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

**K A Jones, M P Harvey and T Anderson**

## ABSTRACT

The European Light Companies Federation has commissioned HPA to carry out a study to assess the radiological consequences arising from the recycling and disposal of lamps containing low levels of $^{3}H$, $^{85}Kr$ and thorium. The assessment was carried out of the doses received by workers and members of the public representative of individuals most exposed during recycling and disposal of these lamps. The amount of radioactive material in lamps depends on the product and its use. The levels of radioactivity assumed in this study were based on the higher end values found in metal halide lamps and the glow switches of first generation non-integrated compact fluorescent lamps. The use of radioactive materials in the glow switches is being phased out. However, since some of the lamps can currently be found at lamp recycling plants, their contribution to the inventory was considered. In addition exposures to radioactivity in starters with glow switches for first generation fluorescent tube systems, which are not sent to recycling plants but directly to disposal, were also considered.

The approach in the assessment was to use cautious assumptions to ensure that the doses are very unlikely to be underestimated. Doses calculated in this study were compared with dose criteria adopted by international organizations to exempt practices from regulatory control. The International Atomic Energy Agency (IAEA) in its 1996 Basic Safety Standards (BSS) states that a practice can be exempted if individual doses are of the order of 10 μSv $y^{-1}$ or less and the collective effective dose is no more than 1 man Sv. Since the 10 μSv $y^{-1}$ individual dose criterion is generally the determining one it has been considered in this study. All the doses calculated in this study were below this criterion. This does not mean that the transport, recycling and disposal of these lamps will be exempt from the requirements of national regulations. This study is an assessment of exposures received from the recycling and disposal of these lamps and as such provides useful information for any discussions with regulators.

This study was funded by the European Lamp Companies Federation (ELC).


Centre for Radiation, Chemical and Environmental Hazards
Chilton, Didcot
Oxfordshire OX11 0RQ

Approval: June 2011
Publication: June 2011
£15.00
ISBN 978-0-85951-697-6

This work was undertaken under the Environmental Assessment Department's Quality Management System, which has been approved by Lloyd's Register Quality Assurance to the Quality Management Standards ISO 9001:2008 and TickIT Guide Issue 5.5, Certificate No: LRQ 0956546.

Report version 1.0

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# 1 INTRODUCTION

A small fraction – about 2% – of the lamps sold on the European market 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 are covered by national and international regulations aimed at minimising the hazard that 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 has commissioned HPA to carry out a study to assess doses arising from the recycling and disposal of lamps containing small quantities of $^{3}H$, $^{85}Kr$ and thorium. About 7% of lamps currently being recycled contain low levels of radioactive material but this value will decrease due to replacement by electronic starters. This study is a follow-up to the study carried out by HPA in 2010 to assess the radiological consequences from the transport and disposal to landfill of lamps containing small quantities of $^{3}H$, $^{85}Kr$ and thorium (Harvey et al, 2010a). The report of that study concluded 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.

The present study considered a range of exposure scenarios in order to estimate the highest doses* that might be received by different individuals (eg, workers at facilities recycling lamps, workers at incineration and foundries and landfill sites and members of the public) in different situations. The doses were then compared with the dose criteria used by the European Commission as the radiological basis for exemption from the Euratom Directive 96/29 (European Commission, 1996). The assumptions made in the calculations were cautious in order to ensure that the doses calculated were not underestimated.

This study is intended to be applicable throughout Europe rather than to a particular country, since it reflects European-wide recycling and disposal practices for lamps. Data on lamp types were provided through the ELC Federation for the major European manufacturers. Information on the process of recycling lamps was obtained by visiting three lamp recycling facilities in the United Kingdom and Germany. These facilities vary considerably in size and there were differences in procedures used but fundamentally the recycling processes were the same. The lamp recycling facility in Germany, which

* 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, 2007).

was the largest of those visited, processes not only lamps from Germany but also a considerable number from France and other neighbouring countries. The study therefore reflects the operations at these facilities. However ELC, whose members have visited facilities throughout Europe, considered them to be typical of European facilities (ELC, 2011).

This document describes in detail the assessment carried out by HPA. Section 2 provides information on the regulatory framework for the disposal of the lamps. Section 3 describes the type of lamps containing low levels of radioactivity and Section 4 details the end-of-life routes for these lamps. Section 5 describes the methodology used in the calculation of doses during and resulting from the recycling, metal melting, incineration and disposal to landfill processes. Section 6 provides the results of the assessment and Section 7 discusses the results and provides conclusions.

# 2 REGULATORY FRAMEWORK FOR EXEMPTION

All EU Member States are required to comply with the Council Directive 96/29/Euratom of 13 May 1996 (European Commission, 1996), which sets out Basic Safety Standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation. The Euratom Directive contains requirements for the authorisation of practices using ionising radiation including the deliberate addition of radioactive substances in the production and manufacture of consumer goods and the import or export of such goods. The Directive also establishes that authorisation or reporting is not required for practices involving radioactive substances where the activities or the activity concentrations per unit mass do not exceed certain values set out in Annex I of the Directive. It also allows an individual Member State to use, in exceptional circumstances, different values authorized by the competent authorities as long as they satisfy the basic general criteria set out in Annex I; such practices are said to be exempted from regulatory control. The reason why practices are granted exemption from regulatory control is that the risk from these levels of radioactive material is sufficiently low that the full rigour of regulation is unwarranted.

The exemption values given in the EU Basic Safety Standards were derived using a methodology described in the European Commission report RP-65 (Harvey et al, 1993). The basic dose criteria adopted in the calculation of exemption levels were those recommended by the IAEA Basic Safety Standards (BSS) (IAEA, 1996) on the basis of its review of the radiological basis for exemption (IAEA, 1988) which 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, the IAEA recommended that exposure from each exempted practice should be of the order of 10 μSv $y^{-1}$ or less. The IAEA also required the collective effective dose to be as low as reasonably achievable (ALARA) and suggested that it may be assumed to be so if it is below 1 man Sv per year of practice. The methodology developed for the EC report RP-65 did not consider collective doses but adopted two additional dose criteria for individual doses. 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 IAEA BSS if it could give rise to doses above the dose limit for members of the public in the event of an accident or misuse. 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 (Harvey et al, 1993).

The IAEA has published a draft version of its Basic Safety Standards (BSS) which may be subject to further revisions before its publication (IAEA, 2010). The dose criterion for the individual dose has remained as it was in the 1996 version of the IAEA BSS but the dose criterion for collective doses has been removed. There is an additional dose criterion to take account of low probability scenarios, namely that the effective dose due to such low probability scenarios does not exceed 1 mSv in a year, which is consistent with the criterion adopted in RP-65. The draft version of the IAEA BSS also gives exemption values that apply to radioactive material in a moderate amount (quantities at the most of the order of a tonne) based on values in the published BSS (IAEA, 1996) and a bulk amount for radionuclides of artificial origin based on values given in IAEA, 2004. The draft version also states that for radionuclides of natural origin, exemption of bulk amounts of material is necessarily considered on a case by case basis by using a dose criterion of the order of 1 mSv in a year, commensurate with typical natural background levels. Notwithstanding the changes in the dosimetric criteria for exemption exempt activity concentrations and activities given in the IAEA (BSS) (IAEA, 1996) have been retained in the revised version of the IAEA BSS (IAEA, 2010). Table 1 gives exemption values recommended by the IAEA BSS (IAEA, 1996) for the radionuclides included in this study.

Doses calculated in the present study were compared against the dosimetric criteria given in RP-65 and the IAEA BSS (IAEA, 1996) since current regulations are based on such criterion. The individual dose criterion of 10 μSv $y^{-1}$ is more restrictive than other criteria proposed in the draft IAEA BSS for some radionuclides of natural origin. Therefore, an assessment which demonstrates compliance with such criterion would also satisfy other criteria that may come into force.

**Table 1. Exemption values for radionuclides contained in lamps***

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

Note

*: Taken from IAEA Basic Safety Standards, 1996

# 3 TYPES OF LAMPS CONTAINING RADIOACTIVITY

Lamps that contain low levels of radioactivity 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, used as a starting aid for fluorescent tubes and compact fluorescent lamps. All these lamps are used predominantly in professional lighting, ie, in shops, cinemas and theatres. Figure 1 shows the different types of lamps commonly available in Europe and those containing low levels of radioactive material. Some of the heavier lamps, such as xenon lamps, are too large to be processed by the machinery in the lamp recycling facilities. They are dealt with by specialist companies and were not considered further in this study.

Tritium ($^{3}H$) is present in the glow-switches used in the older fluorescent lamp systems with a copper iron ballast, either mounted into a plastic canister as used in fluorescent tube systems, or as a unit permanently mounted in the base of a compact fluorescent lamp with two pins. Tritium is applied as elemental gas and is contained in a soft glass canister with walls at least 1 mm thick.

Krypton gas containing $^{85}Kr$ is used as a starting aid in HID and electrodeless induction lamps and is generally mixed with argon and/or neon. This 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. The induction lamps containing $^{85}Kr$ are only sold in very small quantities and therefore were not considered in this study. $^{85}Kr$ is also used in the glow-switches of older fluorescent lamp systems, either mounted into a plastic canister as used in fluorescent tube systems, or as a unit permanently mounted in the base of a compact fluorescent lamp with two pins.

Although tritium- and krypton-based starters are being phased out in the European Union in favour of products free of radionuclides, current annual global production is of the order of 1 billion of the separate canisters and 100 million of the compact fluorescent lamps containing integral tritium-based starters. The starter canisters are

rarely seen in the recycling plants and are presumed to go straight to incineration and/or disposal.

Naturally occurring thorium containing $^{232}$Th and $^{228}$Th is used as $ThO_2$ in the electrodes of HID lamps 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 to improve the lamp's spectral characteristics; it migrates over the lamp's life into the tip of the tungsten electrode (ELC, 2011). The lamps are manufactured with chemically separated thorium. This means that the progeny associated with $^{232}$Th and $^{228}$Th are initially not present. Over a lamp's lifetime, which if conservatively assumed to be 15 years (US Nuclear Regulatory Commission, 2001) the activity of the progeny in the decay chain of $^{232}$Th will reach 75% of the activity of $^{232}$Th. However, for the purposes of this study, it was conservatively assumed that secular equilibrium was reached by the end of the lifetime of the lamp, when it is sent for recycling or disposal.

The large, heavy, high-pressure xenon lamps, which contain 1 kBq to 10 kBq of $^{232}$Th per lamp, are not processed by the recycling plants as they are difficult to crush and there are safety issues related to the high pressure in the tube; these lamps are sent to other specialized plants for further processing or go straight to landfill disposal. These lamps are typically used in cinemas and for ultraviolet curing and have not been considered in this study.

Different lamps contain varying amount of low levels of radioactive material. ELC have provided information on the range of activities in the different lamps and the average activity (ELC, 2011). For the purposes of this study the activity of radioactive material in the lamps assumed for the assessment is at the high end of the range to ensure that the doses were not underestimated. Table 2 gives these values and the average activities for comparison. It should be noted that these values overlap with some of the values used in the previous study (Harvey et al, 2010a) but not all of the same lamps types are covered. For example (Harvey et al, 2010a) considered different types of metal halide lamps and did not include starters with glow switches for first generation fluorescent tube systems. Table 3 reproduces the list of types of lamps considered in (Harvey et al, 2010a).

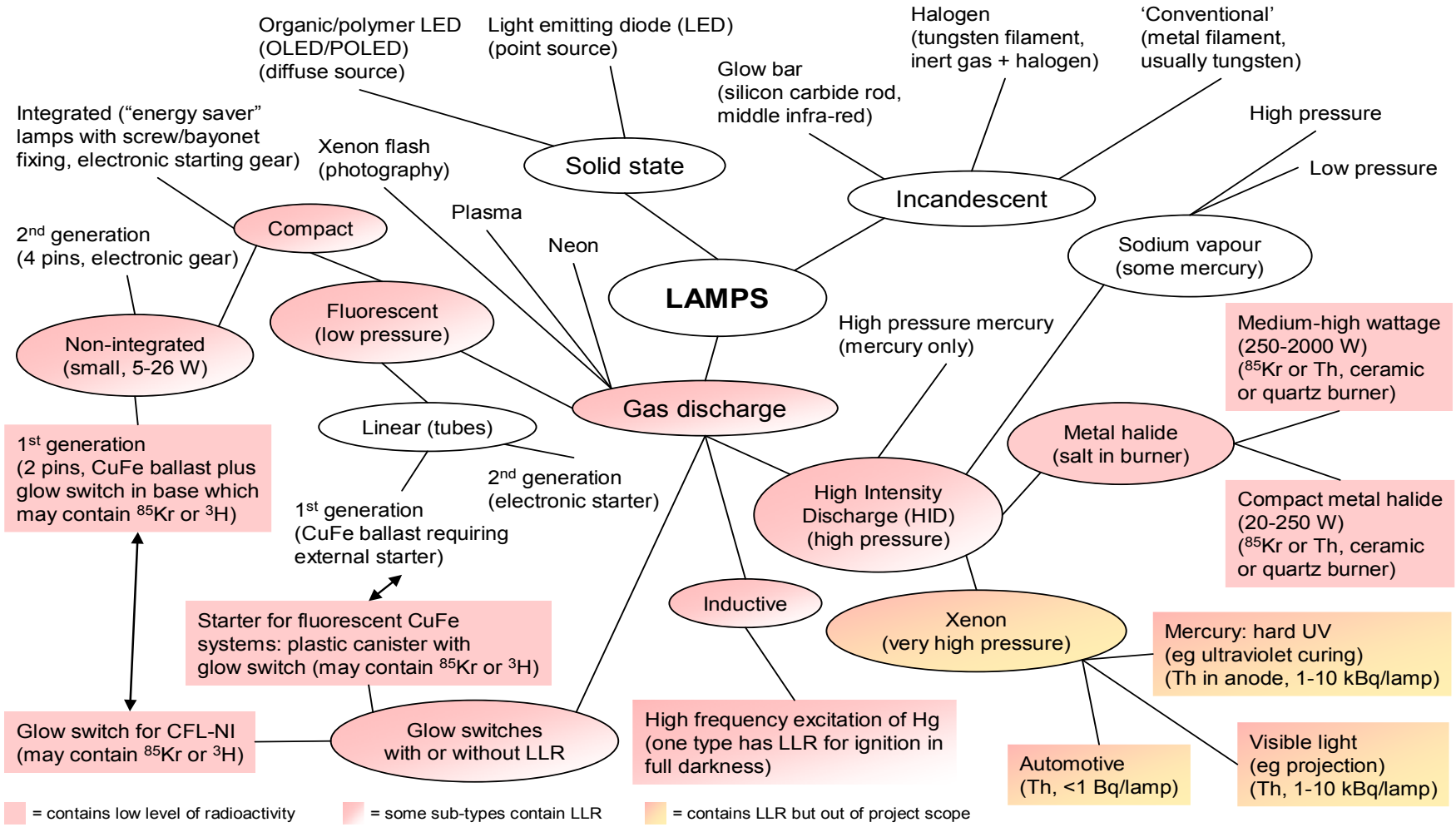


**Figure 1 Different types of lamps commonly used in Europe and those containing low levels of radioactive material**

**Table 2. Types of lamps considered in the assessment***

| Lamp type and description | Radionuclide | Assumed activity in lamp for purposes of this study (Bq) | Average activity in lamp (Bq) |
|---|---|---|---|
| Starter with glow switches for first generation fluorescent tube systems | $^{3}$H (gas) | 1 $10^{3}$ | 250 Bq |
| Glow switches for first generation non-integrated compact fluorescent lamp (with 2 pins) | | 1 $10^{3}$ | 160 Bq |
| Starter with glow switches for first generation fluorescent tube systems | $^{85}$Kr (gas) | 2 $10^{3}$ | 500 Bq |
| Glow switches for first generation non-integrated compact fluorescent lamp (with 2 pins) | | 2 $10^{2}$ | 150 Bq |
| Metal halide (will assume that material present in all three forms) | $^{85}$Kr (gas) | 2 $10^{3}$ | 500 Bq |
| | $^{232}$Th (solid as $ThO_2$) | 1 $10^{2}$ | 5 Bq ( for $ThO_2$ and $ThI_4$) |
| | $^{232}$Th (solid as $ThI_4$) | 1 $10^{0}$ | |

Note

*: The activity in the lamps assumed for the purposes of this study is intended to represent 'higher-than-typical' values. This is to ensure that the doses are not underestimated. Information supplied by ELC, 2011.

**Table 3. Types of lamps considered in (Harvey et al, 2010a)**

| 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 $10^{1}$ |

# 4 END OF LIFE ROUTES OF DISPOSAL

## 4.1 Collection

Within the definitions used to assess waste given in the European Waste Catalogue (European Commission, 2000), fluorescent tubes, sodium and mercury lamps are classed as Hazardous Waste. These lamps cannot be disposed of in general waste and their disposal must be properly documented. In addition, all of the lamps containing low levels of radionuclides fall under the Waste Electrical and Electronic Equipment Directive, known as the WEEE Directive 2002/96/EC (European Commission, 2003), which requires that manufacturers provide for the end of life recycling of the following lamp types:

- All fluorescent tubes (both linear and other shapes)
- All compact fluorescent lamps
- High intensity discharge lamps (mercury, sodium & metal halide)

Collection rates for recycling vary by country and the sector using the lamps. Information provided by ELC (ELC, 2011) indicates that recycling rates for large industrial and individual users are considerably higher than those for small and medium sized users. For the purposes of this study it was assumed that 40% of the lamps which fall under the WEEE Directive are collected. Lamps that are not collected are assumed to be disposed of to landfill or incinerated.

Prior to being received at recycling plants the lamps are amassed at collection points. The study did not consider the doses that may be received by personnel at these collection points. However, given that these workers will only come into contact with a fraction of the lamps compared to recycling workers, it would be expected that their doses would be significantly lower than those received by recycling workers.

## 4.2 Recycling process

Figure 2 gives an overview of the recycling and disposal routes for lamps which fall under the WEEE Directive. Metal components from lamps were assumed to go to foundries and plastic components to incinerators. The diagram in Figure 3 provides a more detailed overview of the recycling process of lamps. It shows how the radioactive content of the lamp moves through the recycling process and the possible exposure pathways for recycling workers. The lamps are manually sorted into lamp types, although some of this will have occurred before arrival at the lamp recycling plants. Lamps are then manually loaded into a crusher. The crushing process is done under negative pressure to ensure that any gases and powder in the lamps is extracted. The solid lamps components, ie, glass, metals and plastics are automatically sorted into different containers awaiting transportation elsewhere.

The starters with glow switches for first generation linear fluorescent lamp systems contain $^{3}H$ or $^{85}Kr$. However, information from ELC (ELC, 2011) and several plants that

recycle lamps indicates that these starters are not sent to the lamp recycling plants. For this study it was assumed that the starters were either sent to an incinerator plant or to a landfill site.

In terms of the radionuclides considered the following assumptions were made:

- $^{3}H$ – Most of the $^{3}H$ in the glow switches of the first generation non-integrated compact fluorescent lamp (CFL-NI) is released during the crushing of the lamps but some glow switches may not be crushed and the $^{3}H$ will remain in the switch. Therefore, two assessments were done: in the first, all the H-3 was assumed to be released during the crushing process; in the second, all the H-3 was assumed to remain in the glow switch and to go with the switches to the incineration plant.
- $^{85}Kr$ – Krypton-85 is released during the crushing process of the metal halide lamps. As for $^{3}H$, two assessments of the release of $^{85}Kr$ were done.
- Thorium radioisotopes – $ThO_2$ is incorporated into a tungsten matrix in the electrodes. Information provided by ELC (ELC, 2011) indicates that thorium remains with the tungsten matrix during the recycling process. Therefore, it was assumed that it stays with the metal components and goes to the foundry. A few of the lamps contain $ThI_4$. Information from ELC indicates that most of this thorium will migrate to the electrode tip during usage and therefore it was assumed that all of the thorium remains with the electrode (ELC, 2011).

For this study it was assumed that the recycling plant processes 10 000 tonnes of lamps per year. This is typical of larger recycling plants (ELC, 2011). Information provided indicates that this amounts corresponds to 5000 lamps in a tonne (ELC, 2011), ie, 50 million lamps being processed each year. Table 4 gives the number of lamps of different types assumed to go through a recycling plant. The bulk of lamps which are processed are linear fluorescent tubes. Information for 2009 provided by ELC (ELC, 2011) indicates that it is reasonable to assume that the lamps being sent for recycling break down into the following categories:

- Linear fluorescent tubes – 77%. The tubes do not contain any radioactive material. Some of the starters for first generation systems, which are not processed by recycling plants, do contain $^{3}H$ or $^{85}Kr$.
- Compact fluorescent lamps – 17%. These are discussed further below.
- Sodium Discharge Lamps – 3%. These do not contain any radioactive material and are included here for information.
- Metal halide lamps – 3%. These all contain either $^{85}Kr$ and/or $^{232}Th$.

As far as the compact fluorescent lamps are concerned it was assumed that the number of first generation lamps at recycling plants, which can contain glow switches containing low levels of radioactivity, is the same as the number of second generation lamps, which use electronic starters and contain no radioactivity (ELC, 2011). Only first generation lamps contain low levels of $^{3}H$ or $^{85}Kr$ and of these only half contain low levels of

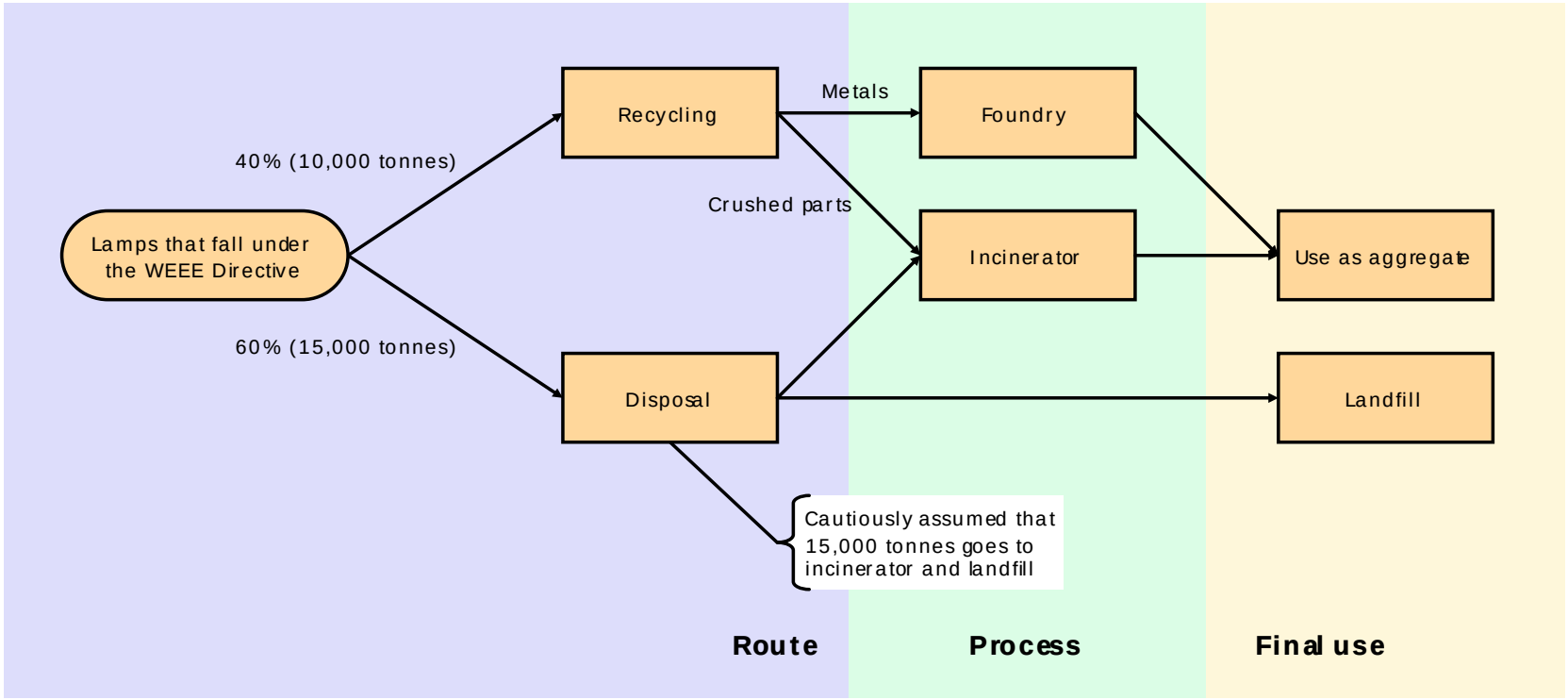


**Figure 2 Diagram showing the possible recycling and disposal routes following the end of life of lamps**

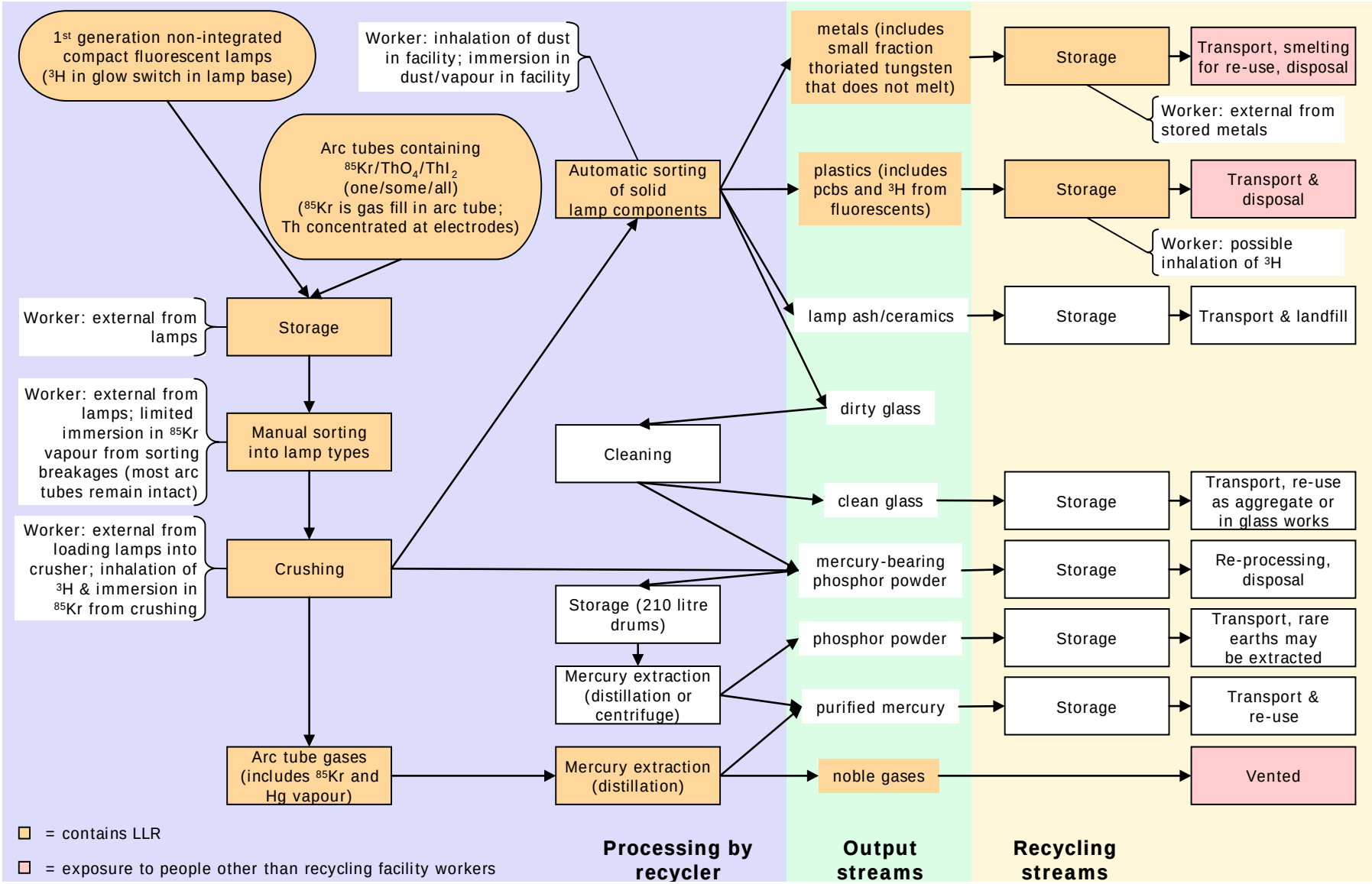


**Figure 3 Diagram showing the recycling process**

radioactive material since these products have not been made with radioactive material for several years. It was therefore assumed that 50% of these lamps contain $^{3}H$ and the other 50% contain $^{85}Kr$ (ELC, 2011). In terms of the total volume of compact fluorescent lamps processed at lamp recycling plants, 12.5% contain $^{3}H$ and 12.5% contain $^{85}Kr$. Therefore, the percentage of lamps which are compact fluorescent lamps containing $^{3}H$ of the total number of lamps is about 2%. This percentage also applies to compact fluorescent lamps containing $^{85}Kr$.

**Table 4. Number of lamps assumed to go through a recycling plant**

| Lamp type and description | Radionuclide | Fraction of lamps going through recycling plant (%) | Lamps going through 'typical' recycling process in a year | |
|---|---|---|---|---|
| | | | Tonnes | Number |
| Linear fluorescent tubes – these do not contain any radioactive material but they are important in the assessment because they are the most numerous type of lamp and therefore dilute the volumes of lamps containing low levels of radioactivity | **Do not contain any radioactive material** | 77 | 7700 | 39 million |
| Starter with glow switches for first generation linear fluorescent tube | $^{3}H$ (gas) | Not going through recycling process but assumed that 5 million starters disposed of to incinerator or landfill site annually | | |
| | $^{85}Kr$ (gas) | Not going through recycling process but assumed that 5 million starters disposed of to incinerator or landfill site annually | | |
| Glow switches in first generation non-integrated compact fluorescent lamp | $^{3}H$ (gas) | 2 | 200 | 1 million |
| | $^{85}Kr$ (gas) | 2 | 200 | 1 million |
| Metal halide (will assume that material present in all three forms) | $^{85}Kr$ (gas) | 3 | 300 | 1.5 million |
| | $^{232}Th$ (solid as $ThO_2$ ) | | | |
| | $^{232}Th$ (solid as $ThI_4$) | | | |

### 4.2.1 Melting of metals containing thorium radioisotopes

Information from ELC (ELC, 2011) and several lamp recycling plants indicates that recovered metals go to foundries. Figure 4 shows a diagram of the processing of metals containing radioisotopes of thorium. The thorium sent to metal melting facilities was assumed to be incorporated into a tungsten matrix. Given tungsten's high melting point (3377 °C) relative to the running temperature of foundries (aluminium has a melting point of 660 °C) (Tennant, 1971), it was assumed that the tungsten matrix, goes into the slag and that the slag is used as aggregate for concrete. During the melting process the mass of the slag is reduced. This procedure has the effect of concentrating

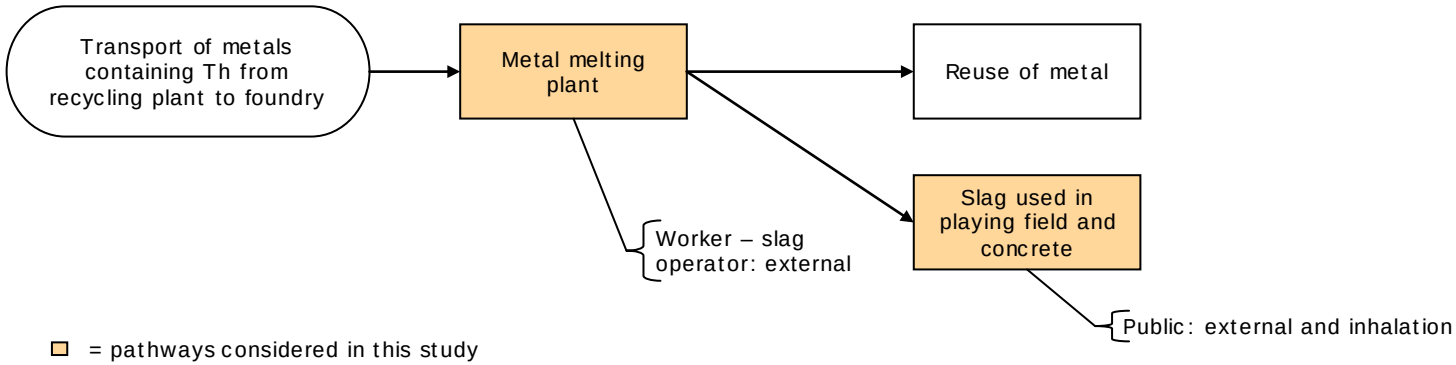


**Figure 4 Diagram showing the metal melting process of lamps containing thorium**

the radioactivity in the slag. A mass reduction factor is used to represent the ratio of the mass of material processed to the mass of the post-refining by-products. For aluminium melting the reduction factor was assumed to be 4.4 (Mobbs and Harvey, 1998).

The total amount of metal produced from each lamp recycling facility each year was assumed to be about 350 tonnes given that the facility recycles 10,000 tonnes of lamps per year. This estimate was based on Rabah, 2004 which gives information about the amount of metal in fluorescent lamps. At the metal recycling facility it was assumed that the metal from the lamps is mixed with a further 9650 tonnes of metal which contains no low levels of radioactivity based on the assumption that the metal recycling facility has a total annual capacity of 10,000 tonnes. This is a cautious assumption based on the throughput of a small facility given in previous work on the recycling of metals (Harvey et al, 1998). In reality it is likely that the fraction of metal containing no radioactivity would be much higher.

### 4.2.2 Incineration of crushed lamp parts containing $^{3}H$ and $^{85}Kr$

Figure 5 shows the process of incineration of crushed lamp parts containing $^{3}H$ and $^{85}Kr$. During the incineration process it was assumed that all of the $^{3}H$ and $^{85}Kr$ was released via the stack.

## 4.3 Disposal

Two disposal routes were considered for the general waste including lamps and starters: firstly, the whole waste inventory being sent to a landfill site; and secondly, the whole waste inventory being sent to an incinerator. The contents of the waste inventory are discussed below. Figure 6 shows the process of incinerating lamps which have been put into general waste. During incineration it was assumed that all of the $^{3}H$ and $^{85}Kr$ was released via the stack and any thorium radioisotopes remained in the bottom ash. It was assumed that the bottom ash was used as aggregate. For landfill all of the radionuclides ($^{3}H$, $^{85}Kr$ and $^{232}Th$) were considered to be disposed of.

### 4.3.1 Waste inventory

It was assumed that 15,000 tonnes of lamps per year were put into general waste. In addition starters with glow switches for linear fluorescent tubes are not being sent to recycling plants and were assumed to be disposed of into general waste.

Starters are not replaced as frequently as fluorescent tubes; therefore, it was assumed that the number of starters disposed of in a year is half of the number of lamps. Only starters for the first generation linear fluorescent systems were historically manufactured with low levels of $^{3}H$ or $^{85}Kr$; this is no longer the case and these starters have been made without radioactive material for several years. Despite the change in manufacturing process, many starters containing low levels of radioactive material are believed to be still in use and it has, therefore, been assumed that 50% of the starters disposed of to general waste contain $^{3}H$ or $^{85}Kr$. These are equally spilt between those containing $^{3}H$ and those containing $^{85}Kr$. For $^{3}H$ this amounts to 5 million from lamps

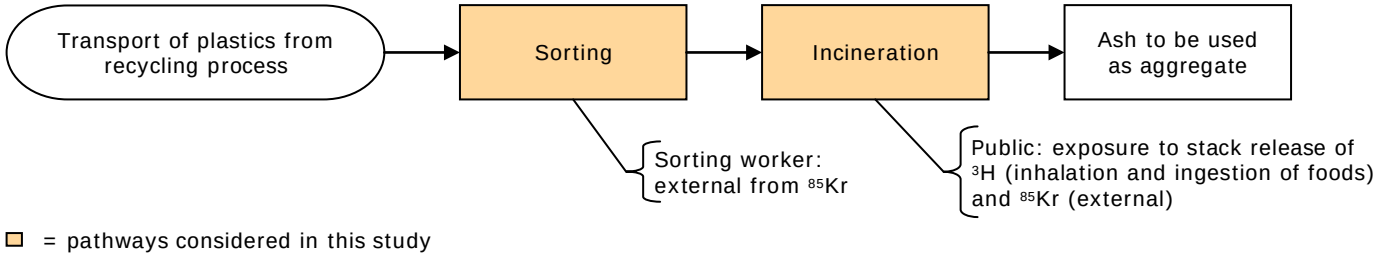


**Figure 5 Diagram showing incineration of plastics containing $^{3}H$ and $^{85}Kr$ from recycling process**

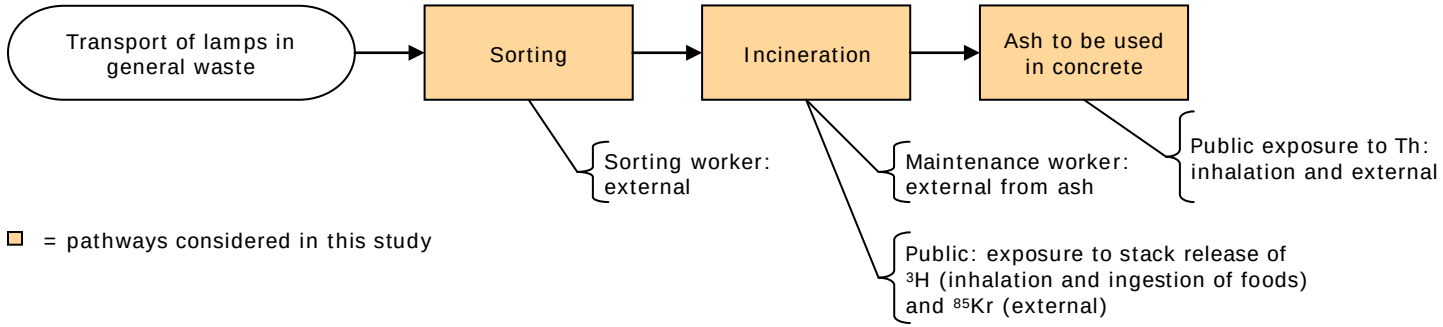


**Figure 6 Diagram showing incineration of lamps in general waste**

where the linear tubes have been sent to lamp recycling plants being disposed of annually to general waste. In addition 7 million linear fluorescent lamps along with their separate starters containing $^{3}H$ are assumed to be disposed of annually in general waste. These numbers also apply to starters containing $^{85}Kr$.

It was assumed that 15,000 tonnes of lamps per year were put into general waste. In addition starters with glow switches for linear fluorescent tubes are not being sent to recycling plants and were assumed to be sent to either an incinerator or a landfill site. Starters are not replaced as frequently as fluorescent tubes and therefore it was assumed that the number of starters disposed of in a year is half of the number of lamps. Only starters for the first generation linear fluorescent systems contain $^{3}H$ or $^{85}Kr$ and therefore it was assumed that only 50% of the starters contain low levels of radioactive material as these products have been made without radioactive materials for several years. These were equally spilt between those containing $^{3}H$ and those containing $^{85}Kr$. It was assumed that 5 million starters containing $^{3}H$ (from lamps where the linear tubes have been sent to lamp recycling plants) are disposed of annually to an incinerator or a landfill site. In addition 7 million linear fluorescent lamps along with their separate starters containing $^{3}H$, were assumed to be disposed of annually in general waste, which is also sent to an incinerator or a landfill site. These numbers also apply to the number of starters containing $^{85}Kr$.

# 5 METHODOLOGY FOR ASSESSMENT OF DOSES

## 5.1 Basic information on radionuclides used in lamps

Tritium, $^{85}Kr$ and the radioisotopes of thorium have different physical and radioactive properties. The following section gives a brief description of the properties of the different radionuclides used and their potential exposure routes. Table 5 summarises the exposure pathways. Appendix A gives additional information on radiological parameters.

**Table 5. Exposure pathways considered for radionuclides**

| Radionuclide | When contained in lamp | When released from lamp |
|---|---|---|
| $^{3}H$ | No significant exposure pathways | Inhalation<br>Ingestion in food<br>Absorption through skin |
| $^{85}Kr$ | External (gamma and bremsstrahlung) | External exposure in air |
| $^{232}Th$ | External exposure (gamma)* | Inhalation<br>External exposure |

Note

*: The contribution from bremsstrahlung was not considered for $^{232}Th$ decay chain as its relative contribution compared to the gamma emissions is low.

### 5.1.1 Tritium

Tritium, used in its gaseous form in lamps, emits weak beta radiation (average energy of 6 keV) which does not travel far in air and is not an external hazard. When contained within the glass tubing exposure is not significant. Potentially radiation doses can be received due to natural leakage of tritium but these are considered to be negligible. Following crushing of the lamps the exposure pathways of interest are inhalation of the gas, ingestion (gaseous tritium released to the environment quickly becomes tritiated water and can enter the body when people eat or drink food or water containing tritium) and absorption through the skin.

### 5.1.2 Krypton-85

Krypton-85 is an inert gas which emits beta radiation (average energy of 250 keV) and gamma radiation. When the $^{85}$Kr gas is in the lamp the beta radiation is attenuated by the glass. However bremsstrahlung radiation is produced when the beta radiation is slowed as it passes through the glass. The contribution of bremsstrahlung to radiation dose is discussed in more detail in (Harvey et al, 2010a) but is assumed to be 70% of the dose from gamma radiation. When the lamps are crushed and the $^{85}$Kr gas is released the exposure pathway of interest is external exposure in air. Since $^{85}$Kr is inert it does not react with biological systems and therefore it is not taken up by the body when inhaled and does not enter the food chain.

### 5.1.3 Thorium-232 and its decay chain

Thorium-232 and $^{228}$Th are naturally occurring radioactive materials. Thorium-232 is also head of a radioactive decay chain called the natural thorium decay series (see Figure A1). Many radioactive elements, including $^{232}$Th, do not decay directly to a stable state, but rather undergo a series of decays until eventually a stable isotope is reached. The first radionuclide is termed the chain header or “parent” radionuclide and this is followed by a series of “progeny” radionuclides all of which radioactively decay until a stable isotope is reached. For the manufacture of lamps thorium ($^{232}$Th and $^{228}$Th) is purified from its progeny by chemical separation. After separation, the amount of radiation (produced by the progeny) is considerably reduced for several years. However the $^{232}$Th will continue to decay and after 15 years the activity of the progeny will reach up to 75% of its parent, $^{232}$Th. Thorium-232 and its progeny emit alpha, beta and gamma radiation so external exposure and inhalation pathways were considered. Almost all of the thorium in lamps will be incorporated into the tungsten matrix so will not be available for inhalation. However, for completeness a few inhalation pathways were considered. It should be noted that thorium is present naturally in the environment, for example it is found in the soil, foodstuffs and building materials. The average activity concentration of the $^{232}$Th decay chain in the soil of the UK for is 0.025 Bq g$^{-1}$ (UNSCEAR, 1977). Natural radionuclides in rocks and clays, including $^{232}$Th, become incorporated into building materials. Typical activity concentrations of $^{232}$Th in building materials range from 0.015 to 0.17 Bq g$^{-1}$(Cliff KD et al, 1984).

Throughout the report where reference is made to $^{232}$Th it means the $^{232}$Th decay chain which includes $^{228}$Th. For simplicity and to make sure that the doses are not

underestimated $^{232}$Th and its progeny were assumed to be in secular equilibrium in this assessment.

## 5.2 General assumptions

Doses were calculated for groups of workers during the normal operation of recycling, foundry and incineration facilities. Exposures to members of the public resulting from these operations were also considered. No accident scenarios were considered in this study, as the most likely accident scenarios are a fire or breakage involving a large number of lamps and both these scenarios have already been considered in (Harvey et al, 2010a). Exposed groups and exposure pathways are summarised in Table 6. (Harvey et al, 2010a) estimated the doses from the disposal of lamps to landfill for a number of groups and pathways, given in Table 7, for a nominal activity concentration of 1 Bq g$^{-1}$. This study considers the same pathways but uses an estimate of the activity concentration disposed which is given in Table 8.

The general equation used in the study for the calculation of doses from external exposure (Sv y$^{-1}$) is:

$$D_{ext} = C T_{exp} DR \quad (1)$$

C is the activity concentration (Bq g$^{-1}$). $T_{exp}$ is the exposure time in a year (h y$^{-1}$) and DR is the effective dose rate per unit activity (Sv h$^{-1}$ per Bq g$^{-1}$). Unit effective dose rates from gamma radiation were calculated using Microshield v7.02 (Negin, 1986), with posterior/anterior geometry. These values are given in Table A2. As discussed in Section 5.1.2 the contribution from bremsstrahlung radiation to the dose rates for external exposure for lamps containing $^{85}$Kr was taken to be 0.7 that from gamma radiation.

The general equation for doses from external exposure from radionuclides in the air (Sv y$^{-1}$) is:

$$D_{ext,cloud} = C_{air}\ T_{exp}\ DR_{cloud} \quad (2)$$

$C_{air}$ is the activity concentration in the air (Bq m$^{-3}$). $DR_{cloud}$ 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$^{-3}$) (Eckerman and Ryman, 1993).

The general equation for doses from inhalation (Sv y$^{-1}$) is:

$$D_{inh} = C_{air}\ T_{exp}\ R_{inh}\ DC_{inh} \quad (3)$$

$R_{inh}$ is the inhalation rate (m$^3$ h$^{-1}$) assumed to be (1.2 m$^3$ h$^{-1}$) (Smith and Jones, 2003) and $DC_{inh}$ is the dose coefficient for inhalation for adult members of the public (Sv Bq$^{-1}$) (ICRP, 1996).

**Table 6. Exposure pathways by exposed group for recycling, metal melting and incineration processes**

| Exposed group | Activity | Exposure pathways |
|---|---|---|
| Recycling worker | Storage before processing | External exposure |
| | Manual sorting before processing | External exposure |
| | | External from immersion in $^{85}$Kr vapour from broken lamps |
| | Loading lamps into crusher | External exposure |
| | | Inhalation and skin absorption of $^{3}$H |
| | | External from immersion in $^{85}$Kr vapour |
| | Sorting after crushing | Inhalation and external exposure from $^{232}$Th dust |
| | Storage of metals | External exposure |
| Incinerator worker | Sorting waste | External exposure |
| | Maintenance work | External exposure |
| Foundry worker | Processing slag | External exposure |
| Member of the public | Living or consuming food grown nearby to recycling plant or incinerator | Inhalation and skin absorption of $^{3}$H |
| | | External from immersion in $^{85}$Kr vapour |
| | | Ingestion terrestrial food with $^{3}$H |
| | Playing on field made from slag aggregate | External exposure |
| | | Inhalation |
| | Living in building made from slag or incinerator ash aggregate | External exposure |

**Table 7. Exposure pathways by exposed group for disposal to landfill**

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

Activity concentrations in materials at different stages of processing and disposal were derived for this study and are given Table 8. The activity concentrations were calculated by assuming that the radioactive material was evenly spread throughout the material considered. Table 9 gives the exposure times assumed in the assessment and Table 10 summarises other general parameters used.

**Table 8. Assumed activity concentrations based on annual activities and masses being processed (Bq $g^{-1}$)**

| Scenario | Radionuclide | Activity (Bq) | Mass (g) | Activity concentration (Bq $g^{-1}$) |
|---|---|---|---|---|
| Lamps | $^{3}H$ | $1.0\ 10^{9}$ | $1.0\ 10^{10}$ | 0.1 |
| | $^{85}Kr$ | $3.2\ 10^{9}$ | | 0.3 |
| | $^{232}Th$ | $1.5\ 10^{8}$ | | 0.02 |
| Metals for recycling | $^{232}Th$ | $1.5\ 10^{8}$ | $3.5\ 10^{8}$ | 0.4 |
| Slag from metal recycling | $^{232}Th$ | | | 0.07 |
| Playing field containing slag | | | | 0.007 |
| Concrete containing slag | $^{232}Th$ | | | 0.009 |
| General waste at incinerator (which contains lamps) | $^{3}H$ | $1.4\ 10^{10}$ | $1.4\ 10^{11}$ | 0.1 |
| | $^{85}Kr$ | $2.9\ 10^{10}$ | | 0.2 |
| | $^{232}Th$ | $2.3\ 10^{8}$ | | 0.002 |
| Crushed plastics from recycling plant at incinerator | $^{3}H$ | $1.1\ 10^{9}$ | $1.4\ 10^{11}$ | 0.008 |
| | $^{85}Kr$ | $2.1\ 10^{8}$ | | 0.002 |
| Ash from Incinerator | $^{232}Th$ | | | 0.006 |
| Concrete containing ash | $^{232}Th$ | | | $8\ 10^{-4}$ |
| General waste in landfill (which contains lamps) | $^{3}H$ | $1.4\ 10^{10}$ | $1.5\ 10^{11}$ | 0.09 |
| | $^{85}Kr$ | $2.9\ 10^{10}$ | | 0.2 |
| | $^{232}Th$ | $2.3\ 10^{8}$ | | 0.002 |

**Table 9. Exposure times assumed in the assessment***

| Activity | Exposure time (h $y^{-1}$) |
|---|---|
| Standing next to lamps at recycling plant before sorting | 100 |
| Sorting lamps at recycling plant | 1000 |
| Crushing lamps at recycling plant | |
| Handling lamps during sorting/crushing | 10 seconds per lamp |
| Immersion in $^{85}Kr$ gas cloud on breakage | 1 minute per lamp |
| Sorting components after crushing | 20 |
| Standing next to skip containing metal components at recycling plant | 100 |
| Standing next to slag at metal reprocessing plant | 250 |
| Playing on field containing slag | 300 |
| Living in building made of concrete containing slag | 2600 |
| Sorting general waste at an incinerator | 1000 |
| Doing incinerator maintenance | 100 |
| Indoor occupancy of member of public | 7884 |

Note

*: The exposure times assumed are discussed in more detail in the text of the report

**Table 10. General parameters used in the assessment***

| Activity | Parameter |
|---|---|
| Inhalation rate (adult worker and active member of public) | 1.20 $m^3$ $h^{-1}$ |
| Inhalation rate (landfill worker) | 1.69 $m^3$ $h^{-1}$ |
| Inhalation rate (sedentary adult member of public) | 0.92 $m^3$ $h^{-1}$ |
| Volume of recycling plant | 3000 $m^3$ |
| Volume of cloud on release from broken lamp | 1 $m^3$ |
| Turnover rate of air in recycling plant | 4 $h^{-1}$ |
| % of time extraction pumps not working | 1 |
| % of lamps broken during sorting process | 1 |
| Fraction of thorium available for release after crushing | 0.1 |
| Respirable fraction of thorium dust | 2 $10^{-3}$ |
| Location factor | 0.2 |
| Mass reduction factor for slag | 4.4 |
| Mass reduction factor for incinerator ash | 4 |
| Radionuclide dependent distribution factor for thorium | 1 |
| Fraction of playing field which is slag | 0.1 |
| Fraction of aggregate which is slag | 0.5 |
| Dilution of aggregate in concrete mix | 0.255 |

Note

*: The parameters used are discussed in more detail in the text of the report

## 5.3 Doses to workers during recycling process

The following sections describe the methodology used to calculate doses to workers during the lamp recycling process. The exposure pathways identified and many of the

parameters used are based on information obtaining during visits to the lamp recycling facilities or from ELC (ELC, 2011).

### 5.3.1 Storage and manual handling before processing

Two types of exposure were considered: from standing near stored lamps and whilst manually sorting the lamps. Whilst manually sorting the lamps it was assumed that 1% of the lamps were broken.

Doses were calculated to a worker standing near cages with lamps containing $^{85}$Kr and $^{232}$Th from external exposure from gamma radiation (Sv y$^{-1}$) using equation (1). It was assumed that the lamps were stored in a stack of 8 cages up to 4 high by 2 wide and 1 deep with the cages being 0.8 m high, 1.3 m deep and 1.3 m wide. Information provided by the recycling plants indicates that the contents of each cage weigh about 150 kg. As there are 5000 lamps per tonnes (see Section 4.2) each cage was assumed to contain 750 lamps. This value represents an average as the number of lamps varies depending on the type and quantity of the lamps. The activity concentration C (Bq g$^{-1}$) is the total activity in all the stored lamps and is given in Table 8. $T_{exp}$ is the time spent 1 m away from stored lamps. This was assumed to be 100 h y$^{-1}$. DR, the effective dose rate per unit activity concentration (Sv h$^{-1}$ per Bq g$^{-1}$) at 1 m assuming that the dimensions of the 8 cages given are as above and a bulk density of 0.1 g cm$^{-3}$. The contribution from bremsstrahlung was considered for $^{85}$Kr.

Doses from external exposure from gamma radiation from $^{85}$Kr and $^{232}$Th were summed from doses from standing near and handling lamps were calculated using the equation:

$$D_{ext} = D_{broken} + D_{unbroken} + D_{proximity} \quad (4)$$

The doses from external exposure to workers from handling broken lamps were calculated using the following equation.

$$D_{broken} = f_{broken} H_{skin} w_{skin} \frac{S_{contact}}{S_{body}} \quad (5)$$

$f_{broken}$ is the fraction of lamps broken and was assumed to be 0.01, ie, 1% of lamps handled were broken. $w_{skin}$ is the tissue weighting factor for skin (0.01) (ICRP, 2007). $S_{body}$ is the surface area of the body exposed to UV radiation (3 $10^3$ cm$^2$) (ICRP, 1991) and $S_{contact}$ is the area of hand in contact with lamp assumed to be the palm of a hand, ie, 100 cm$^2$ (National Radiological Protection Board, 1997). $H_{skin}$ is the equivalent dose to skin. Skin doses were only calculated for the handling of broken lamps. For unbroken lamps there will be considerable attenuation of the beta radiation by the glass and gamma radiation is not a significant contributor to skin doses. $H_{skin}$ (Sv y$^{-1}$) was calculated using the following equation:

$$H_{skin} = \frac{nA}{N_{sorting} S_{contact}} T_{sorting} \left( DR_{skin,\gamma(7)} + DR_{skin,\beta(40)} SF \right) \quad (6)$$

A is the activity in each lamp (Bq) taken from Table 2 and n is the number of lamps containing radioactive material being processed taken from Table 4. $N_{sorting}$ is the numbers of workers involved with sorting lamps which is assumed to be 4. $T_{sorting}$ is the time spent handling each lamp during the sorting process. Linear fluorescent lamps are typically amassed at collection points and therefore only the non-linear fluorescent lamps were considered to be sorted at the recycling plant. It was assumed that over a year there were 4 workers who spent a total of 4000 hours each sorting a total of 11.5 million non-linear fluorescent lamps. This amounts to $3.5\ 10^{-4}$ h, ie, about 1 second per lamp. $DR_{skin,\gamma(7)}$ is the equivalent gamma dose rate to basal layer of skin epidermis (7 mg $cm^{-2}$) (Sv $h^{-1}$ $Bq^{-1}$ $cm^2$) and is taken from (Chaptinel et al, 1988). $DR_{skin,\beta(40)}$ is the equivalent beta dose rate to basal layer of skin epidermis (40 mg $cm^{-2}$) (Sv $h^{-1}$ $Bq^{-1}$ $cm^2$) and is taken from (Cross et al, 1992)

The shielding factor for beta radiation provided by wearing gloves (IAEA, 1987) is calculated using the following equation:

$$SF = e^{-\mu d} \quad \mu = 0.017\left(E_{\beta,max}\right)^{-1.14} \tag{7}$$

$E_{\beta max}$ is the maximum beta energy taken from (Eckerman et al, 1993), d is the mass per unit area of clothing, given by the product of the thickness of the gloves and the density of gloves assumed to be 0.2 cm and 760 mg $cm^{-3}$, respectively.

The dose from handling unbroken lamps was estimated using the following equation.

$$D_{unbroken} = (1 - f_{broken})\, n\, A\, T_{handling}\, DR_{\gamma(30)} \tag{8}$$

$DR_{y(30)}$ is the effective dose rate per unit activity concentration (Sv $h^{-1}$ per Bq) and was calculated using Microshield v7.02 (Negin, 1986) assuming at distance of 30 cm from a point source.

The doses from external exposure from proximity to the lamps (Sv $y^{-1}$) were calculated using equation (1). It was assumed that the worker was standing next to a cage of lamps which contains 750 lamps. The activity concentration (Bq $g^{-1}$) is given in Table 8. $T_{exp}$ is number of hours spent in proximity to the lamps (1000 h $y^{-1}$). DR is the effective dose rate per unit activity at 1 m (Sv $h^{-1}$ per Bq $g^{-1}$).

#### *5.3.1.1 External exposure to $^{85}$Kr in air released by broken lamps*

It was assumed that the $^{85}$Kr gas was released from the arc tube in the metal halide lamp if broken during the sorting process and that a worker was exposed to external radiation from the gas before it dissipates. It was cautiously assumed that it formed a cloud around the worker for a short time (1 minute) before dissipating. It was assumed that only one tube was broken at one time and 1% of lamps were broken.

The doses from external exposure to $^{85}$Kr vapour (Sv $y^{-1}$) were calculated using equation (2). $T_{exp}$ is the time a worker was exposed to vapour released from a single broken lamp. This was assumed to be approximately one minute. $C_{air}$, the activity concentration of $^{85}$K in air (Bq $m^{-3}$) is calculated using the following equation.

$$C_{air} = \frac{N\,A}{V} \quad (9)$$

N is the number of $^{85}$Kr-containing metal halide lamps broken per year. This was assumed to be 15,000 per year (1% of 1.5 million recycled per year), which is equivalent to one lamp broken on average every 8 minutes for a 2000 h working year. A is the activity in a single lamp (Bq), taken from Table 2. V is the volume of the vapour which was assumed to be 1 m$^3$.

### 5.3.2 Crushing process

The crushing process is done under negative pressure to ensure that any gases and powder in the lamps are extracted. However, in order to make an assessment of the doses it was assumed that the extraction pumps were not working for 1% of the time and that during this time the worker inhaled $^3$H and was exposed to $^{85}$Kr in the air.

#### *5.3.2.1 External exposure from loading lamps into crusher*

Doses from external exposure from gamma radiation from $^{85}$Kr and $^{232}$Th whilst loading lamps into the crusher are given by equation (4). The parameters and equations are used are the same as in Section 5.3.1 except for $T_{crushing}$ which is equivalent to $T_{sorting}$. $T_{crushing}$ is the time spent handling each lamp during the crushing process. It was assumed that the linear fluorescent lamps were fed into the crusher in batches of 10 and that all other lamps were handled individually. Over a year 4 workers were assumed to spent a total of 4000 hours each feeding these lamps into the crusher which amounts to 2.6 $10^{-4}$ h, ie, about 1 second per lamp.

#### *5.3.2.2 Inhalation and skin absorption of $^3$H*

Although it is unlikely that any worker at the recycling plant would inhale tritium released from crushed lamps, since the crushing process is done under negative pressure, it was cautiously assumed that the tritium instantly expands on release to fill the small volume surrounding a worker. Calculations of the dose due to tritium were based on the method described in (Harvey et al, 2010a). The total dose is the sum of the dose from inhalation and absorption through the skin. 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, $R_{sedentary}$ of the individual exposed (ICRP, 1993; Osborne, 1966). The total dose (Sv y$^{-1}$) can therefore be written as:

$$D_{tritium} = D_{inh} + D_{abs} = D_{inh}\,F \quad (10)$$

Rearranging equation (10), given that $D_{inh}$ is proportional to the normal inhalation rate, $R_{inh}$, F can be calculated as:

$$F = 1 + 0.5\frac{R_{sedentary}}{R_{inh}} \quad (11)$$

Doses from inhalation were calculated using equation (3). $T_{exp}$ is the time a worker spent loading lamps into the crusher when the extractors were not working (1% of 1000 h, ie, 10 h). $R_{sedentary}$ is the inhalation rate for sedentary member of the public (0.92 $m^3$ $h^{-1}$) and $R_{inh}$ is the inhalation rate for an adult worker (1.2 $m^3$ $h^{-1}$) (Smith and Jones, 2003).

The activity concentration in the air, $C_{air}$, (Bq $m^{-3}$) was calculated using the following:

$$C_{air} = \frac{A_{rel}}{V_{plant}\, R_{turnover}} \quad (12)$$

$A_{rel}$ is the activity release rate (Bq $h^{-1}$) which is the product of the activity of $^3H$ in each lamp (Table 2) and the number of lamps containing $^3H$ crushed per hour, 500 lamps per hour. $V_{plant}$ is the volume of the recycling plant which was assumed to be 3000 $m^3$ and $R_{turnover}$ is the turnover rate of air in the recycling plant. This was assumed to be 4 $h^{-1}$ based on information supplied by the recycling plants visited.

#### *5.3.2.3 External exposure to $^{85}Kr$ released to air*

Doses were calculated from external exposure from $^{85}Kr$ in the air (Sv $y^{-1}$) due to the crushing process (this assumes that extraction system is not working 1% of the time) using Equation (2). The concentration of $^{85}Kr$ in the air (Bq $m^{-3}$) was calculated using Equation (12).

### 5.3.3 Sorting of components after crushing

The only exposures considered were those resulting from the small amount of thorium iodide salt that is used in a few lamps. Most of this salt migrates to the electrode during use of the lamp (ELC, 2011) but it was cautiously assumed that 10% did not and was released to the recycling plant environment. In reality, it is unlikely that this salt is loose since the salt solidified onto the glass when the arc is switched off and the temperature reduces. In addition, if any of the thorium iodide salt was loose it would be removed by the extraction system during crushing.

The doses from inhaling dust (Sv $y^{-1}$) in the recycling facility were calculated using equation (3). $T_{exp}$ was assumed to be 20 h $y^{-1}$ based on the pumps not extracting any loose powder during crushing for 1% of the working year (2000 h). The activity concentration in air (Bq $m^{-3}$) was calculated using the following equation:

$$C_{air} = \frac{A\, F_{res}\, F_{inh}\, N}{V_{plant}\, R_{turnover}} \quad (13)$$

A is the activity of thorium in the $ThI_4$ form per lamp (Bq) which is given in Table 2. $F_{inh}$ is the fraction of activity available for release which is assumed to be 0.1. $F_{res}$ is the respirable fraction (2 $10^{-3}$ (Defense Threat Reduction Agency, 2005)). N is the number of lamps containing $^{232}Th$ crushed per hour, 750 lamps per hour. $R_{turnover}$ is as given for equation (12).

The doses from external exposure to dust in the air (Sv $y^{-1}$) were calculated using equation (2). $T_{exp}$ was assumed to be 20 h $y^{-1}$ with the activity concentration in air (Bq $m^{-3}$) being calculated as given above.

### 5.3.4 Storage of metals before dispatch

Doses from external exposure from gamma radiation from metal containing low levels of $^{232}$Th were considered. The dose from the external exposure (Sv $y^{-1}$) was calculated using equation (1). C is the activity concentration in the scrapped metal which was estimated by dividing the total activity of thorium in the metal halide lamps recycled in a year by the amount of metal recycled annually. This was estimated to be 0.4 Bq $g^{-1}$ and is given in Table 8. $T_{exp}$ is the time spent at 1 m from the scrapped metal which was assumed to be 100 h $y^{-1}$. DR is the effective dose rate per unit activity concentration (Sv $h^{-1}$ per Bq $g^{-1}$) at 1 m; it was calculated assuming a skip is full of material with a bulk density of 1.5 g $cm^{-3}$. The skip was assumed to be 0.97 m by 1.83 m by 1.29 m (Top Skips, 2011). It was cautiously assumed that the skip provided no shielding.

## 5.4 Doses during and resulting from recycling of metal

The metal from the lamp recycling plant containing $^{232}$Th was assumed to be sent a foundry. The cautious assumption was made that the metal was melted in a small foundry with an annual throughput of 10,000 t $y^{-1}$. The thorium was then assumed to go to the slag which was then used for aggregate in a playing field or in building materials.

The activity concentration in the slag $C_{slag}$ (Bq $g^{-1}$) was calculated using the following equation.

$$C_{slag} = \frac{A_m C_m R_{slag}}{M} \quad (14)$$

$A_m$ is the activity of $^{232}$Th (Bq) in recovered metals processed by the lamp recycling facility annually. The value is given in Table 8. $C_m$ is the mass reduction factor in slag (4.4) (Mobbs and Harvey, 1998). $R_{slag}$ is the radionuclide dependent distribution factor for slag during melting which is 1 for thorium (Mobbs and Harvey, 1998). This parameter represents the fraction of the activity in the ingots, the slag or the dust after refining compared to that originally present in the metals before processing. M is the total mass of metal assumed to be processed by the foundry (10,000 tonnes $y^{-1}$) (Harvey et al, 1998).

### 5.4.1 Foundry worker exposed to radioactivity in the slag

It was assumed that a worker in a foundry was exposed while working close to a large pile of slag. The dose to a worker from external exposure from $^{232}$Th (Sv $y^{-1}$) in the slag was calculated using equation (1). $T_{exp}$ is the exposure time for a slag worker in a year (250 h $y^{-1}$) (Harvey et al, 1998)). DR is the unit effective gamma dose rate (Sv $h^{-1}$ per Bq $g^{-1}$) at 1.5 m from external irradiation from a 100 tonne pile of slag of density

1.9 t $m^{-3}$ (Emery, 1982) assuming a rectangular volume of sides 5 m long x 3 m wide x 2.5 m high.

### 5.4.2 Member of public using a playing field built with slag

A member of the public was assumed to use a playing field containing contaminated slag. The pathways considered were external exposure and inhalation of dust. The fraction of the material used that is contaminated slag was assumed to be 10% (Harvey et al, 1998).

The dose from external exposure from $^{232}$Th (Sv $y^{-1}$) in the slag was calculated using equation (1). It was assumed that the concentration of slag in the playing field was 10% of $C_{slag}$ (Bq $g^{-1}$) given in equation (14). $T_{exp}$ is the exposure time for a member of public on a playing field in a year (h $y^{-1}$) (300 h $y^{-1}$) (Harvey et al, 1998). DR is the unit effective dose rate (Sv $h^{-1}$ per Bq $g^{-1}$) at 1 m from external irradiation from an infinite slab source, 0.5 m thickness, density 1.9 t $m^{-3}$ (Emery, 1982). This is similar to the density of compacted soil.

In order to make an estimate of doses from inhalation it was assumed that the tungsten metal containing the thorium in the slag has changed to a form which is respirable. It was assumed that 1% of the thorium was respirable.

The dose from inhalation exposure from a playing field made from material containing the slag (Sv $y^{-1}$) was estimated using equation (3). The activity concentration in air was calculated using the following equation.

$$C_{air} = C_{slag}\, f_{pf}\, DL \qquad (15)$$

$C_{slag}$ is the activity concentration in the slag (Bq $g^{-1}$); $f_{pf}$ is the fraction of slag in the playing field (0.1) (Harvey et al, 1998). DL is the dust loading of thorium, $10^{-5}$ g $m^{-3}$. This value was based on the dust loading of 1 $10^{-3}$ g $m^{-3}$ (Mobbs and Harvey, 1998) and takes account that only 1% of the thorium was respirable.

### 5.4.3 Member of public exposed to a building made from concrete containing slag

A member of the public was assumed to be externally exposed to $^{232}$Th due to residing in a concrete building made using the slag as an aggregate. It was assumed that the aggregate used in the concrete was made of 50% slag from the recycling process and 50% from other material. The aggregate was additionally diluted in the concrete mixing process. The dilution factor of 0.255 (Harvey et al, 1998) was used in the calculation.

The dose from external exposure from $^{232}$Th (Sv $y^{-1}$) in the slag was calculated using equation (1). The activity concentration in the concrete was the activity concentration in the slag (Bq $g^{-1}$) multiplied by the fraction of concrete that contains slag, ie, 0.5 x 0.255 = 0.13. The exposure time, $T_{exp}$, used (2600 h $y^{-1}$) was taken from (Mobbs and Harvey, 1998). $DR_{concrete}$ is the unit effective dose rate at 1 m from external irradiation from a thick disk of 3.8 m diameter and 10 cm thick, density 2.4 t $m^{-3}$ (Sv $h^{-1}$ per Bq $g^{-1}$), (Mobbs and Harvey, 1998).

## 5.5 Doses from incineration of waste

Two types of waste at the incineration plant were considered: 1) general waste and 2) plastic waste from the lamp recycling plants. Table 8 shows that the activity concentrations in the general waste were over 10 and 100 times higher than in plastics from the recycling plant for $^{3}H$ and $^{85}Kr$ respectively. In addition lamps containing thorium radioisotopes were assumed to be disposed of to general waste but no thorium was expected to be found in plastics from the recycling plant.

Section 4.3 discusses the assumptions related to the disposal of lamps in general waste. It was assumed that 15,000 tonnes of lamps per year were put into general waste and incinerated. In addition 10 million starters containing $^{3}H$ and $^{85}Kr$ (from linear fluorescent tubes which have been sent to lamp recycling facilities) were also assumed to be incinerated. The activity concentrations used in this study to assess the doses are summarised in Table 8. For completeness the dose to a worker sorting crushed lamp parts from the lamp recycling plant was also assessed to demonstrate that the doses from this inventory would be much lower. The doses to the other exposure groups from crushed lamp parts were not calculated since they will be lower than those from lamps in general waste.

### 5.5.1 Worker sorting general waste at an incinerator

Doses were assessed due to external exposure of workers to $^{85}Kr$ and $^{232}Th$ in the lamps disposed of to general waste and sent to an incinerator. It was assumed that the lamps were still intact. It was assumed that exposure occurred at 1 m from a sorting stockpile or conveyor, represented by a 1 $m^3$ cylinder with no shielding.

The dose from external exposure to the sorting worker (Sv $y^{-1}$) from $^{85}Kr$ and $^{232}Th$ was calculated using equation (1). The activity concentration of the lamps in general waste C (Bq $g^{-1}$) being sorted annually at the incineration plant is given in Table 8 and was calculated using the following equation.

$$C = \frac{A_{incin}}{M_{incin}} \qquad (16)$$

$A_{incin}$ is the activity of lamps being sorted for incineration in a year. This includes $^{3}H$ and $^{85}Kr$ from the fluorescent tube starters and $^{85}Kr$ and $^{232}Th$ for the metal halide lamps. $M_{incin}$ is the total mass of the incinerator waste (140,000 t $y^{-1}$) (Harvey et al, 1995).

$T_{exp}$ is the time for a worker spends in a year sorting waste at the incinerator (1000 h $y^{-1}$). DR is the unit effective at 1 m from external irradiation from a 1 $m^3$ load of given lamp types mixed with domestic waste (Sv $h^{-1}$ per Bq $g^{-1}$), of density 0.2 g $cm^{-3}$.

### 5.5.2 Worker sorting waste from lamp recycling plant at an incinerator

This calculation was identical to the one described above apart from the activity of the lamps being sorted for incineration in a year, which was based on activity in crushed lamp parts containing $^{3}H$ and $^{85}Kr$ only, from the lamp recycling plant. The activity

concentration of crushed lamp parts being sorted annually at the incineration is given in Table 8.

### 5.5.3 Maintenance worker at a waste at an incinerator

It was assumed that a worker was exposed to bottom ash or grate ash while carrying out monthly maintenance. Exposure to fly ash was not considered as it was assumed that all of the thorium remained in the bottom ash. This exposure pathway was only considered for general waste as no thorium was assumed to be present in the plastics from recycling facilities.

#### *5.5.3.1 External doses from maintenance at an incinerator*

It was assumed that exposure occurs at 1 m from a pile of ash, represented by 1 cylinder with no shielding, as used for the sorting scenario. An exposure time of 100 h $y^{-1}$ (Harvey et al, 1995) was assumed.

The dose to maintenance workers from external exposure was calculated using equation (1). $C_{ash}$ is the activity concentration of the grate ash (Bq $g^{-1}$) which is the product of the activity concentration, $C_{incin}$ being sorted, since all of the thorium was assumed to go to the bottom ash, and $Cm_{ash}$, the mass reduction factor, 4, which represents the average reconcentration in ordinary waste after incineration (Harvey et al, 1995). $T_{maint}$ is the exposure time for a maintenance worker in a year (h $y^{-1}$) (100 h $y^{-1}$). $DR_{maint}$ is the unit effective dose rate at 1 m from external irradiation from a 1 $m^3$ load (equivalent to 1 tonne) of bottom or grate ash (Sv $h^{-1}$ per Bq $g^{-1}$), assuming the same geometry as in $DR_{sorting}$ and a density of 1 t $m^{-3}$. The material composition is given in Cresswell, 2007 for a typical grate ash.

### 5.5.4 Member of public exposed to a building made from concrete containing incinerator ash

The assumptions made for this exposure pathway were similar to those given in Section 5.4.3. The activity concentration in the concrete that contains incinerator ash was calculated by multiplying the concentration in the ash, $C_{ash}$ (discussed in Section 5.3.2.1) by the fraction of concrete which was assumed to contain ash from an incinerator, ie, 0.13 as given in Section 5.4.3.

## 5.6 Doses to the public from atmospheric releases from a lamp recycling facility and an incinerator

When lamps containing $^{3}H$ and $^{85}Kr$ are crushed at recycling plants or burnt at incineration plants the gas is released. Doses were assessed to members of the public from discharges of $^{3}H$ and $^{85}Kr$ from recycling plants and incinerators. Exposure was assumed to be from inhalation, skin absorption and ingestion of foods for $^{3}H$ and external cloud gamma and beta for $^{85}Kr$. For exposures from releases from the recycling plant the gases were assumed to be released from a 5 m high stack, whereas for an incinerator the stack height was assumed to be 70 m. For both plants the

weather conditions were assumed to be 60% category D (Harvey et al, 2010b). For the recycling plant it was assumed that exposure occurs to a resident living 100 m from the stack. Doses from inhalation of and external irradiation from the plume are assumed to occur at 100 m and ingestion of food at 500 m from the release point. For the incinerator all doses were assumed to occur at 1 km downwind of the stack, which is where the maximum concentration in air for this stack height occurs.

### 5.6.1 Inhalation and skin absorption

The dose from inhalation and skin absorption of $^{3}H$ (Sv $y^{-1}$) was calculated using equation (10). The activity concentration in the air, $C_{air}$, (Bq $m^{-3}$) was calculated using the following equation.

$$C_{air} = \frac{A_{disch}\, TIAC}{T_{exp}} \qquad (17)$$

$A_{disch}$ is the annual activity of $^{3}H$ or $^{85}Kr$ discharged from the recycling plant or incinerator assuming no losses through the stack filter (Bq). TIAC is the time integrated air concentration for continuous release for 60% category D (Clarke, 1979): from a 5 m stack for a lamp recycling plant at 100 m = 3 $10^{-5}$ Bq s $m^{-3}$ ; at 500 m = 3 $10^{-6}$ Bq s $m^{-3}$ and from a 70 m stack for an incinerator at 1000 m =1 $10^{-7}$ Bq s $m^{-3}$. $T_{exp}$ is the exposure time for public for inhalation dose (8760 hours). The inhalation rate used in Equation (10), $R_{inh}$, is the inhalation rate for adult members of the public (0.92 $m^{3}$ $h^{-1}$) (Smith and Jones, 2003).

### 5.6.2 External exposure to $^{85}Kr$ in air

The doses from external exposure to $^{85}Kr$ in air (Sv $y^{-1}$) were estimated using the following equation.

$$D_{ext} = C_{air}\, f_{loc}\, T_{exp}\, DR_{cloud} \qquad (18)$$

$C_{air}$ is given above (Bq $m^{-3}$); $T_{exp}$ is the exposure time for members of the public for inside occupancy (8760 x 90% of time spent indoors = 7884 hours) (Smith and Jones, 2003); $f_{loc}$ is the location factor (0.2) (Smith and Simmonds, 2009). $DR_{cloud}$ is the dose rate for effective gamma and beta immersion in a cloud Sv $h^{-1}$ per Bq $m^{-3}$ (Eckerman and Ryman, 1993).

### 5.6.3 Ingestion of food from tritium

Doses were estimated from ingestion of foods containing tritium for adults. The two food groups which give the highest doses were assumed to be ingested at high rates (milk; potatoes and root vegetables) and the next two at average rates (green and domestic vegetables; milk products)

$$D_{ing} = C_{air}\, ING_{public}\, DC_{ing} \qquad (19)$$

$C_{air}$ is the activity concentration in air of $^{3}H$ for release from a stack (see Equation (18)) (Bq $m^{-3}$). $DC_{ing}$ is the dose coefficient for an adult for ingestion for public Sv $Bq^{-1}$ (ICRP, 1996). $ING_{public}$ is the intake of activity concentration in food in the $50^{th}$ year of continuous discharge for a unit activity concentration in air multiplied by the annual consumption of food (Bq $y^{-1}$ per Bq $m^{-3}$) (Harvey et al, 2010b). $ING_{public}$ was calculated using the following equation:

$$ING_{public} = INT_{milk} ING_{milk} + INT_{rv} ING_{rv} + INT_{gv} ING_{gv} + INT_{mp} ING_{mp} \quad (20)$$

$INT_{milk}$, $INT_{rv,}$ $INT_{gv}$ and $INT_{mp}$ are the activity concentrations in milk, root vegetables, green vegetables and milk products respectively. $ING_{milk}$, $ING_{rv}$, $ING_{gv}$ and $ING_{mp}$ are the ingestion rates for adults of milk (240 kg $y^{-1}$), root vegetables (130 kg $y^{-1}$), green vegetables (35 kg $y^{-1}$) and milk products (20 kg $y^{-1}$) respectively (Smith and Jones, 2003).

## 5.7 Doses from disposal to landfill

The methodology used to calculate doses from a number of scenarios which simulate typical exposure situations likely to occur at a landfill site is described in detail in (Harvey et al, 2010a). 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 (Chen et al, 2007). For members of the public, doses in the long-term from exposure to radioactivity released during a fire and deposited on the ground were also calculated. Earlier work (Anderson and Mobbs, 2010) 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 relatively 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. Intrusion 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). The exposed groups and exposure pathways considered are summarised in Table 7.

In (Harvey et al, 2010a) the activity concentration in the waste was nominally assumed to be 1 Bq $g^{-1}$. For this study the activity concentrations were based on the assumption that 15,000 tonnes of lamps per year are put into general waste and disposed of to landfill. The landfill was assumed to accept about 150,000 tonnes of waste per year with the site having an operating lifetime of 15 years. In addition, 10 million starters

containing $^{3}H$ and $^{85}Kr$ from linear fluorescent tubes sent to lamp recycling facilities were also assumed to be disposed to landfill. The assumed activity concentrations are given in Table 8.

On reviewing the methodology in Harvey et al, 2010a it was found that the physical processes that are likely to take place were not fully described. The methodology has, therefore, been modified. The doses calculated using the revised methodology are smaller than those given in Harvey et al, 2010a. However, it should be noted that the methodology is still relatively simplistic and is likely to be overestimate the doses; for example, losses of $^{3}H$ in leachate were not considered. Harvey et al, 2010a gives illustrative calculations of the numbers of lamps that can be disposed of assuming an activity concentration of 1 Bq $g^{-1}$ without exceeding 1 mSv $y^{-1}$. The estimated doses given in this report, based on the revised methodology and likely activity concentrations of $^{3}H$ found in landfill waste, should be used in preference to Harvey et al, 2010a.

As in Harvey et al, 2010a, it was assumed that the inventory at closure is the total of all the $^{3}H$ inventory disposed of to the landfill over its lifetime, and that 30 years elapses between closure and re-use of the land for housing. Clean water was assumed to have infiltrated to the maximum volume, which is governed by the porosity and saturation of the waste in the landfill. Direct evaporation and evapotranspiration from the landfill was considered to still take place at 0.45 m $y^{-1}$, but on reaching the atmosphere above the landfill the evaporate was assumed to expand to the same density as the air and to mix instantaneously with air at a concentration of 1% by volume. By comparison, air at sea level has a water vapour content between about 1% and 5% by volume. This activity concentration in air was assumed to be the same over the entire landfill, both outdoors and indoors.

Activity concentration of $^{3}H$ activity in the landfill water (Bq $g^{-1}$) is given by:

$$C = \frac{A}{M_{water}} \tag{21}$$

A is the activity in landfill after 30 years' decay (Bq) and $M_{water}$ is the mass of clean water that has infiltrated into the landfill (g). A and $M_{water}$ are given by

$$A = A_0 e^{-\lambda t} \tag{22}$$

$$M_{water} = \varepsilon \, \phi \, V_{landfill} \, \rho_{water} \tag{23}$$

where $A_0$ is the activity disposed of to landfill (Bq), $\lambda$ is the radioactive decay constant of $^{3}H$ ($5.61\ 10^{-2}$ $y^{-1}$), t is the time since closure (30 y), $\varepsilon$ is the porosity of the waste (0.5), $\phi$ is the saturation of the waste (0.5), $V_{landfill}$ is the volume of the landfill ($m^3$) and $\rho_{water}$ is the density of water ($1\ 10^{6}$ g $m^{-3}$).

On evaporation/evapotranspiration and subsequent expansion to the density of air above the landfill, assuming that the specific activity in the evaporate is the same as in the landfill water, the activity concentration in the evaporate is given by:

$$C_{evap} = C \rho_{air} \quad (24)$$

where $\rho_{air}$ is the density of air ($1.2\ 10^3$ g $m^{-3}$). The evaporate mixes with air at 1% by volume and hence the activity concentration of $^3H$ in air above the landfill, $C_{air}$, (Bq $m^{-3}$) is given by:

$$C_{air} = f\ C_{evap} \quad (25)$$

where f is the fraction of air that is water vapour (0.01). The dose from this air concentration (Sv $y^{-1}$) is then given by:

$$D = R_{inh}\ O\ C_{air}\ DC_{inh} \quad (26)$$

where $R_{inh}$ is the inhalation rate for adult members of the public (0.92 $m^3$ $h^{-1}$) (Smith and Jones, 2003)), O is the occupancy (0.9 (Smith and Jones, 2003)) and $DC_{inh}$ is the inhalation dose coefficient of $^3H$ (ICRP, 1996).

# 6 RESULTS OF THE ASSESSMENT

Doses estimated for the workers at the recycling plant processing lamps containing low levels of $^3H$, $^{85}Kr$ and $^{232}Th$ are given in Table 11. External exposure to thoriated electrodes used in the metal halide lamps was found to be the most significant pathway. The highest dose was estimated to be from external exposure from standing next to a skip containing metal components including thoriated electrodes (7 µSv $y^{-1}$). If it is cautiously assumed that a recycling worker spends 100 h $y^{-1}$ next to stored lamps, 1000 h $y^{-1}$ manually sorting lamps before processing, 1000 h $y^{-1}$ loading lamps into the crusher and 100 h $y^{-1}$ next to the skip containing metal following crushing then their summed dose will be 9 µSv $y^{-1}$.

Skin doses were calculated for workers handling broken lamps. Since $^{85}Kr$ escapes into the atmosphere once the lamps have been broken doses were only calculated for $^{232}Th$. The skin dose to a worker handling broken lamps during sorting was estimated to be 0.4 µSv $y^{-1}$. This dose also applies to a worker handling broken lamps whilst feeding lamps into the crusher. The total skin dose to a worker handling broken lamps was 0.8 µSv $y^{-1}$. This is significantly lower than the dose criterion for skin of 50 mSv $y^{-1}$ adopted in RP-65 to avoid deterministic effects (Harvey et al, 1993).

Doses were assessed for members of the public assuming that $^3H$ and $^{85}Kr$ were vented from the recycling facility during the crushing of lamps. People were assumed to be exposed by inhalation, skin absorption and ingestion of terrestrial food containing $^3H$ and external exposure to $^{85}Kr$ in air. The assessed doses given in Table 12 are all much lower than 1 µSv $y^{-1}$.

**Table 11. Estimated doses to workers at the lamp recycling plant**

| | | Dose (μSv $y^{-1}$) | | | |
|---|---|---|---|---|---|
| Group | Exposure pathway | $^{3}H$ | $^{85}Kr$ | $^{232}Th$ | Total |
| Worker standing next to stored lamps | External exposure | nc* | 0.005 | 0.1 | 0.1 |
| Workers manually sorting lamps before processing | External exposure (effective) | nc | 0.009 | 0.3 | 0.3 |
| | External exposure (skin) | nc | nc | 0.4 | 0.4 |
| | External from immersion in $^{85}Kr$ vapour | nc | 0.5 | nc | 0.5 |
| Workers loading lamps into crusher | External exposure | nc | 0.009 | 0.3 | 0.3 |
| | External exposure (skin) | nc | nc | 0.4 | 0.4 |
| | Inhalation and skin absorption of $^{3}H$ | 0.01 | nc | nc | 0.01 |
| | External from immersion in $^{85}Kr$ vapour | nc | 0.001 | nc | 0.001 |
| Workers sorting metals | Inhalation of Th dust | nc | nc | 0.02 | 0.02 |
| | External from Th dust | nc | nc | $5\ 10^{-5}$ | $5\ 10^{-5}$ |
| Workers standing next to metals following crushing | External exposure | nc | nc | 7 | 7 |
| Recycling worker | Total dose (effective) | 0.01 | 0.5 | 8 | 9 |
| | Total dose (skin) | nc | nc | 0.8 | 0.8 |

Note

*: nc stands for 'not calculated'

**Table 12. Estimated doses to members of the public due to lamp recycling process**

| Group | Exposure pathway | Dose (μSv $y^{-1}$) |
|---|---|---|
| People living or consuming food grown near to lamp recycling plant | Inhalation and skin absorption of $^{3}H$ | $2\ 10^{-4}$ |
| | External from immersion in $^{85}Kr$ vapour | $4\ 10^{-6}$ |
| | Ingestion of terrestrial food with $^{3}H$ | $8\ 10^{-5}$ |
| Total | | $3\ 10^{-4}$ |

Table 13 gives the estimated doses resulting from the recycling of metal components. Doses were assessed for workers handling the slag from the metal melting process. Additionally doses were estimated for members of the public coming into contact with materials which contain this slag. Thorium is the only radionuclide which was assumed to enter this process as $^{3}H$ and $^{85}Kr$ are not attached to any metal components. The highest estimated dose, 6 μSv $y^{-1}$, was to a person living in a building made of concrete containing some of the slag from the metal recycling process. This estimated dose is based on a number of cautious assumptions. The worker at the metal recycling plant who is processing the slag was estimated to receive a dose of 4 μSv $y^{-1}$.

**Table 13. Estimated doses from metal recycling**

| Group | Exposure pathway | Dose from $^{232}$Th (μSv y$^{-1}$) |
|---|---|---|
| Workers processing slag | External exposure | 4 |
| People playing on field made from slag aggregate | External exposure | 2 |
| | Inhalation | 0.002 |
| People living in building made from slag aggregate | External exposure | 6 |

Table 14 gives the calculated doses from the incineration of lamps which have been put into general waste. Doses of 0.05 μSv y$^{-1}$ and 0.04 μSv y$^{-1}$ were estimated for workers sorting the general waste and doing maintenance on the incinerator, respectively. For members of the public living or eating food grown near the incinerator the doses from atmospheric releases of $^{3}$H and $^{85}$Kr were negligible. The total dose to an adult was estimated to be 5 10$^{-5}$ μSv y$^{-1}$.

**Table 14. Estimated doses from incineration of general waste including lamps**

| | | Dose (μSv y$^{-1}$) | | | |
|---|---|---|---|---|---|
| Group | Exposure pathway | $^{3}$H | $^{85}$Kr | $^{232}$Th | Total |
| Workers sorting waste | External exposure | nc* | 9 10$^{-3}$ | 0.04 | 0.05 |
| Workers doing maintenance | External exposure | nc | nc | 0.04 | 0.04 |
| People living or consuming food grown near to incineration plant | Inhalation and skin absorption | 9 10$^{-6}$ | nc | nc | 9 10$^{-6}$ |
| | External from immersion | nc | 1 10$^{-7}$ | nc | 1 10$^{-7}$ |
| | Ingestion terrestrial food | 4 10$^{-5}$ | nc | nc | 4 10$^{-5}$ |
| People living in building made from slag aggregate | External exposure | nc | nc | 0.5 | 0.5 |

Note

*: nc stands for 'not calculated'

Table 15 gives the calculated doses to sorting workers handling plastic waste from the recycling plant. This waste was assumed to contain only $^{3}$H and $^{85}$Kr in quartz canisters from the non-integrated compact fluorescent lamps that may not have been crushed during the recycling process. For sorting workers the external dose from handling the waste was calculated to be 6 10$^{-5}$ μSv y$^{-1}$. This dose is two orders of magnitude lower than the dose received by the workers sorting general waste. This difference is due to the activity concentrations assumed in the crushed plastics from the recycling plant being much lower than those in general waste, as can be seen in Table 8. Therefore, the doses from the other exposure pathways considered for the incineration of general waste were not calculated for this particular route of disposal as the doses will all be lower than those given in Table 14.

**Table 15. Estimated doses from incineration of waste from lamp recycling facility**

| Group | Exposure pathway | Dose from $^{85}$Kr (μSv y$^{-1}$) |
|---|---|---|
| Workers sorting waste | External exposure | 6 10$^{-5}$ |

Table 16 gives the annual doses calculated for the disposal of lamps containing $^{3}$H, $^{85}$Kr and $^{232}$Th to landfill. The highest doses, 1 μSv y$^{-1}$, were estimated to be for landfill workers during the operation of the site and to members of the public who inadvertently intrude into the site following closure.

**Table 16. Annual estimated doses from disposal to landfill of lamps containing low levels of radioactivity**

| | Dose (μSv y$^{-1}$) | | | |
|---|---|---|---|---|
| Scenario | $^{3}$H | $^{85}$Kr | $^{232}$Th | Total |
| Operational phase | | | | |
| Landfill worker | 2 10$^{-5}$ | 4 10$^{-2}$ | 1 | 1 |
| Members of the public due to exposure from contaminated ground and food following landfill fire | 3 10$^{-6}$ | 0 | 8 10$^{-4}$ | 8 10$^{-4}$ |
| Post-closure phase | | | | |
| Inhalation of landfill gases (resident) | 0.2 | 0 | 0 | 0.2 |
| Migration of groundwater (member of the public) | 0 | 0 | 6 10$^{-4}$ | 6 10$^{-4}$ |
| Intrusion (resident) | 8 10$^{-6}$ | 0.3 | 0.7 | 1 |
| Bathtubbing (resident) | 7 10$^{-7}$ | 3 10$^{-2}$ | 7 10$^{-2}$ | 0.1 |

Table 17 gives the calculated doses to landfill workers and members of the public resulting from a fire. Doses of 10 μSv and 1 μSv were calculated for landfill workers and members of the public respectively. These doses are dominated by the contribution from the inhalation of thorium.

**Table 17. Acute estimated doses from disposal to landfill of lamps containing low levels of radioactivity**

| | | Dose (μSv) | | | |
|---|---|---|---|---|---|
| Scenario | Group | $^{3}$H | $^{85}$Kr | $^{232}$Th | Total |
| Fire (acute) | Landfill workers | 7 10$^{-2}$ | 4 10$^{-3}$ | 10 | 10 |
| | Members of the public | 8 10$^{-3}$ | 9 10$^{-4}$ | 1 | 1 |

Table 18 gives a summary of the estimated doses based on the assumed activities of the lamps given in Table 2. In order to give an indication of doses more likely to be received, doses calculated using the average activities of the lamps (Table 2) have also been given. Doses calculated based on the average activities of the lamps are much lower than those using activities assumed for this study, typically by a factor of about ten and up to a factor of twenty.

**Table 18. Summary of estimated doses based on the assumed and average activities of the lamps***

| Group | Dose (μSv $y^{-1}$) unless otherwise indicated | |
|---|---|---|
| | Based on assumed activities in lamps | Based on average activities in lamps |
| Lamp recycling workers | 10 | 0.6 |
| People living or consuming food grown near to lamp recycling plant | $3\ 10^{-4}$ | $4\ 10^{-5}$ |
| Workers processing slag from metal melting | 4 | 0.2 |
| People playing on field made from slag aggregate | 2 | 0.1 |
| People living in building made from slag aggregate | 6 | 0.3 |
| Workers sorting general waste | 0.05 | $4\ 10^{-3}$ |
| Workers doing maintenance at incineration plant | 0.04 | $2\ 10^{-3}$ |
| People living or consuming food grown near to incineration plant | $5\ 10^{-5}$ | $1\ 10^{-5}$ |
| Workers sorting plastic waste from lamp recycling plant | $6\ 10^{-5}$ | $5\ 10^{-5}$ |
| Landfill workers | 1 | 0.08 |
| Members of the public (exposure from contaminated ground and food following landfill fire) | $8\ 10^{-4}$ | $4\ 10^{-5}$ |
| Landfill workers – fire (acute) | 10 μSv | 0.6 μSv |
| Members of public – fire (acute) | 1 μSv | 0.07 μSv |
| Residents on landfill site following closure | 1 | 0.2 |
| Members of public (migration of groundwater following closure) | $6\ 10^{-4}$ | $3\ 10^{-5}$ |

Note

*: Activities are given in Table 2

# 7 DISCUSSION AND CONCLUSIONS

This study assessed doses to a number of different individuals who may be exposed to low levels of the radionuclides $^{3}H$, $^{85}Kr$ and the two thorium isotopes $^{232}Th$ and $^{228}Th$ used in lamps during the recycling and disposal processes. Information provided by the European Lamp Companies Federation (ELC) and several lamp recycling facilities was used to give a realistic picture of the types and quantities of lamps being recycled and current recycling and disposal practices in Europe. Some of the large, heavy high-pressure xenon lamps are too bulky to be processed by the machinery in the lamp recycling facilities and were not considered in this study.

The objective of this study was to calculate doses to workers and members of the public representative of the most exposed individuals resulting from the recycling and disposal of lamps. These doses were then compared with the dose criteria adopted by the IAEA and the European Commission to calculate activity and activity concentrations for exemption from regulatory requirements. These criteria are discussed in detail in Section 2 but the primary ones are that the effective doses to individuals should be of the order of 10 μSv or less in a year and that the effective doses due to low probability events should not exceed 1 mSv in a year.

It should be stressed that the calculations in this report were based on cautious assumptions to ensure that doses were not underestimated. For example the activities assumed for this study are much higher than the average found in the lamps. For example, information from ELC indicates that the average activity of $^{232}$Th in the metal halide lamps is about 5 Bq or less (ELC, 2011). For this study it was assumed that all of the lamps contain 100 Bq. Doses calculated should, therefore, be considered the highest doses likely to be received by these individuals and are unlikely to be exceeded.

All the doses assessed in this study are of the order of 10 μSv or less in a year and therefore meet the radiological criteria for exemption as defined by the IAEA (IAEA, 1996). Of the three radionuclides considered in this study, $^{232}$Th, which is used in metal halide lamps, is the most radiologically significant. The highest dose estimated, 10 μSv for an acute exposure to a worker at a landfill site during a fire, results from inhalation of $^{232}$Th. It should be highlighted that a number of cautious assumptions were made in this assessment. For example, it is assumed that the fire has an effective release height of 0 m. If the effective release height is increased to 10 m then the assessed dose would decrease by at least an order of magnitude. As can be seen in Table 18 if the dose was based on the average activity of the lamps rather than the assumed activities, it would be more than an order of magnitude lower at 0.6 μSv. Landfill fires can occur frequently or not at all depending on the type of disposed waste and the management of the site. Therefore, it is not clear-cut whether the dose criterion of 1 mSv $y^{-1}$ for low probability events such as accidents is applicable to this situation. However, given all the cautious assumptions in the assessment it can be said that the annual dose received by landfill workers during a fire will be less than 10 μSv.

The estimated doses given in this report were based on the assumption that lamps containing low levels of radioactive material, ie, the metal halide lamps and glow switches in first generation non-integrated compact fluorescent lamps, are mixed with other lamps. This was observed to be current recycling practice at the lamp recycling facilities visited. If lamps containing radioactive material are separated out from other lamps and processed by fewer lamp facilities, ie, effectively concentrating the radioactive material, the doses to lamp recycling workers and some of the other exposure groups have the potential to be higher than those presented in this study and could be higher than 10 μSv $y^{-1}$, using the assumptions of this assessment.

Prior to being received at recycling plants the lamps are amassed at collection points. The study did not consider the doses that may be received by personnel at these collection points. However, given that these workers will only come into contact with a fraction of the lamps compared to recycling workers, it would be expected that their doses would be significantly lower than those received by recycling workers.

The purpose of this study was to assess the doses to individuals most exposed during recycling and disposal of lamps containing low levels of radioactive material and as such provides useful information for any discussions with regulators. However, the assessed doses are just one of a number of factors that regulatory authorities will consider when deciding whether to grant exemption.

In summary, despite the cautious assumptions made in the assessment, all the estimated doses from the recycling and disposal processes calculated in this study were below the radiological dose criteria for exemption.

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# APPENDIX A Parameters used for the assessment of doses

This Appendix provides some of the important parameter values used in the assessment of doses. Figure A1 shows the thorium-232 decay chain. The symbols α and β indicate alpha and beta decay with the asterisk indicating if the radionuclide is also a significant gamma emitter. The times shown are the half-lives. Progeny that exist with less than 1% of their parent's activity, as a result of branching, are not shown. Table A1 gives radioactive half-lives, branching ratios and mean beta energies (ICRP, 1983); Tables A2 and A3 give the external gamma dose rates calculated using Microshield (Negin, 1986); Table A4 gives other dose coefficients for external exposure and Table A5 gives dose coefficients for internal irradiation used in the assessment.

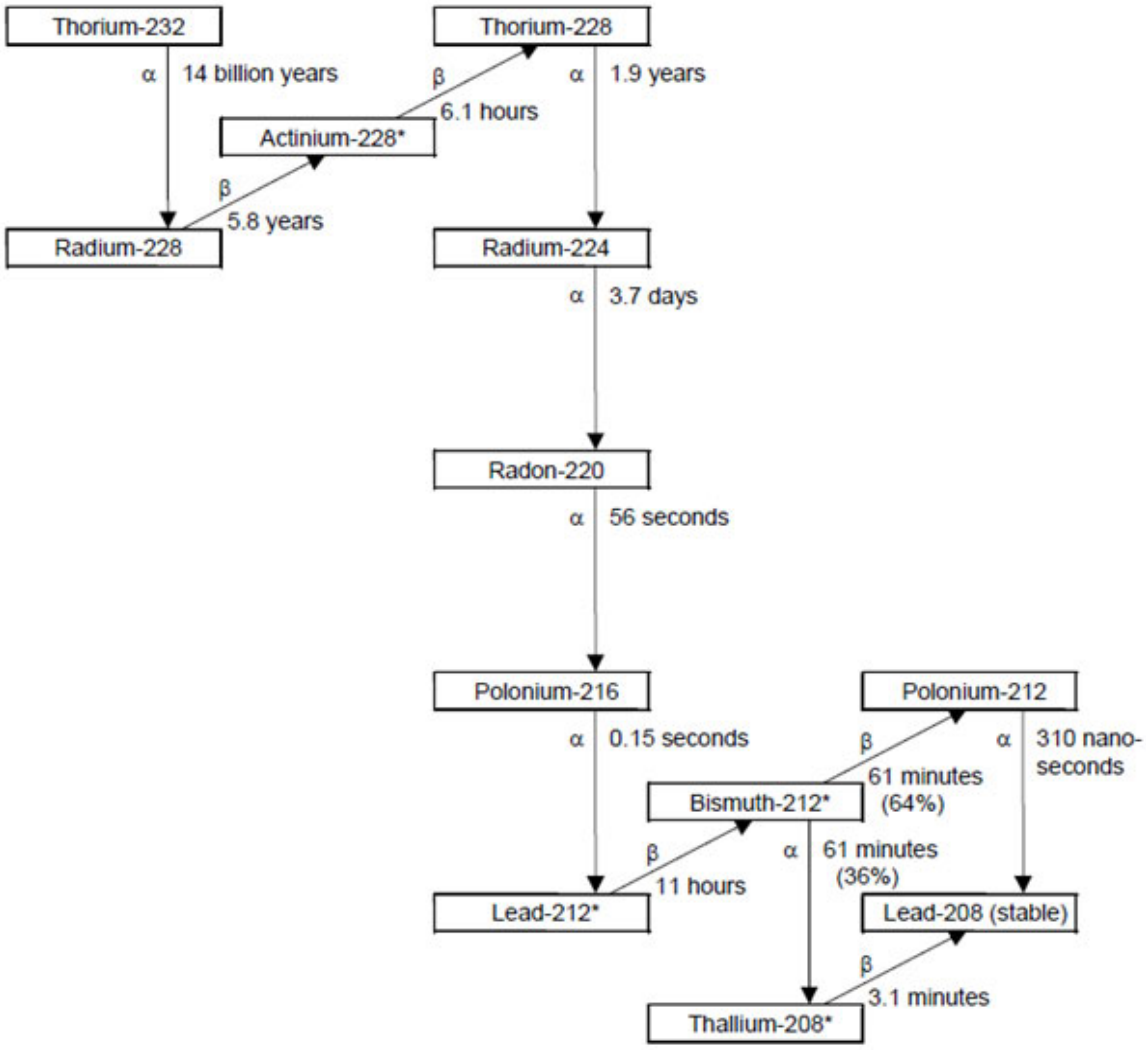


**Figure A1. The thorium-232 decay chain.**

**Table A.1 Parameters values for $^{3}H$, $^{85}Kr$ and members of the $^{232}Th$ decay chain***

| Radionuclide | Half-life | Branching ratio Secular equilibrium | Mean beta energy (MeV) |
|---|---|---|---|
| $^{3}H$ | 12.35 y | - | $5.68\ 10^{-3}$ |
| $^{85}Kr$ | 10.72 y | - | $2.50\ 10^{-1}$ |
| $^{232}Th$ | $1.41\ 10^{10}$ y | - | $1.25\ 10^{-2}$ |
| $^{228}Ra$ | 5.75 y | 1 | $1.69\ 10^{-2}$ |
| $^{228}Ac$ | 6.13 h | 1 | $4.60\ 10^{-1}$ |
| $^{228}Th$ | 1.91 y | 1 | $2.05\ 10^{-2}$ |
| $^{224}Ra$ | 3.66 d | 1 | $2.21\ 10^{-3}$ |
| $^{220}Rn$ | 55.6 s | 1 | $8.91\ 10^{-6}$ |
| $^{216}Po$ | 0.15 s | 1 | $1.61\ 10^{-7}$ |
| $^{212}Pb$ | 10.64 h | 1 | $1.75\ 10^{-1}$ |
| $^{212}Bi$ | 60.55 m | 1 | $4.69\ 10^{-1}$ |
| $^{212}Po$ | 0.31 μs | 0.641 | 0 |
| $^{208}Tl$ | 3.07 m | 0.359 | $5.91\ 10^{-1}$ |

Notes:

*: (ICRP, 1983)

**Table A2. Gamma dose rates for external exposure per unit activity concentration (Sv $h^{-1}$ per Bq $g^{-1}$) calculated using Microshield***

| Exposure scenario | Gamma dose rate for external exposure per unit activity concentration (Sv $h^{-1}$ $Bq^{-1}$ g) $^{85}Kr$ | $^{232}Th$ |
|---|---|---|
| 1 m for 8 cages containing lamps | $8.60\ 10^{-11}$ | $1.53\ 10^{-7}$ |
| 1 m from 1 cage containing lamps | $1.54\ 10^{-11}$ | $2.74\ 10^{-8}$ |
| 1 m from skip contained metal | na* | $3.19\ 10^{-7}$ |
| 1.5 m from 100 t pile of slag from metal melting | Na | $2.43\ 10^{-7}$ |
| 1.0 m from playing field made of slag from metal melting | Na | $9.65\ 10^{-7}$ |
| 1.0 m from a concrete wall containing aggregate/incinerator ash | na | $2.44\ 10^{-7}$ |
| 1.0 m from a $1m^3$ of general waste | $2.44\ 10^{-11}$ | $2.42\ 10^{-8}$ |
| 1.0 m from a $1m^3$ of incinerator ash | na | $6.10\ 10^{-8}$ |

Note

*: (Negin, 1986)

na stands for 'not applicable'

**Table A3. Gamma dose rates for external exposure per unit activity (Sv $h^{-1}$ $Bq^{-1}$) calculated using Microshield***

| | Gamma dose rate for external exposure per unit activity concentration (Sv $h^{-1}$ $Bq^{-1}$) | |
|---|---|---|
| **Exposure scenario** | $^{85}Kr$ | $^{232}Th$ |
| 30 cm from point source | $3.57\ 10^{-15}$ | $3.61\ 10^{-12}$ |

Note

*: (Negin, 1986)

**Table A.4 Dose coefficients for external irradiation used in the assessment**

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

Notes

*: Values for 7 mg $cm^{-2}$ (Chaptinel et al, 1988);

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

‡: From (Eckerman and Ryman, 1993).

**Table A.5 Dose coefficients for internal irradiation used in the assessment***

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

*: (ICRP, 1996)

#: 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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