 10^{-3}$	$2.4\ 10^{-3}$	$5.9\ 10^{-4}$	$2.7\ 10^{-5}$	$7.5\ 10^{8} – 8.4\ 10^{8}$

Notes:

*: For accident scenarios the dose criterion for exemption is 1 mSv y^{-1} for effective dose and 50 mSv y^{-1} for dose to the skin.

#: Lower value is for LTH232_4

5 RESULTS OF THE ASSESSMENT OF DOSES FROM DISPOSAL OF LAMPS CONTAINING LOW LEVELS OF RADIOACTIVITY

Doses from all scenarios are summarised in Table 14; more detailed information is given in Appendix B. Doses from disposal to landfill of lamps containing ^{3}H, ^{85}Kr and thorium with an activity concentration in the waste of 1 Bq g^{-1} did not exceed any dose criterion, with the exception of thorium in the case of a fire. In calculating doses in Table 14, it was assumed that the activity from all lamps in the landfill is available instantaneously; in reality, lamps would be put into a landfill over a period of time, thus at any instant, the activity in older lamps will have decreased through radioactive decay. The calculations also assumed that all the lamps were broken, when this may not be the case since many of the sources are enclosed in quartz glass containers with 1 mm thick walls.

Table 14. Summary of doses from disposal to landfill of lamps containing low levels of radioactivity

Scenario		Dose criterion ($mSv\ y^{-1}$, unless otherwise stated)	Dose ($mSv\ y^{-1}$, unless otherwise stated)		
			^{3}H	^{85}Kr	^{232}Th
Operational phase					
Normal operation		1	$1.9\ 10^{-7}$	$1.9\ 10^{-4}$	$9.3\ 10^{-1}$
Fire (acute)	Landfill workers	1 mSv	$7.5\ 10^{-4}$ mSv	$2.1\ 10^{-5}$ mSv	$7.8\ 10^{0}$ mSv
	Members of the public	1 mSv	$8.5\ 10^{-5}$ mSv	$4.4\ 10^{-6}$ mSv	$8.8\ 10^{-1}$ mSv
Fire (annual exposure)		1	$3.2\ 10^{-8}$	0	$4.9\ 10^{-4}$
Post-closure phase					
Normal evolution		1	$3.7\ 10^{-1}$	0	0
Migration		0.15	0	0	$3.9\ 10^{-4}$
Intrusion		3	$8.2\ 10^{-8}$	$1.8\ 10^{-3}$	$4.8\ 10^{-1}$
Bathtubbing		1	$7.2\ 10^{-9}$	$1.6\ 10^{-4}$	$4.2\ 10^{-2}$

The maximum activities that can be disposed of into a landfill facility that meets the dose criterion for each scenario are given in Table 15. These values were calculated by scaling the total inventory of the landfill assumed in this study (2.2 TBq) by the ratio of the dose criterion to the dose calculated for each scenario given in Table 14. For ^{3}H these activities range from $6\ 10^{12}$ Bq to $3\ 10^{20}$ Bq; for ^{85}Kr these activities range from $4\ 10^{15}$ Bq to $5\ 10^{17}$ Bq, while for thorium they are between $3\ 10^{11}$ Bq and $4\ 10^{15}$ Bq. The lowest of such activities provide general upper limits on the activities that can be disposed of in order to remain below all dose criteria.

Table 15. Disposed activities meeting dose criteria

Scenario		Activity (Bq)		
		^{3}H	^{85}Kr	^{232}Th
Operational phase				
Normal operation		$1\ 10^{19}$	$1\ 10^{16}$	$2\ 10^{12}$
Fire (acute)	Landfill workers	$3\ 10^{15}$	$1\ 10^{17}$	$3\ 10^{11}$
	Members of the public	$3\ 10^{16}$	$5\ 10^{17}$	$3\ 10^{12}$
Fire (annual exposure)		$7\ 10^{19}$	-	$4\ 10^{15}$
Post-closure phase				
Normal evolution		$6\ 10^{12}$	-	-
Migration		-	-	$8\ 10^{14}$
Intrusion		$8\ 10^{19}$	$4\ 10^{15}$	$1\ 10^{13}$
Bathtubbing		$3\ 10^{20}$	$1\ 10^{16}$	$5\ 10^{13}$

Taking the highest activity for each radionuclide from Table 2, the maximum number of lamps that can be disposed of without exceeding the dose criteria are $6\ 10^{9}$ for lamps containing ^{3}H, $2\ 10^{12}$ for lamps containing ^{85}Kr and $3\ 10^{8}$ for lamps containing ^{232}Th. These values were calculated assuming that all lamps disposed of contain the highest activity for each type of lamp; it is likely that lamps sent to a landfill facility for disposal have a wide range of activities and that the average activity would be much lower than the maximum value considered in these calculations.

It should be noted that in Europe the vast majority of lamps containing low levels of radioactivity are collected along with other non-incandescent lamps and are recycled at specialist plants. Although the assessment of doses associated with recycling of lamps containing small quantities of radioactivity was outside the scope of this study some general points can be made.

Since many of the collected lamps contain mercury, the recycling process is designed so that the operators do not come into contact with mercury when the lamps are crushed and the phosphor powder containing mercury is extracted. This precaution also ensures that the operator does not come into contact with either ^{3}H or ^{85}Kr.

The recycling process splits the waste into several streams, each of which is sent on separately for further processing. Each stream, including that containing ^{232}Th, is stored in containers with capacity of the order of 2 m^3 to 5 m^3 until it is despatched to the next processor. Since the containers are bulky, storage is out of the way of operators. The closest exposure scenario which simulates the way this operation is carried out is that of the landfill worker under normal conditions, in which the worker is assumed to be 1 m from the waste and that the waste geometry is a semi-infinite slab with an activity concentration of 1 Bq g^{-1}. The highest activity concentration of ^{232}Th in electrodes is 7.4 10^{1} Bq g^{-1} (ELC, 2010), but this is mixed with metal waste from all lamps at a concentration of about 2%, thus the activity concentration in the whole waste stream is around 1.5 Bq g^{-1}. Taking into account that dose rates from a finite object containing ^{232}Th are around an order of magnitude smaller than those from a semi-infinite slab, the maximum dose a worker at a recycling facility receives from lamps containing low levels of radioactivity is of the order of 0.2 mSv y^{-1}.

6 DISCUSSION AND CONCLUSIONS

6.1 Transport

This study assessed dose to a number of different individuals who may be exposed to the radiation emitted by lamps containing low levels of the radionuclides ^{3}H, ^{85}Kr and the two thorium isotopes ^{232}Th and ^{228}Th for transport scenarios under routine conditions and scenario for accidents during transport. The scenarios were based on information provided by the European Lamp Companies Federation (ELC) to provide a realistic picture of the working practices currently adopted by the lamp industry in Europe.

The main objective of this study was to calculate doses received by workers and members of the public representative of the individuals most exposed, for comparison with the dose criteria adopted to calculate activity limits for exempt consignments given in the IAEA Transport Regulations (IAEA, 2009). These dose criteria are an effective dose of 10 μSv y^{-1} for routine transport scenarios and an effective dose of 1 mSv y^{-1} for accident scenarios, with an additional dose criterion of a skin dose of 50 mSv y^{-1}. The higher value for accident scenarios takes account of the low probability of occurrence of these accidents.

All doses calculated in this study were below the dose criteria for exemption even when the activity assumed in the consignment are well above the activity limits for exemption. The highest dose for transport under routine conditions was calculated for a lorry driver carrying a load of lamps each containing 2000 Bq of ^{85}Kr, who was calculated to receive a dose of 7.2 μSv y^{-1}. Similar doses (7.0 μSv y^{-1}) were calculated for lorry drivers transporting consignment of lamps containing 1000 Bq and 100 Bq of ^{232}Th. The highest effective dose for accident scenarios (2.4 10^{-3} mSv y^{-1}) was calculated for a worker involved in the clean-up operations at a warehouse following a fire of LTH232_1 or LTH232_2 lamps. The maximum dose to skin for thorium lamps was 1.5 10^{-1} mSv y^{-1}. Doses for accident scenarios involving lamps containing ^{85}Kr or ^{3}H were lower; maximum doses were estimated to be 5.4 10^{-5} mSv y^{-1} and 3.2 10^{-4} mSv y^{-1} well below the dose criterion for exemption of 1 mSv y^{-1}. It should be noted that the probability of occurrence of these accidents is very low.

The study also estimated activities for lighting products as consumer goods in transport up to the end-users which would give rise to doses equal to the dose criteria for exemption for the scenarios considered in the assessment. These activities are all higher than the current activity limits for exempt consignments given in the IAEA Transport Regulations (IAEA, 2009) for the radionuclides considered. For ^{3}H, for which only accident scenarios were considered, the activities were estimated to be between 1.9 10^{9} Bq and 2.8 10^{13} Bq, at least 2 times the activity limit for an exempt consignment recommended by the IAEA (IAEA, 2009). For ^{85}Kr the activities were between 5.0 10^{8} Bq and 1.6 10^{11} Bq for routine transport scenarios involving new packaged lamps, and between 5.7 10^{10} Bq and 1.6 10^{12} Bq for accident scenarios, at least 5 10^{4} times the activity limit for an exempt consignment recommended by the IAEA (IAEA, 2009). For thorium these activities were estimated to be between 2.9 10^{6} Bq and 9.1 10^{8} Bq for routine transport scenarios involving new packaged lamps, and between 3.4 10^{5} Bq and 9.1 10^{9} Bq for accident scenarios, at least about 300 times the activity limit for an exempt consignment recommended by the IAEA (IAEA, 2009).

For ^{85}Kr and thorium the study also estimated activities which would give rise to doses equal to the dose criteria for exemption for 2 scenarios involving disused, unpackaged lamps, collected for recycling or disposal. These activities were estimated to be higher than the current activity limits for exempt consignments given in the IAEA Transport Regulations (IAEA, 2009), but lower than those estimated for other routine transport scenarios. For ^{85}Kr the activities were between 4.0 10^{7} Bq and 8.2 10^{7} Bq at least 4 10^{3} times higher than the activity limit for an exempt consignment recommended by the IAEA (IAEA, 2009). For thorium these activities were estimated to be between 6.3 10^{4} Bq and 1.3 10^{5} Bq at least 60 times higher than the activity limit for an exempt consignment recommended by the IAEA (IAEA, 2009). For ^{85}Kr and thorium, therefore, the most limiting scenarios are transport of disused, unpackaged lamps to a recycling plant or a landfill site.

On the basis of the outcome of this assessment the exemption limits for consignments recommended by the IAEA in its Regulations for the Safe Transport of Radioactive Material (IAEA, 2009) appear to be restrictive when applied to the transport of lamps containing low levels of radioactive material. The dose criteria on which the exemption limits are based would be met by consignments of lamps containing activities of ^{3}H, ^{85}Kr and thorium, greater than the limits on activity concentration and activity for consignments recommended by the IAEA by factors of 2, 4000 and 60 respectively.

6.2 Disposal to landfill

In the second part of this study doses from disposal to landfill of disused lamps containing small quantities of radioactivity were also estimated. In Europe most of these disused lamps are recycled; only a small fraction is sent to municipal landfill sites. The objective of the assessment was to carry out a scoping calculation of doses for a number of different scenarios for comparison with dose criteria relevant to disposal to landfill currently applied in the United Kingdom in order to determine maximum activities of ^{3}H, ^{85}Kr and ^{232}Th which can be disposed of to landfill in a year. Doses were therefore calculated, using cautious assumptions, for unit activity concentrations in the waste (1 Bq g^{-1}) of the radionuclides considered in this study without making a distinction between different types of lamps. Maximum activities that can be disposed of to landfill were then determined by scaling the total activity assumed to be disposed of to landfill on the basis of the activity concentration in the waste (2.2 TBq) by the ratios of the dose criteria to the dose calculated in the assessment. The lowest values of these activities can be taken as general upper limits on the activities that can be disposed of to landfill in order to meet all dose criteria. These activities were 6 10^{12} Bq for ^{3}H, 4 10^{15} Bq for ^{85}Kr and 3 10^{11} Bq for thorium.

Using the highest activity in lamps for each radionuclides provided by ELC (ELC, 2010), the maximum number of lamps that can be disposed of without exceeding the dose criteria were calculated to be 6 10^{9} for lamps containing ^{3}H, 2 10^{12} for lamps containing ^{85}Kr and 3 10^{8} for lamps containing ^{232}Th. These numbers vastly exceed the numbers of lamps containing low levels of radioactivity which are currently disposed to landfill each year (about 1 10^{6} for each type of lamps).

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APPENDIX A

Radionuclide parameters used for the assessment of doses from transport and disposal of lamps containing low levels of radioactivity

A1 TABLES OF PARAMETERS

This Appendix provides the most important parameter values used in the assessment of doses. Table A1 gives radioactive half-lives, decay constants, branching ratios, mean beta energies and release fraction from a fire; Table A2 gives dose coefficients for external exposure and Table A3 gives dose coefficients for internal irradiation used in the assessment

Table A1. Parameters values for ^{3}H, ^{85}Kr and members of the ^{232}Th decay chain

Radionuclide	Half-life*	Decay constant (y^{-1})	Branching ratio* Secular equilibrium#	Branching ratio* Non secular equilibrium†	Mean beta energy (MeV)	Release fraction for fire
^{3}H	12.35 y	$5.61\ 10^{-2}$	-	-	$5.68\ 10^{-3}$	1
^{85}Kr	10.72 y	$6.47\ 10^{-2}$	-	-	$2.50\ 10^{-1}$	1
^{232}Th	$1.41\ 10^{10}$ y	$4.92\ 10^{-11}$	-	-	$1.25\ 10^{-2}$	$1\ 10^{-3}$
^{228}Ra	5.75 y	$1.21\ 10^{-1}$	1	-	$1.69\ 10^{-2}$	$1\ 10^{-3}$
^{228}Ac	6.13 h	$9.91\ 10^{2}$	1	-	$4.60\ 10^{-1}$	$1\ 10^{-3}$
^{228}Th	1.9131 y	$3.62\ 10^{-1}$	1	0.5	$2.05\ 10^{-2}$	$1\ 10^{-3}$
^{224}Ra	3.66 d	$6.91\ 10^{1}$	1	0.5	$2.21\ 10^{-3}$	$1\ 10^{-3}$
^{220}Rn	55.6 s	$3.93\ 10^{5}$	1	0.5	$8.91\ 10^{-6}$	1
^{216}Po	0.15 s	$1.46\ 10^{8}$	1	0.5	$1.61\ 10^{-7}$	$1\ 10^{-3}$
^{212}Pb	10.64 h	$5.71\ 10^{2}$	1	0.5	$1.75\ 10^{-1}$	$5\ 10^{-1}$
^{212}Bi	60.55 m	$6.02\ 10^{3}$	1	0.5	$4.69\ 10^{-1}$	$1\ 10^{-3}$
^{212}Po	0.305 μs	$7.17\ 10^{13}$	0.641	0.32	0	$1\ 10^{-3}$
^{208}Tl	3.07 m	$1.19\ 10^{5}$	0.359	0.18	$5.91\ 10^{-1}$	$1\ 10^{-3}$

Notes:

*: (ICRP, 1983)

#: Used for routine transport scenarios T4 and T5 and accident scenarios A1, A2 and A3 and for disposal;

†: Used for routine transport scenarios T1, T2 and T3

Table A2. Dose coefficients for external irradiation used in the assessment

Radionuclide	Equivalent dose rate to the basal layer of skin epidermis per unit contamination ($Sv\ h^{-1}\ Bq^{-1}\ cm^{2}$)		Dose rate for external exposure per unit activity concentration ($Sv\ h^{-1}\ Bq^{-1}\ g$)†		Dose rate for exposure to radionuclides in the air per unit activity concentration ($Sv\ h^{-1}\ Bq^{-1}\ m^{3}$) ‡
	Gamma*	Beta#	Gamma	Beta	
^{3}H	0	0	0	0	0
^{85}Kr	0	0	$1.72\ 10^{-10}$	$1.84\ 10^{-11}$	$8.64\ 10^{-13}$
^{232}Th	$2.2\ 10^{-9}$	0	$5.96\ 10^{-11}$	0	$2.61\ 10^{-14}$
^{228}Ra	$3.4\ 10^{-14}$	0	0	0	0
^{228}Ac	$6.3\ 10^{-8}$	$5.39\ 10^{-7}$	$3.09\ 10^{-7}$	$3.47\ 10^{-10}$	$1.62\ 10^{-10}$
^{228}Th	$2.6\ 10^{-9}$	0	$8.50\ 10^{-10}$	0	$2.92\ 10^{-13}$
^{224}Ra	$6.5\ 10^{-10}$	0	$4.23\ 10^{-9}$	0	$1.54\ 10^{-12}$
^{220}Rn	0	0	$2.76\ 10^{-11}$	0	$6.19\ 10^{-14}$
^{216}Po	0	0	$1.59\ 10^{-12}$	0	$2.79\ 10^{-15}$
^{212}Pb	$1.3\ 10^{-8}$	$7.16\ 10^{-8}$	$6.16\ 10^{-8}$	$2.17\ 10^{-12}$	$2.25\ 10^{-11}$
^{212}Bi	$1.3\ 10^{-8}$	$5.95\ 10^{-7}$	$5.77\ 10^{-8}$	$3.66\ 10^{-10}$	$3.22\ 10^{-11}$
^{212}Po	0	0	0	0	0
^{208}Tl	$1.6\ 10^{-7}$	$9.05\ 10^{-7}$	$1.04\ 10^{-6}$	$6.80\ 10^{-10}$	$6.08\ 10^{-10}$

Notes:

*: Values for 7 mg cm^{-2} (Chaptinel et al, 1985);

#: Values for 40 mg cm^{-2} (Cross et al, 1992);

†: Calculated using Microshield 7.02 ;

‡: (Ekermann and Ryman, 1993).

Table A3. Dose coefficients for internal irradiation used in the assessment (ICRP, 1996)

Radionuclide	Dose coefficient for internal irradiation (Sv Bq^{-1})		
	Inhalation		Ingestion
^{3}H	$1.8\ 10^{-11}$		$1.8\ 10^{-11}$
^{85}Kr	0		0
	Oxide form (ThO_2)	Iodide form (ThI_4)	
$^{232}Th^{\#}$	$2.5\ 10^{-5}$	$4.5\ 10^{-5}$	$2.3\ 10^{-7}$
^{228}Ra	$2.6\ 10^{-6}$	$2.6\ 10^{-6}$	$6.9\ 10^{-7}$
^{228}Ac	$1.6\ 10^{-8}$	$1.7\ 10^{-8}$	$4.3\ 10^{-10}$
^{228}Th	$4.0\ 10^{-5}$	$3.2\ 10^{-5}$	$7.2\ 10^{-8}$
^{224}Ra	$3.0\ 10^{-6}$	$3.0\ 10^{-6}$	$6.5\ 10^{-8}$
^{220}Rn	0	0	0
^{216}Po	0	0	0
^{212}Pb	$1.7\ 10^{-7}$	$1.9\ 10^{-7}$	$6.0\ 10^{-9}$
^{212}Bi	$3.1\ 10^{-8}$	$3.1\ 10^{-8}$	$2.6\ 10^{-10}$
^{212}Po	0	0	0
^{208}Tl	0	0	0

Notes:

*: Value for tritiated water;

#: For the assessment of doses from disposal of landfill the higher of the two values for all the radionuclides in the decay chain was used

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APPENDIX B

Detailed results for the assessment of doses from disposal of lamps containing low levels of radioactivity

B1 OPERATIONAL PHASE

B1.1 Normal operations: landfill workers

The results of the remaining calculations for landfill worker doses are shown in Table B1. The symbols used in the table heading are described in Section 2.1.1.

Table B1. Results of landfill worker dose calculations

	Dose (Sv y^{-1})					
	Skin					
Radionuclide	Equivalent (H_{skin})	Effective (D_{skin})	Inhalation	Ingestion	External	Total
^{3}H	0	0	6.6 10^{-12}	1.8 10^{-10}	0	1.9 10^{-10}
^{85}Kr	0	0	0	0	1.9 10^{-7}	1.9 10^{-7}
^{232}Th	0	0	1.7 10^{-5}	2.3 10^{-6}	6.6 10^{-8}	1.9 10^{-5}
^{228}Ra	0	0	9.6 10^{-7}	6.9 10^{-6}	0	7.9 10^{-6}
^{228}Ac	5.4 10^{-6}	7.2 10^{-9}	6.3 10^{-9}	4.3 10^{-9}	3.4 10^{-4}	3.4 10^{-4}
^{228}Th	0	0	1.5 10^{-5}	7.2 10^{-7}	9.4 10^{-7}	1.6 10^{-5}
^{224}Ra	0	0	1.1 10^{-6}	6.5 10^{-7}	4.7 10^{-6}	6.4 10^{-6}
^{220}Rn	0	0	0	0	3.0 10^{-8}	3.0 10^{-8}
^{216}Po	0	0	0	0	1.8 10^{-9}	1.8 10^{-9}
^{212}Pb	7.2 10^{-7}	9.5 10^{-10}	7.0 10^{-8}	6.0 10^{-8}	6.8 10^{-5}	6.8 10^{-5}
^{212}Bi	6.0 10^{-6}	7.9 10^{-9}	1.1 10^{-8}	2.6 10^{-9}	6.4 10^{-5}	6.4 10^{-5}
^{212}Po	0	0	0	0	0	0
^{208}Tl	3.2 10^{-6}	4.3 10^{-9}	0	0	4.1 10^{-4}	4.1 10^{-4}
Total ^{232}Th	1.5 10^{-5}	2.0 10^{-8}	3.3 10^{-5}	1.1 10^{-5}	8.9 10^{-4}	9.3 10^{-4}

B2 FIRE SCENARIO

B2.1 Landfill workers

The adjusted time-integrated air concentration (*TIAC*) at 100 m, allowing for a 1 hour release and converting from seconds to hours, is 1.13 10^{-6} Bq h m^{-3} per Bq released. The results of the calculations for acute doses to landfill workers during a fire are summarised in Table B2.

Table B2. Acute doses to landfill workers during a fire

Radionuclide	Activity concentration in air (Bq m^{-3})	Dose (Sv)		
		Inhalation	External exposure	Total
^{3}H	$2.5\ 10^{4}$	$7.5\ 10^{-7}$	0	$7.5\ 10^{-7}$
^{85}Kr	$2.5\ 10^{4}$	0	$2.1\ 10^{-8}$	$2.1\ 10^{-8}$
^{232}Th	$2.5\ 10^{1}$	$1.9\ 10^{-3}$	$6.5\ 10^{-13}$	$1.9\ 10^{-3}$
^{228}Ra	$2.5\ 10^{1}$	$1.1\ 10^{-4}$	0	$1.1\ 10^{-4}$
^{228}Ac	$2.5\ 10^{1}$	$7.1\ 10^{-7}$	$4.0\ 10^{-9}$	$7.2\ 10^{-7}$
^{228}Th	$2.5\ 10^{1}$	$1.6\ 10^{-3}$	$7.2\ 10^{-12}$	$1.7\ 10^{-3}$
^{224}Ra	$2.5\ 10^{1}$	$1.3\ 10^{-4}$	$3.8\ 10^{-11}$	$1.3\ 10^{-4}$
^{220}Rn	$2.5\ 10^{4}$	0	$1.5\ 10^{-9}$	$1.5\ 10^{-9}$
^{216}Po	$2.5\ 10^{1}$	0	$6.9\ 10^{-14}$	$6.9\ 10^{-14}$
^{212}Pb	$1.2\ 10^{4}$	$4.0\ 10^{-3}$	$2.8\ 10^{-7}$	$4.0\ 10^{-3}$
^{212}Bi	$2.5\ 10^{1}$	$1.3\ 10^{-6}$	$8.0\ 10^{-10}$	$1.3\ 10^{-6}$
^{212}Po	$1.6\ 10^{1}$	0	0	0
^{208}Tl	$8.9\ 10^{0}$	0	$5.4\ 10^{-9}$	$5.4\ 10^{-9}$
Total ^{232}Th		$7.8\ 10^{-3}$	$2.9\ 10^{-7}$	$7.8\ 10^{-3}$

B2.2 Members of the public

The adjusted time-integrated air concentration at 250 m, allowing for a 1 hour release and converting from seconds to hours, is $2.33\ 10^{-7}$ Bq h m^{-3} per Bq released. The results of the calculations for acute doses to nearby residents during a fire are summarised in Table B3 along with annual effective dose from living on land contaminated by deposition from a fire. Although radionuclides in the decay chain of ^{232}Th are considered to be in secular equilibrium at the time of the fire, they have different release fractions, dry deposition velocities and washout coefficients and therefore the activities deposited onto the surface of the ground vary. The dose for ^{228}Ra includes the contribution from ^{228}Ac as these radionuclides have the same activity deposited on the ground.

Table B3. Acute and annual effective doses to nearby residents from a fire

Radionuclide	Activity concentration in air (Bq m^{-3})	Acute dose (Sv) Inhalation	External exposure	Total	Activity deposited on the ground (Bq m^{-2})	Activity concentration in soil (Bq g^{-1})	Annual effective dose (Sv y^{-1})
^{3}H	5.1 10^{3}	8.5 10^{-8}	0	8.5 10^{-8}	1.8 10^{4}	4.9 10^{-2}	3.25 10^{-11}
^{85}Kr	5.1 10^{3}	0	4.4 10^{-9}	4.4 10^{-9}	0	0	0
^{232}Th	5.1 10^{0}	2.1 10^{-4}	1.3 10^{-13}	2.1 10^{-4}	1.8 10^{1}	4.9 10^{-5}	5.1 10^{-10}
^{228}Ra	5.1 10^{0}	1.2 10^{-5}	0	1.2 10^{-5}	1.8 10^{1}	4.9 10^{-5}	1.5 10^{-8}*
^{228}Ac	5.1 10^{0}	8.0 10^{-8}	8.3 10^{-10}	8.1 10^{-8}	1.8 10^{1}	4.9 10^{-5}	
^{228}Th	5.1 10^{0}	1.9 10^{-4}	1.5 10^{-12}	1.9 10^{-4}	1.8 10^{1}	4.9 10^{-5}	4.8 10^{-10}
^{224}Ra	5.1 10^{0}	1.4 10^{-5}	7.9 10^{-12}	1.4 10^{-5}	1.8 10^{1}	4.9 10^{-5}	4.2 10^{-10}
^{220}Rn	5.1 10^{3}	0	3.2 10^{-10}	3.2 10^{-10}	0	0	0
^{216}Po	5.1 10^{0}	0	1.4 10^{-14}	1.4 10^{-14}	1.8 10^{1}	4.9 10^{-5}	1.6 10^{-13}
^{212}Pb	2.6 10^{3}	4.5 10^{-4}	5.8 10^{-8}	4.5 10^{-4}	9.2 10^{3}	2.5 10^{-2}	4.5 10^{-7}
^{212}Bi	5.1 10^{0}	1.5 10^{-7}	1.7 10^{-10}	1.5 10^{-7}	1.8 10^{1}	4.9 10^{-5}	1.8 10^{-9}
^{212}Po	3.3 10^{0}	0	0	0	1.2 10^{1}	3.2 10^{-5}	0
^{208}Tl	1.8 10^{0}	0	1.1 10^{-9}	1.1 10^{-9}	6.6 10^{0}	1.8 10^{-5}	1.6 10^{-8}
Total ^{232}Th		8.8 10^{-4}	6.0 10^{-8}	8.8 10^{-4}			4.9 10^{-7}

Notes:

*: Includes the contribution from ^{228}Ac

B3 POST-CLOSURE PHASE

B3.1 Landfill gases: residents

Doses from inhalation of landfill gases were calculated for ^{3}H only. The activity concentration in landfill water was 7.3 10^{0} Bq g^{-1}; the activity concentration after 30 years was 1.4 10^{0} Bq g^{-1}; the release rate after 30 years was 4.90 10^{12} Bq y^{-1} and the effective annual dose was 3.7 10^{-4} Sv y^{-1}.

B3.2 Doses to members of the public form migration with groundwater

The dose for ^{232}Th was obtained by scaling the peak dose of 1.8 10^{-13} Sv y^{-1} calculated in a previous study (Anderson and Mobbs, 2010) for an activity of 1 10^{6} Bq, to the activity of 2.2 10^{12} Bq assumed in this study; the resulting dose was 3.9 10^{-7} Sv y^{-1}.

B3.3 Doses to residents from inadvertent intrusion

For this scenario, doses for radionuclides in the decay chain of ^{232}Th were calculated assuming that ^{228}Ac was in equilibrium with ^{228}Ra and ^{228}Th was in equilibrium with all the other radionuclides in the decay chain. Activity concentration in the waste and doses for this scenario are given in Table B4.

Table B4. Doses to residents in housing built on landfill

Radionuclide	Activity concentration in waste (Bq g^{-1})	Dose (Sv y^{-1})
^{3}H	1.2 10^{-1}	8.15 10^{-11}
^{85}Kr	9.6 10^{-2}	1.8 10^{-6}
^{232}Th	6.7 10^{-1}	6.9 10^{-6}
^{228}Ra	6.7 10^{-1}	2.0 10^{-4}
^{228}Th	6.7 10^{-1}	2.7 10^{-4}
Total ^{232}Th		4.8 10^{-4}

B3.4 Doses to residents from bathtubbing

In this scenario it was assumed that the overflowing leachate contains all members of the ^{232}Th decay chain in secular equilibrium. Doses were calculated ^{228}Ra in equilibrium with ^{228}Ac and ^{228}Th in equilibrium with all the other radionuclides in the decay chain. A retardation coefficient equal to 1 was assumed; infiltration rate, Q_{inf}, and leachate rate, I_L, were calculated to be 1.2 10^{10} cm^3 y^{-1} and 0.04 y^{-1} respectively. The results of the calculations are shown in Table B5.

Table B5. Doses to residents after a bathtubbing event

Radionuclide	Activity concentration in leachate (Bq cm^{-3})	Soil activity (Bq g^{-1})	Dose (Sv y^{-1})
^{3}H	4.1 10^{-1}	1.1 10^{-2}	7.2 10^{-12}
^{85}Kr	3.2 10^{-1}	8.5 10^{-3}	1.6 10^{-7}
^{232}Th	2.2 10^{0}	5.9 10^{-2}	6.1 10^{-7}
^{228}Ra	2.2 10^{0}	5.9 10^{-2}	1.8 10^{-5}
^{228}Th	2.2 10^{0}	5.9 10^{-2}	2.4 10^{-5}
Total ^{232}Th			4.2 10^{-5}

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