DRAFT REPORT

IAEA-Consultancy Service 170

IAEA-Safety report for manufactured items containing small amounts of radioactive material
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5. List of Contributors
1. Introduction

Small amounts of radioactive material may be added to items, devices or equipment for functional reasons. Such items \(^1\) are available on the market. Following manufacture, certain of those items do not warrant further regulatory control as they are inherently safe. Adequate safety assessment is pivotal for showing that there is no need for exercising regulatory control from the moment the manufacturer places the produced items on a global market.

The manufacture of items is a planned exposure situation requiring authorization by a competent regulatory body. The first step towards authorizing the manufacture of items is for the regulatory body to consider justification for its use and its safety as a whole during the controlled phase of manufacture (occupational exposure) and the subsequent period of time, once the items are placed on the market (public exposure). The appropriate protection for members of the public can only be provided if the use of items is in compliance with the criteria for exemption of the Basic Safety Standards [IAEA-BSS-115, IAEA-DS-379, IAEA-GS-G-1.5].

Certain single items do not exceed the exemption levels for radionuclides laid down in the Basic Safety Standards [IAEA-BSS-115, IAEA-DS-379]. Many items are, due to their properties or function, typically applied or present in some or even large numbers \(^2\). As a consequence, the exemption level for total activity within a premise may be exceeded in some practices under different circumstances. When under such conditions only exemption level is considered as the criterion for exemption, the practice has to meet BSS-requirements [IAEA-BSS-115, IAEA-DS-379]. Studies indicate that many of such items are inherently safe and meet the dose criteria for exemption [IAEA-BSS-115, Schedule I, IAEA-DS-379, Schedule I para I.1 and I.2] during the entire life cycle of the item [EU-RP-146, EU-RP-147, IAEA-GS-G-1.5, NUREG-1717]. Provided the use of items is justified and BSS-criteria for exemption are met,

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\(^1\) An “item” is a device such as a smoke detector, luminous dial, electrical component or a lamp (component) that contains a small amount of radioactive material. More generally, it is an item that is readily available on the market without any requirements being imposed in relation to any radiation source therein. They may be available as “consumer products” through commercial outlets where personal and household products are normally purchased, and there is a reasonably large market for such products, resulting in their wide scale distribution to the end-user. Items may also be made available to members of the public involved in applications that are regarded professional use; examples of such applications with items are: transport, warehouse storage, whole sale, assembly into other products, installation, replacement, service, repair and maintenance. Following a professional application items may, but not necessarily, become available as “consumer products”.

\(^2\) Examples of items that can meet this description are: electrical components in (household) appliances, measuring equipment containing an internal reference source or lamp (components). An example of items that does usually not meet this description is: smoke detector containing an Am-241 source.
regulatory control without gaining safety should not be required on such items because it would be an economical burden to manufacturers and suppliers of these products, an unnecessary burden for regulatory bodies to monitor compliance with BSS-requirements and of no further benefit to members of the public or society as a whole.

The regulatory control on the supply of items - which are within the scope of this report - in the public domain, is the same as laid down for the supply of consumer goods [IAEA-BSS-115, IAEA-DS-379, IAEA-GS-G-1.5, para 4.15 – 4.21]. This process of regulatory control is initiated by the application for authorization to manufacture items with the intention to place them on the market in country of manufacture. Items are usually produced for a global market. According to the current BSS-requirements, suppliers must request authorization for use by members of the public in every country. Whereas there may be grounds for regulatory bodies to differ in deciding on the approval for the use of items, there should, however, be no difference in the interpretation of the safety assessment of items. Regulatory bodies have a shared interest to regulate radiation safety internationally. An internationally accepted example of this shared interest is the understanding between IAEA Member States to have uniform regulations for the safe transport of radioactive material according to IAEA-TS-R-1 [IAEA-TS-R-1]. Once exemption has been granted by a competent regulatory body, the results of the safety assessment may be acceptable for regulatory bodies in other IAEA Member States.

Objective

This report is intended to provide a methodology for a safety assessment in order to assist member states in the decision making process for exemption of items from further regulatory control following their manufacture and to contribute to the international harmonization of such exemption.

An example of such a safety assessment is made for lamps containing small amounts of radioactive material and is added to this report.
a. Definition of the Terms Used

Item [new definition, based on consumer good definition EU-RP-147; see also IAEA-DS-379, IAEA-safety glossary]

manufactured product or appliance, in which radionuclides are deliberately added or intentionally incorporated and which can be supplied to members of the public without special surveillance and control.

member of the public [IAEA-safety glossary]

In a general sense, any individual in the population except, for protection and safety purposes, when subject to occupational or medical exposure.

Radioactive material [IAEA-safety glossary]

Material designated in national law or by a regulatory body as being subject to regulatory control because of its radioactivity.

Sealed source [IAEA-BSS-115]

a radioactive source in which the radioactive material is (a) permanently sealed in a capsule or (b) closely bonded in a solid form.

b. Scope

The scope of the safety report is restricted to items that

a. Contain radionuclides in a permanently sealed capsule or in a closely bonded solid form;

b. do not need further steps of manufacture;

c. do, as a single item, not exceed the exemption level for total activity in Schedule I of the Basic Safety Standards [IAEA-BSS-115, IAEA-DS-379];
d. exceed or are likely to exceed the exemption level for total activity when multiple numbers of items are involved within a practice.

c. Radiation Protection Principles

i. Justification and Optimization

[reference IAEA-GS-G-1.5, para 4.5]

Various factors influence decisions about justification. Some may be characterized as reflecting societal values independent of the associated risk, whereas others are more oriented towards safety. For instance, a regulatory body may decide to approve certain uses of radiation sources or radioactive material if the associated doses are trivial; another may decide to discourage or not to approve the same product because members of the public would then be exposed to radiation, irrespective of the magnitude of the exposure. As a consequence, there will be differences in national attitudes; there will probably also be differences in points of view even within the same regulatory body. National guidelines on the acceptability would therefore be useful in order to provide a consistent approach. To help in the establishment of these guidelines, the Basic Safety Standards [IAEA-BSS-115, IAEA-DS-379] stated that practices involving the frivolous use of radiation or radioactive material in commodities or products such as toys or jewellery are deemed to be not justified.

[reference IAEA-GS-G-1.5, para 4.6]

Important factors that are relevant to justification in relation to safety and which may lead to optimized protection, as required in the Basic Safety Standards [IAEA-BSS-115, para III.15 IAEA-DS-379, para 3.1.41], include the following:

a) Selection of the most appropriate radionuclides with respect to the half life, radiation type, energy and amount of radioactive material necessary for the product to function effectively;

b) Selection of the chemical and physical forms of the radionuclide that provide the highest degree of intrinsic safety under both normal and accident conditions and for disposal;

c) Construction of the product;

d) Prevention of access to the radioactive substance without the use of special tools;

e) Experience with other products, particularly similar products, that have previously been assessed;

f) Verification of quality.
ii. Dose Criteria for Members of the Public

[see IAEA-GS-G-1.5, para 4.1]

The risks associated to the items available to members of the public are so small that they meet the criteria for exemption laid down in Schedule I of the Basic Safety Standards [IAEA-BSS-115, IAEA-DS-379].

[see Schedule I, IAEA-DS-379]

A justified practice involving a typical number of items, may be exempted if the effective dose expected to be incurred by any member of the public due to the exempted practice or items is of the order of 10 μSv per year or less. To take account of low probability scenarios for which the above criterion fails, an additional criterion can be used, namely that the effective dose due to such low probability events does not exceed 1 mSv in a year.

[see EU-RP-65, para 3.2, p.6]

Additional radiological protection criteria may, however, be required. In some circumstances it is possible for selective localized exposure of the skin to occur. In order to exclude the possibility of any deterministic effects, a constraint value on the annual equivalent dose to the skin of 5 mSv has been adopted; this dose constraint is applied to any exposed area of 1 cm².

A safety assessment should demonstrate compliance to these criteria during all phases of the life-cycle of the item. If compliance cannot be met during waste disposal, a recycling scheme should be adopted.

2. Considerations for Manufacture and Technical Design

a. Technical requirements

An individual item is by definition not classified as a sealed source but has to be tested according to the general requirements described for sealed sources in the Internationally Standards ISO 9978. Items have only to be submitted to an appropriate leakage test in accordance with ISO 9978, provided the activity of an individual item exceeds 200 Bq.

Alternatively, items may be subjected to equivalent (functional) tests, according to internally accepted criteria. The U.S. Nuclear Regulatory Commission allows the use of functional tests to demonstrate the leak tightness of certain items containing radioactive material [byproduct material] [NUREG-1556]. In
addition, worldwide organizations such as the International Electrotechnical Commission (IEC, www.iec.ch) publish International Standards, which include product safety specifications.

\[ \text{b. Operational dose rate criteria} \]

These criteria apply to items during all phases of the life cycle of the product. The dose rate has to be assessed at 10 cm from the surface of a single item. The following criteria are applied:

- for the strongly penetrating radiation the ambient dose equivalent rate at 10 mm depth does not exceed 1 \( \mu \text{Sv} \) per hour;
- for weakly penetrating radiation the directional dose equivalent rate at 0.07 mm depth does not exceed 1 \( \mu \text{Sv} \) per hour.

\[ \text{c. Radiological assessment} \]

The safety assessment is to be evaluated by a competent authority, for the entire life cycle of the item following manufacture. Each safety assessment has to be provided by the manufacturer or supplier, according to this document.

\[ \text{i. Dose Calculations} \]

A generic safety assessment should be conducted on the use of items during all stages of the life-cycle of the product, including the waste phase. The choice of scenario’s should be such as to cover all the reasonably likely exposure pathways and exposure situations that arise with the item.\(^3\) Situations of potential exposure, such as accidents and misuse, should be considered to assess whether the product is inherently safe [IAEA-GS-G-1.5, para 4.11]. A conservative safety assessment can be based on the method used for determining the exemption values for radionuclides [EU-RP-65]. An example is given in the Annex of this document and in studies from NRPB-GRS, RIVM and NUREG [EU-RP-146, NRPB-1992, NRPB-GRS-2001, NUREG-1717, RIVM-2000]. The scenario’s and exposure pathways can, for good

\[^3\] Scenario’s should be based on a conservative but realistic number of items. Examples of scenario’s to be taken in consideration are: warehouse storage, shipment, end-use and disposal.
reasons, be adapted in order to obtain a more realistic dose assessment. For example, there may be justified reasons to take for the scenario into account the actual activity present in a large, but typical, number of items. An example for an amended exposure pathways may be to take into account the actual shielding provided by the capsule surrounding the radioactive material in the item.

**d. Regulatory guidelines for manufacturing and placing on the market**

[IAEA-GS-G-1.5, para 4.15 and 4.16] The regulatory body should require the manufacturer of items to apply to the regulatory body and receive authorization to supply items to the public to ensure that these products meet all the requirements for design and performance that were taken into account in the generic safety assessment. The manufacturer should provide the regulatory body with sufficient documentation and certification to enable it to review and assess the proposed product. The documentation should include the following:

a) A description of the item, its intended uses and benefits, the radionuclide(s) incorporated and the function served by the radionuclide(s). Documentary evidence that the radioactive material fulfils its function should also be provided.

b) The activity of the radionuclide(s) to be used in the product.

c) Justification of the choice of a radionuclide, particularly in relation to other radionuclide(s) that could be of lower toxicity (e.g. emit less penetrating radiation and/or have a shorter half-life). The reason for choosing the radioactive material in preference to a non-radioactive alternative should also be justified.

d) The chemical and physical forms of the radionuclide(s) contained in the item.

e) Details of the construction and design of the item, particularly as related to the containment and shielding of the radionuclide in normal and adverse conditions of use and disposal, and the degree of access to the radioactive material.

f) The quality testing and verification procedures to be applied to radioactive sources, components and finished products to ensure that the maximum specified quantities of radioactive material

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4 It has been argued that depending on the type of application, a higher exemption value may be granted for specific radionuclides, e.g. Kr-85 [EU-RP-122].
or the maximum specified radiation levels are not exceeded, and that devices are constructed according to the design specifications.

g) A description of the prototype tests for demonstrating the integrity of the product in normal use and for possible misuse and accidental damage, and the results of these tests.

h) External radiation levels arising from the product and the method of measurement.

i) Dose assessments, including individual doses and, if appropriate, collective doses arising from normal use, possible misuse and accidental damage and disposal and, if applicable, servicing and repair.

j) The anticipated useful lifetime of the product and the total number of items expected to be distributed annually.

k) Information about any advice to be provided to members of the public on the correct use, installation, maintenance, servicing and repair of the item.

l) An analysis to demonstrate that the item is inherently safe.

[IAEA-GS-G-1.5, para 4.17]. A manufacturer should satisfy the regulatory body that the assumptions made in the safety assessment in relation to the design of the item are valid for any particular proposal. This is usually accomplished by means of a system of regulatory control, which often includes:

a) Specifications for radiation levels or the radionuclide content, durability and integrity of the source, the solubility or dispersibility of the radionuclide, during normal use, possible misuse and accidental damage.

b) Prototype tests developed to determine that the materials of construction and the methods of manufacture are such that the ultimate item will meet the specifications for safety performance as well as any other design requirements that are imposed on the item. Certification of prototype testing may form a part of the conditions applying to an authorization.

c) Quality assurance consisting of statistical sampling of items, components, materials and manufacturing methods together with a test regime sufficient to confirm that manufactured items are within the specifications of the prototype. The number of items selected for testing should be such that there is only a small probability that a defective item would be distributed to the public.
Safety Study According to Criteria of “IAEA-Safety Report for Manufactured Items Containing Small Amounts of Radioactive Material”:

Radiological Assessment on Lamps Containing Small Amounts of Radioactive Krypton ($^{85}$Kr) and/or Thorium ($^{232}$Th)
1. Introduction

HighIntensity Discharge lamps (HID-lamps) produce bright white light with a high intensity in an energy efficient manner. These lamps are typically applied in large numbers in public and professional environments such as shops, warehouses, hotels and offices. They are also used in outdoor applications to illuminate streets, buildings, statues, flags, gardens and further as architecture lighting, in cinemas as classic film projection, sky beamer, Manufacture of semiconductors, Fluorescence endoscopy and microscopy, Schlieren photography, Hologram projection, UV-curing, car headlight (Automotive), etc. Some types of High Intensity Discharge Lamps (HID-lamps) contain radioactive material for functional reasons. The radionuclides that are typically applied in HID-lamps are $^{85}$Kr and Thorium.

HID lamps with Kr-85

Light is produced in the discharge or arc tube of the lamp. Ignition of the lamp cannot occur without a starting aid helping towards the formation of an arc between the electrodes in the burner. The arc tube is a sealed compartment filled with a noble gas mixture containing small amounts of the radioactive noble gas $^{85}$Kr. $^{85}$Kr provides the starter aid function by supplying free electrons. The outer glass bulb envelopes and protects the arc tube and other lamp components. This outer compartment is, just as the arc tube, a sealed and gas tight compartment.

Some types of HID-lamps do not have an outer envelope, but consist of a single compartment. These so called “burner only” lamps produce light in the same way as the lamps described above and an example is shown in Annex 1. Another example of “burner only lamps” is the QL-induction lamp shown in Annex 2. The operating principle differs from that of HID-lamps, but QL-lamps also require $^{85}$Kr as an ignition aid.

Once the manufacture of HID-lamps is completed, they are made available in large quantities to a global market. Several steps lead towards end-use. The first step is the logistic process involving transport and warehouse storage. Before being supplied, HID-lamps may be assembled into luminaires. The subsequent retail, installation, replacement, service repair and maintenance of lamps or luminaires typically involves members of the public, as these lamps are supplied to clients in large numbers. In these many steps members of the public may not necessarily be aware of their (potential) exposure to the radiation emitted by $^{85}$Kr. Members of the public are not only persons exposed during end-use, but are also lighting industry, logistic and other professionals involved in the chain of events described above.

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5 QL-lamps are compared to HID-lamps provided in very limited amounts to the market. This study evaluates HID-lamps but is equally applicable to QL-lamps. Differences of QL-lamps compared to HID-lamps are addressed in Annex 2.
HID-lamps with Th-232
Thorium oxide has been used in electrode systems internationally since several decades in various high performance and special lighting products as the common state of the art of science and technology. The deliberate addition of thorium to these products is indispensable for their function and high performance.

Thorium is a naturally occurring radioactive material and is added to the lamp as thoriated tungsten electrodes, or less frequently in the form of ThO₂ coated tungsten or as thorium iodized admixture in the filling depending on the type and application of the light source. An advantage of the application of thorium in the lamp is an improvement of the electrode’s metallurgical properties necessary for an excellent lamp performance. Thorium iodide is applied to optimize the light spectrum of the lamp.

Once the manufacture of HID-lamps is completed, they are made available in large quantities to a global market. Several steps lead towards end-use. The first step is the logistic process involving transport and warehouse storage. Before being supplied, HID-lamps may be assembled into luminaires. The subsequent retail, installation, replacement, service repair and maintenance of lamps or luminaires typically involve members of the public, as these lamps are supplied to clients in large numbers. In these many steps members of the public may not necessarily be aware of their (potential) exposure to the radiation emitted by ²³²Th. Members of the public are not only persons exposed during end-use, but are also lighting industry, logistic and other professionals involved in the chain of events described above.

Annex 1 show examples and an overview of the types of HID-lamps evaluated in this study.
Objective of the Radiological Assessment

This radiological assessment is aimed to demonstrate that the use of small quantities of thorium and/or krypton-85 in the presented HID-lamps is justified and to provide evidence that these items can be made available to a global market without any restrictions as the consequences of exposure for members of the public are well within the boundaries of the dose criteria for exemption from further regulatory concern⁶.

a. Definition of the Terms Used

High Intensity Discharge Lamp: HID-lamp

Electric discharge lamp in which the light-producing arc is stabilized by wall temperature and the arc has a bulb wall loading in excess of 3 watts per square centimetre [IEC-62035]. It produces light by means of an electric arc between tungsten electrodes housed inside a transparent or translucent arc tube made of quartz glass or alumina ceramics. This tube is filled with both gas and metal salts. The gas facilitates the arc's initial strike. Once the arc is started, it heats and evaporates the metal salts forming a plasma, which greatly increases the intensity of light produced by the arc and reduces its power consumption. High-intensity discharge lamps are a type of arc lamps.

⁶ The criteria for exemption are described in the IAEA Basic Safety Standards [IAEA-BSS-115]. The dose criteria for exemption are described in Schedule I of these Standards. Further guidance material on the regulatory control of radiation sources and in particular consumer goods is found in [IAEA-GS-G-1.5].
b. Scope

The scope of this radiological assessment is restricted to lamps that

a. Contain $^{85}$Kr in a permanently sealed capsule or contain $^{232}$Th in a closely bonded solid form within a permanently sealed capsule

b. do not need further steps of manufacture;

c. do, as a single item, not exceed the exemption level for total activity in Schedule I of the Basic Safety Standards [IAEA-BSS-115 DS-379] (March 2010).

- current exemption level for $^{85}$Kr-activity for is 10,000 Bq [IAEA BSS-115];
- current exemption level for $^{232}$Th activity is 1,000 Bq [IAEA BSS-115];
- current exemption level for $^{232}$Th (mother nuclide) activity is 10,000 Bq [IAEA DS-379];

d. exceed or are likely to exceed the exemption level for total activity when multiple numbers of items are involved within a practice.

c. Radiation Protection Principles, Justification and Optimization

In this paragraph the justification of the products/lamps with a small quantity of radioactive material is described. The main justification for using HID-lamps is that there are currently no suitable alternatives that can save so much energy as these lamps by the same outcome of lumens/watt. In addition HID-lamps produce light with a high intensity that can neither be produced by alternative technologies. These products are typically applied in a professional environment. Typical applications of these lamps are shown and described in Annex 1.

Therefore, important reasons for the industry [Kyoto-targets ELC] for placing these products on the market are:

1. To promote the use of energy efficient lighting systems;
2. To provide savings in term of energy and cost;
3. To help EU Member States to meet the Kyoto targets on CO$_2$ emissions reduction.
HID-lamps with Kr-85

An HID-lamp cannot ignite without a starting aid helping towards the formation of an arc between the electrodes in the light producing compartment. \(^{85}\text{Kr}\) provides this function by supplying free electrons. The added \(^{85}\text{Kr}\)-activity is optimized in such a way that only the required quantity is present in order to guarantee lamp ignition throughout the anticipated lifetime of up to 20,000 hours. This is substantially longer compared to the life expectancy of halogen lamps (2,000 hours).

The choice of \(^{85}\text{Kr}\) as a radionuclide is also the most optimal choice for this application since the selected radionuclide (i) must be a noble gas, (ii) emits predominantly or exclusively electrons, (iii) emits no or with a relative low emission probability penetrating gamma-radiation and (iv) has a half-life that is compatible with the need to provide sufficient electron supply during the expected life time of the item.

A major benefit of this technology is that light of a desired spectral quality is produced in a very energy efficient manner. The light yield of HID-lamps is typically 90-100 lumen per watt and is substantially higher compared to the performance of that of halogen lamps (20-30 lumen per watt). As this energy-saving technology is ubiquitously available in society, the utilization of this lamp technology makes an important contribution to a reduction of \(\text{CO}_2\)-emission and helps society towards achieving the objectives of the Kyoto protocol.

Other energy efficient technologies, such as LED-technology, become increasingly more available in modern life. This technology is, however, not a suitable alternative for many HID-applications. This is in particular the case for applications requiring high light intensity.

There is a continuous effort from the industry to develop non-radioactive alternative ignition aids, such as UV-enhancers. However, they do not perform with equal reliability compared to the current \(^{85}\text{Kr}\)-technology. Another disadvantage is that is for manufacturers impossible to equip smaller lamps of this product range with UV-enhancers. In addition, this alternative is more expensive to produce. The limited radiological consequences of the items evaluated in this study are neither a justification to substantially increase investment that may, but not necessarily, lead towards the development of a reliable alternative at reasonable cost. In conclusion, no reliable and reasonable non-radioactive HID-alternatives are available till date and in the foreseeable future.

HID-lamps with thorium

The deliberate addition of Thorium (as \(\text{ThO}_2\)) to the tungsten of the electrode improves the metallurgical properties and increases the stability of the electric arc between the electrodes. By the addition, the operating temperature of the electrode decreases, by which:
- the life time of the electrodes is prolonged as less material is lost and
- the lumen maintenance over lamp life is better, as less electrode material evaporates and do not darken the glass bulb.
Thorium iodide (ThI₄) is added to the salt mix in the burner:

- to improve the spectral characteristics of the lamp so a good color rendering (the higher, the more natural the goods under the light are presented) can be achieved and
- to improve the metallurgical properties of the electrodes as the Thorium migrates into the hot surface of the electrodes and helps to lower the surface temperature (see above the effect of the addition of ThO₂ to tungsten.

The addition of Thorium of the lamp types as shown in Annex 1, Table 1 is really needed at this moment as there are no alternatives yet to give the lamps a comparable performance.

A major benefit of this technology is that light of a desired spectral quality and with a high color rendering index (Ra > 90) is produced in a very energy efficient manner. The light yield of HID lamps is typically 90-100 lumens per watt and is substantially higher compared to the performance of that of halogen lamps (20-30 lumens per watt).

Also for many lamp types there are simply no alternatives at this moment in other lamp technologies. The use of this kind of lamps contributes substantially to the reduction of CO₂-emissions.

Other energy efficient technologies, such as LED-technology, become increasingly more available in modern life. This technology is, however, not a suitable alternative for many HID-applications. This is in particular the case for applications requiring high light intensity in a small space.

Replacing Thorium by non-radioactive elements like Lanthanum and Hafnium is not possible because of vaporisation and other metallurgical properties. Up to date, no other elements with similar characteristics as Thorium were found. In lamp development there is continuous search for possibilities to decrease or eliminate the Thorium in the lamps (ALARA-principle).
2. Considerations for Manufacture and Technical Design

a. Technical Design and Quality Assurance

Technical Description

HID light sources (overview and pictures shown in Annex 1) generally consist of an arc tube (quartz glass or ceramic material) containing the radioactive material ($^{85}$Kr or thorium) and an outer envelope of quartz or other glass material with one or two bases for electrical and mechanical contact with the luminaires. Lamp bases are generally made of ceramic material and/or metal with insulating material and withstand high temperatures. The purpose of the arc tube is to maintain over a prolonged lifetime a vacuum tight noble gas environment for the electric arc, to preserve the filling during operation and to resist high temperatures as well as high temperature gradients. The pressure in the arc tube under normal conditions is typically a few hundred of mbar below atmospheric pressure. The primary function of the outer envelope (outer jacket) is to protect and maintain an inert atmosphere for the arc tube and its mechanical and electrical supportive metal/glass components. Sealing of envelopes are very well engineered and controlled processes.

Some types of HID-lamps do not have an outer envelope, but consist of a single compartment. These so called “burner only” lamps produce light in the same way as the lamps described above and an example is shown in Annex 1. These burners also require a conditioned environment and for this functional reason need always to be assembled into closed luminaires. Another example of “burner only lamps” is the QL-induction lamp shown in Annex 1. The operating principle differs from that of HID-lamps, but QL-lamps also require $^{85}$Kr as an ignition aid.

The Thorium amount in the lamp electrodes depends on the lamp wattage. It is fixed and insoluble bounded in the Tungsten matrix. The mass concentration of Thorium dioxide in the Tungsten electrode material is in the range of 1–2 weight%.

Thorium Iodide is applied in certain lamp types, in the filling up to only a few tenths of micrograms.

Quality Assurance Programme

Produced HID-lamps are subject to a quality assurance programme in order to guarantee leak tightness of critical seals as well as product quality and safety throughout the entire life cycle of the items. This programme consists of running tests as well as type and design tests (see IEC 60235 for the definitions of these tests).

The purpose of the leakage tests is to demonstrate that lamps remain their integrity and that the arc burner remains permanently sealed with the purpose to contain $^{85}$Kr and hence to maintain its
functionality. Functional tests can be considered equal to the ISO-norm designed for leakage testing of sealed radioactive materials [ISO 9978] as lamps having a leaky arc tube fails to ignite according to the specified quality criteria. In fact the U.S. Nuclear Regulatory Commission allows the use of functional tests to demonstrate the leak tightness of lamps containing byproduct materials when applying for a distribution license [US-NRC-1556]. The excerpt on the use of functional tests is provided in Annex 3.

The mechanical product safety of HID-lamps is tested according to the requirements laid in international electrotechnical norms IEC 62035 and ANSI/IEC C78.62035. Temperature tests are part of both the functionality and safety test programme.

In addition a programme of tests is used to ensure that packages of lamps are protected during transport until the end-user.

**Running Tests, including Leakage Test, during Lamp Manufacture**

The manufacturing process of each lamp is concluded with a functional running test. This test comprises of full light up and the evaluation of several photometric (e.g. lamp light output level, colour, temperature) and electrical parameters (e.g. starting capability, lamp voltage, lamp wattage).

Photometric and electrical parameters are measured on lamps at full operation when the arc tube temperature reaches or exceeds 1,000 °C. These parameters are highly dependent on the arc tube filling gas as well as outer jacket pressure; arc tubes with insufficient leak tightness will be rejected as they will fail to meet the high performance specifications.

**Mechanical Safety Tests**

Representative samples of produced lamps are subjected to a mechanical type test (torque or pull test) to ensure that they do not rupture during either installation or when handled by the end-user or during replacement. Additional criteria are described for lamps applied in open luminaires. Under these circumstances the outer glass bulb should contain the arc tube particles and other components if the inner tube ruptures in the event of abnormal lamp failure. When applied in the outdoor environment such lamps must also be resistant to moisture and water droplets. Testing methods and criteria are defined in IEC 62035 and ANSI/IEC C78.62035 standards together with sampling rates and acceptable quality levels (AQL).

**Temperature Test**

Lamp ignition at –30 °C is a design test requirement according to the ANSI C78.43/C78.44 standard and this test is commonly used in Europe as well. The lamp body develops a very rapid temperature increase to a maximum value of approximately 1,000 °C at the hottest part and a minimum value of about 150 °C at the lamp base. Lamp bases have to be able to resist a temperature of 650 °C without degradation. This so called glow wire test for lamp bases is described in IEC 62035, IEC/ANSI C78.62035.
Testing Packages of Lamps for Transport

A number of standard tests are used to ensure that packages of lamps are protected during transport until the end-user. This program of tests is executed for every new lamp type or new package design and includes conditioning, drop, rolling, toppling, vibration, stacking and impact tests. The test programme used by one of the members of the European Lamp Company Federation (ELC) is described in Annex 4. This programme is derived from relevant ISO-norm requirements. Other ELC-members use similar test programmes.

b. Radiophysical properties of $^{85}$Kr

$^{85}$Kr is a radioactive noble gas that decays with a half-life of 10.7 years and emits beta-radiation with a maximum energy of 687 keV [ICRP-38; RPD-2002]. In 0.4 % of its transformations, $^{85}$Kr also emits gamma-radiation with an energy of 514 keV [ICRP-38].

c. Radiophysical properties of Thorium

Thorium $^{232}$Th is a natural occurring radioactive material with a low specific activity. It is purified from the progenies by chemical separation before manufacture of lamps. Therefore the $^{232}$Th mother activity is taken as the reference value.

After separation, the amount of radiation (produced by the progenies) within the thoriated electrode is considerably reduced for several years but of course, the progenies will grow up and will reach up to 75 % of the mother nuclide activity ($^{232}$Th) in a time period of 15 years (conservative estimate for the lifetime of the lamp) [NUREG 1717]. The whole Thorium-decay-chain is shown in Annex 7.

d. $^{85}$Kr-activity in HID-lamps

The $^{85}$Kr-activity in individual HID-lamps does not exceed the exemption level [IAEA-BSS-115] for total $^{85}$Kr-activity of 10,000 Bq. The incorporated activity depends on the $^{85}$Kr-activity concentration in and pressure of the noble gas mixture and the arc tube volume. The incorporated $^{85}$Kr-activity varies from a value of about 50 Bq up to a value of 10,000 Bq. The noble gas mixtures used in manufacture have a $^{85}$Kr-activity concentration that typically varies between 0.65 to 11 MBq per litre of gas, equaling to
concentrations ranging from to 3 E+ 5 to 70 E+5 Bq per gram. If concentrations below the exemption level were to be used, the desired incorporated $^{85}$Kr-activity would not be obtained in the arc tube.

**e. Thorium $^{232}$Th activity in HID- lamps**

The maximal values for $^{232}$Th activity and specific activity in thorium containing lamps

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>max. Activity</th>
<th>Specific Activity</th>
<th>Specific Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{232}$Th</td>
<td>4500 Bq</td>
<td>max. 6 Bq/g</td>
<td>max. 72 Bq/g</td>
</tr>
<tr>
<td></td>
<td></td>
<td>based on the weight of the lamp</td>
<td>based on the weight of the electrode</td>
</tr>
</tbody>
</table>

An exemption level for $^{232}$Th (with all progenies) of 4,700 Bq can be derived from the exemption level described in Schedule I [IAEA BSS-115; IAEA DS-379]

Thorium-containing items exceed the limit values for the specific activity (1 Bq/g).

**f. Operational Dose Rates close to pallet stacked with lamps containing $^{85}$Kr**

Operational dose rates were not evaluated for individual lamps, but for the situation in which lamps are typically packed in large numbers on a pallet for transport or stored in a warehouse. The maximum activity that can be stored on a pallet depends on lamp dimensions, incorporated activity and package size. Using these criteria, 18 MBq $^{85}$Kr was found to be the maximum amount that can be stored on a pallet. For determining the operational dose rates, the following conservative approach was applied: a pallet is assumed to contain an activity of 20 MBq $^{85}$Kr and this activity is uniformly distributed over a cubic volume of 1 m$^3$.

The radionuclide $^{85}$Kr is contained in the arc tube of the lamp. The arc tube and the glass envelope have in total a thickness of at least 1.0 mm and will, therefore, provide effective shielding against the emitted beta-radiation [RPD-2002]. This is also the case for “burner only” lamps. Thus only the emitted gamma-radiation will contribute to the dose in the surrounding environment close to lamps. The codes of the program Microshield Version 8.01 (Grove Software Inc., Lynchburg, USA 2008) were used to calculate the ambient dose equivalent rate at 10 mm depth and the directional dose equivalent rate at 0.07 mm.

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7 For this calculation, Argon is assumed to be carrier in the noble gas mixture. Other noble elements may be used in other applications.

8 Analysis of the complete $^{85}$Kr-lamp portfolio of the involved members of the European Lamp Company Federation (ELC) revealed that a total activity of 18 MBq is the maximum activity that can be packed onto a pallet; this amount equals to 9,000 lamps of a particular lamp type, each containing 2,000 Bq $^{85}$Kr.
depth as defined in [ICRP-51] 9. Both operational radiation protection quantities were found to increase with a value of 25 nSv per hour. At a distance of 1 meter from the surface of the pallet both dose rates were found to increase with a value of 4 nSv per hour.

**g. Operational Dose Rates close to pallet stacked with lamps containing $^{232}$Th**

Operational dose rates were evaluated for individual lamps and for the situation in which lamps are typically packed on a pallet for transport or stored in a warehouse. The maximum activity for a single lamp is 4500 Bq $^{232}$Th (which relates to about 1 g of Thorium). The maximum activity that can be stored on a pallet depends on lamp dimensions, size of package and incorporated activity. Using these criteria, 0.1 MBq $^{232}$Th was found to be the maximum amount that can be stored on a pallet 10. For determining the operational dose rates, the following conservative approach was applied: a pallet is assumed to contain an activity of 0.1 MBq $^{232}$Th and this activity is uniformly distributed over a cubic volume of 1 m$^3$.

The radionuclide $^{232}$Th is contained in the electrodes of the lamp which causes low dose rates also by gamma-radiation of the daughter nuclides. Alpha- and beta-radiation is shielded fully; gamma-radiation is shielded partly by the Tungsten and the quartz glass bulb(s). The resulting external gamma radiation caused by the daughter nuclides is negligibly low, because of the high self absorption in the heavy Tungsten matrix and the age of the Thorium (see 2b).

Thus only the emitted external gamma-radiation will contribute to the dose in the surrounding environment close to lamps. The codes of the program Micro shield Version 8.03 (Grove Software Inc., Lynchburg, USA 2008) were used to calculate the ambient dose equivalent rate at 10 mm depth and the directional dose equivalent rate at 0.07 mm depth as defined in [ICRP-51].

For a single lamp both operational dose rates were found to increase up to 123 nSv per hour in a distance of 0.1 m and up to 1 nSv per hour in 1m.

For a pallet of lamps both operational dose rates were found to increase with a value of 47 nSv per hour. At a distance of 1 meter from the surface of the pallet both dose rates were found to increase with a value of 8 nSv per hour.

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9 Where applicable in this study, this programme was also used to calculate the effective dose and the equivalent skin dose as defined in ICRP-74.

10 The type of lamps evaluated in this study each contains an activity of maximally 4500 Bq and up to 6 lamps can be packed on a pallet. Analysis of the complete $^{232}$Th lamp portfolio revealed that a total activity of 0.1 MBq is the maximum activity that can be packed onto a pallet; this amount equals to 100 lamps each containing 1000 Bq $^{232}$Th which is more than the average of transported lamps.
h. Radiological Assessment on lamps with $^{85}$Kr

Exposure Scenario’s and Pathways of Exposure to $^{85}$Kr

The radiological assessment was made for the entire life-cycle of lamps that do not need any further steps of manufacture. To this end, various exposure scenario’s were developed to representatively describe the various phases of the life cycle of the product. Not only normal scenario’s, but also potential and accidental exposure situations were developed for this analysis. Due to the radiophysical properties of the noble $^{85}$Kr-gas, the (potential) exposure pathways for $^{85}$Kr are: exposure to external radiation of emitted gamma-rays and beta-particles and to submersion when $^{85}$Kr is released into the environment.

Normal exposure conditions  During normal use, $^{85}$Kr is contained within the arc tube of the lamp and exposure due to submersion of $^{85}$Kr does not occur. The physical properties of the lamp provide effective shielding against the emitted beta-particles. Therefore, persons can only be externally exposed to the gamma-radiation emitted by $^{85}$Kr during conditions of normal use.

Exposure during accident conditions  The scenario to describe accidents is loss of containment of the otherwise occluded radioactive gas. In a conservative approach it is assumed that all lamps involved in a particular accident scenario will instantaneously release their $^{85}$Kr-content into the environment. As $^{85}$Kr is a noble gas, submersion will be the dominant exposure pathway contributing to the dose of exposed persons.

Life cycle of lamps  Following manufacture the life cycle of a lamp comprises of the following elements: (i) transportation, (ii) warehouse storage, (iii) assembly of lamps into luminaires as well as installation, servicing, maintenance, repair, replacement and sale, (iv) end-use and finally (v) disposal of used lamps.

Transport

The occupational and public radiation doses resulting from transport operations with lamps containing radioactive material have been evaluated in a study funded by the European Commission [NRPB-GRS-2001]. Risk analysis showed that estimated contribution of such shipments to the effective dose of involved employees does not exceed 1 $\mu$Sv per year under normal circumstances. The resulting increase of the effective dose for members of the public is not expected to be higher than 10 nSv per year. The radiological consequences of a transport accident were also evaluated in this study according to the Q-system described in the advisory material published by the IAEA for the safe transport of radioactive material [IAEA-TS-G-1.1 (Rev. 1)]. The instantaneous release of a consignment of 20 pallets of lamps
products equaling to an activity of 100 MBq $^{85}$Kr results in an estimated equivalent skin dose of 5 $\mu$Sv and an increase of the effective dose of about 0.1 $\mu$Sv (see Annex 5 for details of calculation). Analysis of reported transport accidents with consumer goods containing radioactive material shows that substantial release of radioactive material have an infrequent occurrence [NRPB-GRS-2001]. It is, therefore, unlikely that a person becomes more than once in his life time involved in such accidents.

**Warehouse storage**

Exposure to lamps containing radioactive materials stored in a warehouse is an occupational exposure scenario. The adopted scenario to evaluate exposure of employees was similar to that described in [NRPB-GRS-2001]. When assuming an annual occupational exposure of 400 h at 1 m distance from a pallet of lamps with a total activity of 20 MBq $^{85}$Kr, the incurred effective dose will be less than 2 $\mu$Sv per year 11. For an accident scenario in a warehouse the same scenario as described above for transport was adopted. The resulting estimated equivalent skin dose and effective dose will not exceed 5 $\mu$Sv and 0.1 $\mu$Sv respectively (see Annex 5 for details of calculation).

**Professional use**

During scenario’s describing professional use other than warehouse storage, employees will work close to a pack of lamps and will pick up and manually handle substantial number of lamps as part of their daily work. Examples of such use are assembly of lamps into luminaires, installation, replacement, service repair and maintenance. Another example is the retailer who is selling lamps. According to workplace scenario’s described in [EU-RP-65], not only external exposure of the whole body to a pack of lamps needs to be evaluated but also the exposure of hands and the skin must be evaluated. The annual increase of the effective dose of employees exposed to the gamma radiation emitted from a pack of lamps will be less than 2 $\mu$Sv when the same conservative scenario described for warehouse storage was adopted.

During manual handling any surface of the skin can only be exposed to the radiation emitted by a single lamp. As a consequence, any surface of the skin will not be in close contact to a $^{85}$Kr-activity exceeding the exemption level of 10,000 Bq defined in Schedule I of BSS [IAEA-BSS-115]. The skin is, due to the lamp construction, effectively protected against the emitted beta-radiation that would otherwise dominantly contribute to the equivalent skin dose. When assuming an annual exposure time of 10 hours

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11 The assumed exposure time at 1 meter for a pallet is twice as long as the 200 h of exposure time assumed for operators working near a non-dispersable source in [EU-RP-65].
for direct contact during manual handling [as defined in EU-RP-65], an equivalent skin dose of up to 400 nSv can be calculated 12. (See Annex 5 for details of calculation).

The radiological consequences resulting from an accident scenario will be of limited importance if only one pallet of lamps is involved. The dose contributions of exposed persons will be no more than the doses estimated for transport or warehouse accidents.

End-Use

End-users benefit from the light produced by the lamps and are, from a certain distance, exposed to the emitted gamma-radiation of the lamps. In this phase of the lamp life-cycle, members of the public are at a distance of a few meters exposed to a substantial smaller number of lamps compared to that packed on a pallet. The same “dilution” applies to an accident scenario in which a few lamps might loose their integrity. When relating this exposure condition to smaller numbers of lamps to the warehouse exposure scenario’s, it can be deducted that the annual dose for members of the public will not exceed a value of 1 µSv per year. These dose estimates are in line with those published by the European Commission [EU-RP-146] and the Dutch National Institute for Public Health and the Environment, RIVM [RIVM-2000]

End of Life - Treatment and Disposal

Collection & Recycling in the law

At the end of lamp life it depends on the national requirements on how to proceed with lamp disposal. According to the legislation in many countries (e.g. WEEE in the EU countries) collection is mandatory for all lamps. Incandescent lamps are excluded from this requirement. Fluorescent lamps represent the largest part of the mix put on the market.

In the recycling process the lamps are treated and useful materials are recovered as recycled materials. Due to the mercury content in the lamps, this work is done in well ventilated environments with a negative pressure compared to the employees’ environment thus preventing inhalation of any vapour content of the lamps by the employees [EU-2009/161/EU]. This measure will also minimise the risk of submersion of employees to $^{85}$Kr.

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12 Calculations were done for a typical lamp described having a diameter of 2 cm. The arc tube containing $^{85}$Kr is centred in the middle of the lamp, is 1 cm long and has a diameter of 0.7 cm and contains an activity of up to 300 Bq. For a conservative assumption, the dose rate is calculated at 1 cm distance from a point source having a $^{85}$Kr-activity of 10,000 Bq.
Recycling process of \(^{85}\text{Kr}\)-containing products

Many of the lamps contain small amounts of \(^{85}\text{Kr}\) and Mercury. As most of the \(^{85}\text{Kr}\)-lamps are HID lamps, they are normally very compact and difficult to disassemble, especially the burners (or Discharge Tubes) that are made of quartz or ceramic material and contain the radioactive material. Because of these characteristics, the burners are crushed and then recycled or disposed for controlled landfill. As a consequence of crushing \(^{85}\text{Kr}\) is released into the environment.

Due to the ventilation measures taken at the workplace, the workplace \(^{85}\text{Kr}\)-concentration will be of little relevance to contribute to the effective dose \(^{13}\).

The crushing will ultimately lead to release and subsequent dilution of \(^{85}\text{Kr}\) into the atmosphere. The effect of this environmental release is insignificant compared to the concentration of 1 Bq/m\(^3\) already present in the atmosphere due to other man-made activities [Smith et al.]. The RIVM, estimated that the effective dose of members of the public will increase with a value of around 2 pSv per year when the \(^{85}\text{Kr}\)-activity of 1 million light products (equaling to an activity of 20 GBq) is released into the atmosphere during waste processing [RIVM-2000] \(^{14}\).

Disposal: Land-fill

Waste treatment employees and members of the public visiting land fill sites who are externally exposed to disposed intact lamps, cannot be expected to incur a higher dose compared to employees involved in transport or logistic work in a warehouse. Waste treatment will ultimately lead to release and dilution of \(^{85}\text{Kr}\) into the atmosphere. The resulting environmental effects are described above in the paragraph “Recycling process of \(^{85}\text{Kr}\)-containing products”.

Disposal: Incineration

Alternative way of treatment includes incineration as part of total generic disposal stream in a country. This case was evaluated by the Dutch RIVM studies of 2000 and 2002 [RIVM-2000 and RIVM-2002] of

\(^{13}\) According to German regulation (Strahlenschutzverordnung) employees do not need to be considered as exposed workers if the \(^{85}\text{Kr}\)-concentration at the workplace does not exceed 1 E+6 Bq/m\(^3\). It is not realistic to assume that this concentration will be met in a recycling facility. This is due to the well confined environment in which lamps are crushed. This concentration can neither be met due to amount of HID-lamps processed.

\(^{14}\) According to German regulation (Strahlenschutzverordnung) the maximum \(^{85}\text{Kr}\)-concentration is limited to 1 E+4 Bq/m\(^3\) when the emitted volume does not exceed 1 E+4 m\(^3\)/h. Under these circumstances, the effective dose for a member of the public at the point of emission will be restricted to 0,3 mSv per year.
which the outcomes are taken over in EU Review 146 on radiation protection [EU-RP-146]. Waste treatment will ultimately lead to release and dilution of $^{85}$Kr into the atmosphere. The resulting environmental effects are described above in the paragraph “Recycling process of $^{85}$Kr-containing products”.

**Comparison to Exemption Levels EU-RP-65**

Publication Radiation Protection-65 of the European Commission describes the principles and methods for establishing exemption values [EU-RP-65]. In this study, the critical exposure pathways determining the $^{85}$Kr-exemption levels for activity concentration and total activity were found to occur during normal conditions in a workplace environment. The critical pathway determining the exemption value for $^{85}$Kr-activity concentration (100,000 Bq/g) is external exposure to gamma-radiation emitted from a 100 litre gas cylinder. For dose estimation the European Lamp Company Federation assumed the cylinder to contain 2.7 GBq $^{85}$Kr when filled under pressure of 150 bar $^{15}$ with an activity concentration of 100,000 Bq per gram of gas. In other words, the activity present in a 100 litre cylinder containing an exempt $^{85}$Kr-concentration is equal to that of 135 pallets of lamps each containing 20 MBq $^{85}$Kr. At a distance of 1 metre from such a model cylinder, the ambient dose equivalent rate at 10 mm depth was found to increase with a value of about 0.7 µSv per hour. Although the activity concentration of the lamp filling gas is about ten-fold higher than the exemption level, the resulting increase of the ambient dose equivalent rate at 10 mm depth at 1 metre distance from a pallet of lamps will be more than one hundred fold lower (4 nSv per hour) compared to that of the smaller sized model cylinder.

The critical exposure pathway determining the exemption level for total $^{85}$Kr-activity (of 10,000 Bq) is based on external exposure of the skin to the emitted beta-radiation during handling of a source [EU-RP-65]. Although the total activity within a practice may exceed the exemption level, a person will only handle lamps with an activity of no more than 10,000 Bq. In addition, the lamp construction was demonstrated to effectively attenuate the beta-particles. Moreover, the skin surface cannot be contaminated as $^{85}$Kr is a noble gas. This comparison shows that skin exposure is not a critical exposure pathway when handling lamps containing $^{85}$Kr.

The critical exposure pathways determining the exemption levels for activity and activity concentration are relevant for workplace scenario’s. Comparison with the presented radiological assessment for lamps containing $^{85}$Kr shows, however, that the assumptions for the radioactive materials used for these workplace scenario’s do not apply for the radiological assessment of critical groups of members of the public exposed to these types of items containing radioactive material.

$^{15}$ This assumption is based on the properties of gas cylinders typically used for lamp manufacture. Such cylinders are delivered with a pressure of 150 bar and with the noble gas Argon as the carrier gas.
i. Radiological Assessment on lamps with $^{232}$Th

Exposure scenarios and pathways of exposure to $^{232}$Th

The radiological assessment was made for the entire life-cycle of lamps that do not need any further steps of manufacture. To this end various exposure scenarios were developed to representatively describe the various phases of the life cycle of the product. Not only normal scenarios, but also potential and accidental exposure situations were developed for this analysis. Due to the radio physical properties of Thorium, the (potential) exposure pathways are: external exposure to alpha-, beta-, gamma- radiation when $^{232}$Th is released into the environment due to an accident (crash and fire scenario).

Normal exposure conditions.

During normal use, Thorium $^{232}$Th is contained within the electrodes and within the arc tube of the lamp and exposure due to alpha- and beta- radiation by $^{232}$Th and its progenies does not occur. The physical properties of the lamp provide effective shielding against the emitted alpha and beta-particles. Therefore, under conditions of normal use persons can only be externally exposed to the gamma-radiation emitted by the progenies of $^{232}$Th.

Exposure during accident conditions.

The external gamma radiation and furthermore the alpha-and beta-radiation on the surface of the thoriated Tungsten is taken into account after lamp breakage. Incorporation by inhalation is not possible, because Thorium is fixed bounded in the Tungsten matrix or in a solid form. Contamination is also not relevant with these thoriated electrodes, because the activity is fixed bounded and therefore smear-resistant. The ingestion case is possible if a complete electrode is swallowed which is however very unlikely in particular for big electrodes.

If during the crash scenario also fire occurs the inhalation pathway is taken into account because Thorium particles at the surface can leave the solid matrix.

Life cycle of lamps.

Following manufacture the life cycle of a lamp involves following steps: (i) transportation, (ii) warehouse storage, (iii) assembly of lamps into luminaries as well as installation, servicing, maintenance, repair, replacement and sale, (iv) operation by end- user and finally (v) disposal of used lamps.
**Transport**

The occupational and public radiation doses resulting from transport operations with lamps containing radioactive material have been evaluated in a study funded by the European Commission [NRPB 01]. Risk analysis showed that estimated contribution to the effective dose of employees involved in the transport of such lamps under normal circumstances is far below 1 µSv per year. Indeed, the resulting increase of the effective dose for members of the public is not expected to be higher than 10 nSv per year. The radiological consequences of a transport accident were also evaluated in this study according to the Q-system described in the Advisory material published by the IAEA for the safe transport of radioactive material [IAEA-TS-G-1.1 (Rev. 1)]. The release of a consignment of 20 pallets of lamp products equaling to an activity of 2 MBq $^{232}$Th results in an estimated equivalent skin dose of 5.2 µSv and, hence, an increase of the effective dose of about 0.52 µSv for the employee when collecting the lamp parts by hand. The case of fire is explained under warehouse accident. (See Annex 6 for details of calculation).

**Warehouse storage**

Exposure to lamps containing radioactive materials stored in a warehouse is an occupational exposure scenario. The scenario to evaluate exposure of employees was similar to that described in [NRPB-GRS-2001]. When assuming an annual occupational exposure of 400 h at 1 m distance from a pallet of lamps with a total activity of 0.1 MBq $^{232}$Th, the incurred effective dose will be less than 1 µSv per year$^{16}$. For an accident scenario in a warehouse the broken lamp scenario as described for transport can be applied. For the fire scenario the estimated equivalent skin dose and effective dose will not exceed 0.0001 µSv and 5 µSv respectively by using very conservative calculation. In the fire scenario, the inhalation pathway is the dominant one. The effective dose through inhalation doesn’t exceed 5 µSv. (See Annex 6 for details of calculation).

**Professional use**

During scenarios describing professional use other than warehouse storage, employees will work close to a pack of lamps and will pick up and manually handle great numbers of lamps as part of their daily work. Examples of such use are assembly of lamps into luminaries, installation, replacement, service repair and maintenance. Another example is the retailer who is selling lamps. According to workplace scenarios described in [EU-RP-65], not only external exposure by the pack of lamps needs to be evaluated but also the exposure of hands and the skin must be evaluated. Realistic exposure parameters (time, distance and shielding, low number of lamps at one time) were taken into account, which limit the exposure in practice. The annual increase of the effective dose of employees exposed to the gamma

$^{16}$ The assumed exposure time at 1 meter for a pallet is twice as long as the 200 h of exposure time assumed for operators working near a non-dispersible source in EC RP-65.
radiation emitted from lamps will be less than 6 µSv in a distance of 0.2 m and 0.23 µSv for 1.0 m. The dose contributions of exposed persons do not exceed the doses estimated for transport or warehouse accidents. (See Annex 6 for details of calculation).

**End-use**

End-users benefit from high efficient light items but they are exposed to the emitted external gamma-radiation of the $^{232}$Th progenies from a certain distance. In this phase of the lamp life-cycle, members of the public are usually at a distance of a few meters exposed to a substantial smaller number of lamps compared to that packed on a pallet. In an accident scenario are also just one or few lamps in concern. Therefore compared to the warehouse and transport accident scenarios the resulting annual dose for members of the public will be significantly lower and will not exceed a value of 1 µSv p.a. These dose estimates are in line with those published by the U.S. Nuclear Regulatory Commission [NUREG 1717]. (See Annex 6 for details of calculation).

**End of Life - Treatment and Disposal**

**Collection & Recycling in the law**

At the end of lamp life it depends on the national requirements on how to proceed with lamp disposal. According to the legislation in many countries (e.g. WEEE in the EU countries) collection is mandatory for all lamps. Incandescent lamps are excluded from this requirement. Fluorescent lamps represent the largest part of the mix put on the market.

In the recycling process the lamps are treated and useful materials are recovered as recycled materials. Due to the mercury content in the lamps, this work is done in well ventilated environments with a negative pressure compared to the employees’ environment thus preventing inhalation of any vapour content of the lamps by the employees [EU-2009/161/EU]. This measure will also minimise the risk of contamination of the workplace with Thorium and thereby the exposure risk of the employees.

**Recycling process of Thorium containing products**

Many of the lamps contain small amounts of Thorium and Mercury. As most of the Thorium lamps are HID lamps, they are normally very compact and difficult to disassemble, especially the burners (or
Discharge Tubes) that are made of quartz or ceramic material and contain the thorium material. Because of these characteristics, the burners are either left intact or are crushed and then recycled or disposed for controlled landfill. In the first case the radioactivity remains contained in the burner, while in the second case the Thorium can be released: in case of thoriated tungsten electrodes, some material parts will be still protected/sealed by glass, whereas other parts are not.

Another important fact is that all HID lamps are processed in a similar way, so in the average mix with non-Thorium containing products, Thorium materials will be a non-significant part of the total volume.

Disposal: Municipal waste landfill

When end-of-life lamps are directly sent to a municipal waste landfill, the resulting annual doses are below 0.1 µSv [NUREG 1717]. In the unlikely case that someone swallows a thoriated lamp electrode (intake by ingestion) on a landfill site, the resulting dose of 0.4 µSv (calculated by [EU-RP-65]) doesn’t exceed the dose criteria. (See Annex 6 for details of calculation).

Disposal: Incineration

Alternative way of treatment includes incineration as part of total generic disposal stream in a country. This case was evaluated by the Dutch RIVM studies of 2000 and 2002 [RIVM-2000 and RIVM-2002] of which the outcomes are taken over in EU Review 146 on radiation protection [EU-RP-146]. The resulting dose of the study was 0.0002 µSv by incineration of 20 MBq $^{232}$Th for members of the public.
3. Conclusion

This radiological assessment demonstrated that the use of radioactive $^{85}$Kr and or Thorium in HID-lamps is justified and optimized. The radiological consequences for members of the public, including lighting industry and other involved professionals, were demonstrated to be insignificant during the entire life cycle of the lamps, including waste disposal. This study also demonstrated that the applied scenario’s and exposure pathways, to derive the exemption levels for the Basic Safety Standards, are of little relevance in the case of the evaluation of the radiological consequence for members of the public when exposed to items under normal as well as accident scenarios. In conclusion, this study provides support for the idea that the $^{85}$Kr and Thorium containing items can be made available to a global market without any restrictions. This free trade is possible as the consequences of exposure for members of the public are well within the boundaries of the dose criteria for exemption.

Additionally, several published independent studies on lamps containing thoriated electrodes [NUREG-1717, NRPB-GRS-2001, RIVM-2000, RIVM-2002] demonstrate the safe nature of the items produced by the lamp industry during all aspects of their life cycle. The exposure risk for any member of the public is far below the 10 $\mu$Sv per year.

The results from other already public available studies mentioned above, concerning the different pathways of exposure scenarios with electrical lamps, are considered and summarized in the following diagram 1.
4. References

EU-2009/161/EU

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Commission of the European Communities
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A Review of Consumer Products Containing Radioactive Substances in the European Union
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NRPB Occupational Services Department

EU-RP-147
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Safety series No. 115 (1996)

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International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of
Radiation Sources
IAEA Revision of BSS, latest draft 3.0 (January 2010)

IAEA-GS-G-1.5
IAEA Safety Guide
Regulatory Control of Radiation Sources

IAEA-Safety Glossary
IAEA Safety Glossary
Terminology used in Nuclear Safety and Radiation Protection
2007 Edition

IAEA-TS-G-1.1 (Rev.1)
Advisory Material for the IAEA Regulations for the Safe Transport
Safety Guide No. TS-G-1.1 (Rev. 1)

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Krypton-85 and other airborne radioactivity measurements throughout Ireland

WEEE-2002/96/EC
Access: 02-16-2010
Annex 1  

Typical Examples of lamps containing $^{85}$Kr and Thorium

Figure 1  
Typical example of an HID-lamp containing an inner quartz glass arc tube, a quartz glass outer envelope and an Edison fitting.
Figure 2  Typical example of a single ended HID-lamp containing an inner ceramic arc tube and a quartz glass outer envelope

Ceramic arc tube containing $^{85}\text{Kr}$

Outer quartz glass bulb

Single lamp base

Figure 3  Double ended HID-lamp containing an inner ceramic arc tube and a quartz glass outer envelope

Two lamp bases

Ceramic arc tube containing $^{85}\text{Kr}$

Outer quartz glass bulb
Figure 4  Typical example of a “Burner only” HID-lamp without an outer envelope

Figure 5  QL-induction Lamps containing $^{85}\text{Kr}$
Figure 6  Xenon short arc lamp with a thoriated tungsten electrode (cathode)

Figure 7  Mercury short arc lamp with a thoriated tungsten electrode
Figure 8  Automotive Xenon lamp with thoriated tungsten electrodes

Figure 9  Metal halide lamp with thoriated tungsten electrodes
<table>
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<tr>
<th>Type of lamp</th>
<th>Typical application</th>
<th>Typical $^{85}$Kr-activity per item</th>
<th>Maximal $^{85}$Kr-activity per item</th>
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<tr>
<td>Metal halide lamps or arc tubes</td>
<td>Shop lighting; Hotel and restaurant lighting Office lighting; Stadium lighting; Street – Area lighting</td>
<td>100 - 2,500 Bq</td>
<td>&lt; 10,000 Bq</td>
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<tr>
<td>Entertainment short arc lamps</td>
<td>TV / Film studio lighting Stage / Concert lighting Sport Event lighting</td>
<td>1,500 – 9,500 Bq</td>
<td>&lt; 10,000 Bq</td>
</tr>
<tr>
<td>QL-induction lamp</td>
<td>High-Bay indoor and outdoor applications</td>
<td>1,000 – 5,000 Bq</td>
<td>&lt; 10,000 Bq</td>
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</table>
Table 2  Typical Examples and overview of HID-lamps containing Thorium

<table>
<thead>
<tr>
<th>Type of HID lamp</th>
<th>Electric Power consumption per item</th>
<th>Typical Activity per item</th>
<th>Max. Activity per item $^{232}$Th</th>
<th>Typical application</th>
<th>Information on the radio nuclides</th>
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</thead>
<tbody>
<tr>
<td>Xenon short arc lamps</td>
<td>50 – 12,000 W</td>
<td>50 - 500 Bq</td>
<td>&lt; 2,000 Bq</td>
<td>Architecture lighting</td>
<td>$^{232}$Th (mother activity)</td>
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<td>Example see Figure 1</td>
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<td>Classic film projection</td>
<td>Thoriated tungsten electrodes (max. 2 weight-% ThO$_2$ in Tungsten)</td>
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<td>Light guide applications</td>
<td>Max. activity concentration per electrode: 72 Bq/g $^{232}$Th</td>
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<td>Solar simulation</td>
<td>Functions:</td>
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<td></td>
<td></td>
<td></td>
<td>Light houses, sky beamer</td>
<td>1) Reduces the electron discharge level at the cathode, start aid, prolongs life span</td>
</tr>
<tr>
<td>Mercury short arc lamps</td>
<td>50 – 25,000 W</td>
<td>100 – 1,000 Bq</td>
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<td>Manufacture of semiconductors</td>
<td>2) Improves metallurgical qualities</td>
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<td>Example see Figure 2</td>
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<td>Fluorescence endoscopy</td>
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<td>Schlieren photography</td>
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<td>Hologram projection</td>
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<td>UV curing</td>
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<td>Automotive Xenon lamps</td>
<td>2 - 35 W</td>
<td>0.1 - 0.5 Bq</td>
<td>&lt; 1 Bq</td>
<td>Car headlight</td>
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<td>Example see Figure 3</td>
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<td>Metal halide lamps</td>
<td>20 - 5,000 W</td>
<td>10 - 80 Bq</td>
<td>&lt; 100 Bq</td>
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<td>Example see Figure 4</td>
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<td>Hotel and restaurant lighting</td>
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<td>Office lighting</td>
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<td>Stadium lighting</td>
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<td>Street –Area lighting</td>
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<td>special types with Thorium - Iodide</td>
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<td>max. 0.04 weight-% of the lamp filling (&lt; 0.05 Bq)</td>
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</tr>
</tbody>
</table>
Calculation of the $^{232}$Th activity $A$ per lamp

$$A = m_{\text{electrode, filling}} \times A_{\text{spec}} \times R_{^{232}\text{Th}/\text{ThO}_2} \times c_{^{232}\text{Thw}}$$

$m_{\text{electrode, filling}} = \text{Weight of the electrode or filling in which the Thorium is embedded [g]}$

$A_{\text{spec}} = \text{Specific Activity of pure } ^{232}\text{Th} = 4,058 \text{ [Bq/g]}$

$R_{^{232}\text{Th}/\text{ThO}_2} = \text{Relation } ^{232}\text{Th}/\text{Thorium dioxide} = 0.88 \text{ (Thorium is embedded in the form of ThO}_2 \text{)}$

$c_{^{232}\text{Thw}} = \text{Concentration of Thorium (here Thorium dioxide) in the embedded solid by weight}$

Example:

Electrode $m = 0.1 \text{ g}$

$c_{^{232}\text{Thw}} = 2\% = 0.02$;

$$A = 7.1 \text{ [Bq]}$$
Annex 2  QL-induction Lamps containing small amounts of $^{85}$Kr

In QL-induction lamp is a gas discharge lamp in which electrical energy is supplied to the mercury vapour by means of a high frequency electromagnetic field without any electrodes (see Figure in Annex 1). Just as for HID-lamps, $^{85}$Kr is added as an ignition aid to the noble gas filling of these lamps. Since electrodes are absent, the life time of can be up to 60,000 hours or about 15 years. The operational reliability during its relative extreme long life time and its energy efficient manner to produce light are benefits that justify the use of $^{85}$Kr. In other words, the justification and optimization principles for using $^{85}$Kr in QL-lamps are similar to those described for HID-lamps.

The maximal $^{85}$Kr-activity added to QL-lamps depends on the size of the spherical bulb and does not exceed 5,000 Bq. The dose consequences, due to external exposure to gamma-radiation during normal conditions and submersion following an accident, will not differ from those described for HID-lamps containing up to 10,000 Bq $^{85}$Kr in this study.

In contrast to HID-lamps, the bulb of QL-lamps is made of glass with a minimal thickness of 0.4 mm. This thickness of less than 1 mm will, therefore, not completely attenuate the emitted beta-radiation emitted within the lamp bulb [RPD-2002]. The skin dose resulting from manual handling of QL-lamps may be more elevated compared to HID-lamps. For the reasons described in the paragraphs on the radiological assessment for professional use and on Comparison to exemption levels in EU-RP-65, the resulting increase of the skin equivalent dose will be rather limited. Again, the critical exposure pathway determining the exemption level for total activity of 10,000 Bq $^{85}$Kr is based on external exposure of the skin to the emitted beta-radiation during handling of a source [EU-RP-65]. Although the total activity within a practice may exceed the exemption level, a person will at any time only handle lamps with an activity of no more than 5,000 Bq. Even if beta-particle attenuation by the 0.4 mm of glass bulb is not taken into account, the beta-particle fluence rate per cm² is, due to the area of the bulb surface of at least 230 cm², substantially smaller compared to the area of 0.5 cm² described for the 10,000 Bq $^{85}$Kr-source used for the skin exposure model described in EU-RP-65. For these reasons, the dose limit for the skin will not be exceeded for any 1 cm² area of skin.

In conclusion the justification and optimization principles for using $^{85}$Kr in QL-lamps are similar to those described for HID-lamps. The radiological consequences due to exposure to QL-lamps will neither differ from those described for HID-lamps.
Annex 3  The Use of Functionality Tests in Demonstrating Leak Tightness of Arc Tubes

Excerpt from NUREG-1556 publication.

Consolidated Guidance about Materials Licenses.
Program-Specific Guidance about Exempt Distribution Licenses
U.S. Nuclear Regulatory Commission
Office of Nuclear Material Safety and Safeguards
NUREG-1556, Vol. 8
September 1998
http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1556/v8/

Chapter 9  Information Required for specific types of distribution licenses

Paragraph 9.3  10 CFR 32.14: CERTAIN ITEMS CONTAINING BYPRODUCT MATERIAL

Under 10 CFR 30.15, persons who apply or incorporate byproduct material into or who initially transfer or distribute products such as electron tubes, watches with luminous paint, or ionizing radiation measuring instruments containing calibration sources to persons exempt from licensing, must have a license pursuant to §32.14, "Certain items containing byproduct material; requirements for license to apply or initially transfer." The product information as outlined in §§ 32.14, 32.15, and 32.16 must be provided for review in order to obtain an exempt distribution license.

For electron tubes, lamps, etc., applicants can use mathematical calculations or functionality tests to demonstrate and verify that each product contains no more than the quantity of byproduct material specified for that product, pursuant to §32.14(c). The functionality tests may involve testing each tube or lamp to confirm that it works and that the light output is within the range known for that tube or lamp for which the specific activity has been determined. Non-working product or below par output are considered indicative of leaking tubes.
Annex 4 Example of a Safety Testing Programme for the Transport of Packages of Lamps

A number of standard tests are used to ensure that packages of lamps are protected during transport until the end-user. This programme of tests is executed for every new lamp type or new package design and includes conditioning, drop, rolling, toppling, vibration, stacking and impact tests. The test programme is used by one of the members of the European Lamp Company Federation (ELC) and is derived from ISO-norm requirements. Other ELC-members use similar test programmes.

Annex 5   Dose Calculations for scenarios of exposure to lamps containing small amounts $^{85}$Kr

Increase of the effective dose during normal occupational exposure to intact lamps containing small amounts of $^{85}$Kr

- The maximum activity that can be loaded is described in paragraph 2.d “Operational Dose Rates Close to Pallet Stacked with lamps”. For a conservative approach a pallet of 1 m$^3$ is assumed to contain 20 MBq $^{85}$Kr.

- Only the emitted gamma-radiation will contribute to the dose in the surrounding environment close to lamps as discussed in paragraph 2.d “Operational Dose Rates Close to Pallet Stacked with lamps”. The codes of the program Microshield Version 8.01 (Grove Software Inc., Lynchburg, USA 2008) were used to calculate the ambient dose equivalent rate at 10 mm depth and the directional dose equivalent rate at 0.07 mm depth as defined in [ICRP-51] $^{17}$. Both operational radiation protection quantities were found to increase with a value of 25 nSv per hour. At a distance of 1 meter from the surface of the pallet both dose rates were found to increase with a value of 4 nSv per hour.

- Annual occupational exposure to 1 pallet containing 20 MBq $^{85}$Kr during 400 h.

- Annual increase of Effective dose due to occupational exposure to lamps containing $^{85}$Kr

\[
\text{Annual Increase} = 4 \text{ nSv/h} \times 400 \text{ h/y} = 1.6 \mu \text{Sv per year}
\]

$^{17}$ Where applicable in this study, this programme was also used to calculate the effective dose and the equivalent skin dose as defined in ICRP-74.
Increase of the skin equivalent during normal occupational exposure to intact lamps containing small amounts of $^{85}$Kr

- During manual handling any surface of the skin can only be exposed to the radiation emitted by a single lamp. As a consequence, any surface of the skin will not be in close contact to a $^{85}$Kr-activity exceeding the exemption level of 10,000 Bq defined in Schedule I of BSS [IAEA-BSS-115]. The skin is, due to the lamp construction, effectively protected against the emitted beta-radiation that would otherwise dominantly contribute to the equivalent skin dose.

- Calculations were done for a typical lamp described having a diameter of 2 cm. The arc tube containing $^{85}$Kr is centred in the middle of the lamp, is 1 cm long and has a diameter of 0.7 cm and contains an activity of up to 300 Bq. For a conservative assumption, the dose rate is calculated at 1 cm distance from a point source having a $^{85}$Kr-activity of 10,000 Bq. The codes of the program Microshield Version 8.01 (Grove Software Inc., Lynchburg, USA 2008) were used to calculate the directional dose equivalent rate at 0.07 mm depth. The dose rate was found to increase with a value of 40 nSv per hour.

- An annual exposure time of 10 hours for direct contact during manual handling is assumed according to EU-RP-65.

- Annual occupational skin exposure to lamps each containing 10,000 Bq $^{85}$Kr during 10 h of direct contact per year

\[
40 \text{ nSv/h} \times 10 \text{ h/y} = 400 \text{ nSv per year} \\
= 0.4 \text{ µSv per year}
\]
Submersion to $^{85}$Kr under incident conditions due to loss of containment.

- The radiological consequences of loss of containment of $^{85}$Kr were evaluated according to the Q-system described in the advisory material published by the IAEA for the safe transport of radioactive material [IAEA-TS-G-1.1 (Rev. 1)].

  - The instantaneous release of a consignment of 20 pallets of lamps products equaling to an activity of 100 MBq $^{85}$Kr;

  - $^{85}$Kr is released and uniformly distributed into a storeroom of dimensions $3 \times 10 \times 10$ m$^3$;

  - The storeroom is ventilated with four air changes per hour; i.e. the $^{85}$Kr-air concentrations falls exponentially with a decay constant of $4$ h$^{-1}$;

  - A person is exposed during 0.5 h. For a conservative approach, full decay of the concentration is assumed.

  - The dose coefficients to estimate the increase of the effective dose due to submersion to $^{85}$Kr = $2.40 \times 10^{-16}$ Sv.Bq$^{-1}$.s$^{-1}$.m$^3$;

  - The dose coefficients to estimate the increase of the skin equivalent dose due to submersion to $^{85}$Kr = $1.32 \times 10^{-14}$ Sv.Bq$^{-1}$.s$^{-1}$.m$^3$;

- Increase of the effective dose due to submersion to $^{85}$Kr under incident conditions

  \[
  = 2.40 \times 10^{-16} \text{ Sv.Bq}^{-1} \cdot \text{s}^{-1} \cdot \text{m}^3 \times 60 \text{ sec/min} \times 60 \text{ min/h} \times 1/4 \cdot 1/\text{h}^{-1} \\
  \times 100 \text{ MBq} / 300 \text{ m}^3
  \]

  \[
  = 0.1 \mu\text{Sv per incident}
  \]
Increase of the skin equivalent dose due to submersion to $^{85}$Kr under incident conditions

\[
= 1.32 \times 10^{-14} \text{ Sv.Bq}^{-1} \text{s}^{-1} \text{m}^{-3} \times 60 \text{ sec/min} \times 60 \text{ min/h} \times \frac{1}{4} \frac{1}{h} \\
\times \frac{100 \text{ MBq}}{300 \text{ m}^3}
\]

\[
= 4 \mu\text{Sv per incident}
\]
Annex 6  Dose Calculations for scenarios of exposure to lamps containing Thorium

Additionally to the dose results in the above mentioned independent studies there were made dose calculations according to the conditions of the Doc. XI-028/93-DE RP 65 [EU-RP-65] and sophisticated codes of computer modelling Microshield V. 8.03. For the calculations Thorium was assumed in the equilibrium with the progenies (= Th- nat) as a conservative approach.

Transport Accident case of broken lamps:

Parameters:

20 pallets with altogether 2,000 lamps (2,000 x 1,000 Bq/lamp) are involved in an accident and all the lamps are fully destroyed. The radioactive parts are fixed inside the Tungsten matrix and can therefore be collected and put into a box were they can be disposed afterwards. The exposure is caused by the gamma- and beta radiation of the electrodes. The dose contribution of the alpha radiation is not relevant due to the low reach in air (few centimeters).

The time for collecting the lamp parts is assumed to 2 hours/employee. This case overestimates the dose because the employees who handle the metal and glass parts will wear gloves to protect the skin from injuries.

acc. to [EC RP 65] A 1.1: External exposure by handling

\[ E = H_{\text{Skin}} \cdot W_{\text{Skin}} \cdot (\text{contact/body}) ; \]
\[ H_{\text{Skin}} = A_5 \cdot T \cdot (R_7 + R_{24}) = \text{equivalent dose of skin} ; \]
\[ A_5 = C \cdot U = \text{activity of contaminated area} ; \]
\[ C = \text{activity concentration of the radiation source max 72 Bq/g} ; \]
\[ U = \text{relation mass/surface (17.1) g/cm}^2 ; \]
\[ R_7 = \text{equivalent dose rate by gamma for skin} = 1.65 \cdot E \cdot 7 \quad (\text{Sv/h}) / (\text{Bq/cm}^2) ; \]
\[ T = 2 \text{ h} ; \]
\[ R_{24} = \text{equivalent dose rate by beta radiation} = 1.94 \cdot E \cdot 6 \quad (\text{Sv/h}) / (\text{Bq/cm}^2) ; \]
\[ \text{contact} = 100 \text{ cm}^2 \text{ area} ; \quad \text{body} = 1E+4 \text{ cm}^2 \text{ area} ; \]
\[ W_{\text{Skin}} = \text{tissue weight factor Skin} = 1E-2 ; \]
\[ E = 0.52 \mu\text{Sv/ accident} \]
Warehouse Accident fire scenario

acc. to [EC RP 65] B 2.7: Fire: Contamination of the skin

This pathway considers a warehouse fire in which the radioactive source is ignited. The fraction of the source which is combustible into ash is assumed to be 0.1% for solid waste forms [NUREG 1717]. For skin contamination it is assumed that the ash is deposited over a large area of the workplace, to a thickness of 0.1 mm. The skin dose was calculated assuming that a skin area of 100 cm² was exposed to the deposit for 10 minutes. This is likely to be the pans of the face or the back of the hands, where the skin thickness is only 40 μm.

Pre conditions:

The total amount of burned sources will be 24 palettes and therefore about 144 Mercury Short Arc Lamps with each 4,500 Bq = 648 kBq²³²Th (max. value!)

The ash will be spread over the workplace up to a deposit thickness of 0.1 mm.

Exposure time \( T = 10 \text{ Minutes}=0.16h \)

Skin dose by skin contamination

\[
H_{\text{skin}} = \frac{As \cdot (R_7 + R_8)}{s}
\]

\( R_7 = \) Equivalent dose rate for the basal cell layer by Gamma radiation²³²ThN: \( 1.65E-07 \text{ (Sv/h)/(Bq/cm²)} \)

\( R_8 = \) Equivalent dose rate for the basal cell layer by Beta radiation²³²ThN: \( 9.46E-06 \text{ (Sv/h)/(Bq/cm²)} \)

\( s = \) Incident probability of an event during a year \((1E-2/a)\)

\( A = \) Activity of source before ignition \((144x4,500 \text{ Bq})\)

\( c = \) Fraction of source which is combusted into ash \((= 1E-3)\)

\( As = \frac{(A \cdot c)}{\text{AREA}} = 648 \text{ 000 x1E-3/ 86 400 = 7.5E-3 Bq/cm²} \)

The ash covered area will be determined as follow:

\[
\text{AREA} = \frac{(M \cdot c)}{(\rho \cdot t)} = 86,400 \text{ cm}^2
\]

\( M = \) mass of the source at the beginning of the fire \((144 \times 3,000 \text{ g})\)

\( c = \) Fraction of source which is combusted into ash \((= 1E-3)\)

\( \rho = \) Density of deposit on surface \((= 0.5 \text{ g/cm}^3)\)

\( t = \) Thickness of deposit \((1E-2 \text{ cm})\)

Effective dose by skin contamination:

\[
E = H_{\text{skin}} \cdot w_{\text{skin}} \cdot (\text{CONTACT} / \text{BODY})
\]

\( w_{\text{skin}} = \) weighting factor for the skin \((0.01)\)

\( \text{CONTACT} = \) area of the skin Contamination \((100 \text{ cm}^2)\)

\( \text{BODY} = \) total skin area \((1E+4 \text{ cm}^2)\)

\[
H_{\text{skin}} = 7.5E-3 \times 0.16 \times (1.65E-7 + 9.46E-6) \times 0.01 = 1.16 \text{ E-10 Sv}
\]
\[ E = 0.116 \text{ nSv} \times 0.01 \times (100/1E+4) \]
\[ E = 0.01 \text{ pSv} \]

acc. to [EC RP 65] B 2.8: Fire: Inhalation of dust or volatiles

This pathway considers the same fire as in B 2.7, in which a person inhales the combustion products for 10 minutes. This could occur even after the fire is extinguished, if the air remains burdened with combustion products. It is assumed that 100% of the combusted fraction (according to [NUREG 1717] = 0.1% for all other waste forms) fills a room of 32 m\(^3\) and remains at the same air concentration for at least 10 minutes.

Effective dose for Inhalation of aerosols and ash in case of fire:

\[ E = X \times T \times \text{INH} \times R_{10} \times s \]

- \( E \) = Annual effective Dose
- \( X \) = Activity per unit volume of air (Bq/m\(^3\)) due to fire
- \( T \) = Exposure time 10 min.
- \( \text{INH} \) = Breathing rate (1 m\(^3\)/h)
- \( R_{10} \) = Effective dose coefficient
- \( {}^{232}\text{Th} : 1.53\times10^{-4} \text{ Sv/Bq} \)
- \( s \) = Probability of exposure during one year = 1E-2/a

Calculation of activity per unit volume:

\[ X = \frac{(A \times c)}{\text{VOL}} \]

- \( A \) = Activity of the radiation source prior combustion
- \( c \) = Fraction of the radiation source, combusted to ash (\( = 10^{-3} \))
- \( \text{VOL} \) = Volume of the location wherein combustion takes place (proposal = 32 m\(^3\), e.g. warehouse)

Inset of X in the formula:

\[ E = \frac{(A \times c \times \text{INH} \times R_{10} \times s)}{\text{VOL}} \]
\[ E = 5.0 \text{ µSv} \]
acc. to [EC RP 65] B 2.9: Fire: External dose from combustion products

In this scenario it is assumed that the fire in scenario B2.7 forms a cloud which persists for at least 10 minutes, in which time an individual will be exposed by an external dose from the gamma-and beta-radiation within the cloud (as in B2.6). It is assumed that 100% of the combustible fraction fills a room of 32 m³, with the same air concentration for 10 minutes.

Effective Dose caused by external beta- and gamma radiation exposure:

\[ E = (X \cdot T \cdot (R_1 \cdot CF_1) + (R_2 \cdot CF_2 \cdot w_{skin})) \cdot s / h \]

- \( T = \) Exposure time (=0.16h)
- \( R_1 = \) average photon energy per nuclear transformation
  - \( {}^{232}\text{Th} \): 2.52E+00 MeV
- \( CF_1 = \) eff. dose rate within a cloud of 1 Bq/m³ per MeV gamma energy
  - \( (1.6 \cdot 10^{-6} \text{ Sv/h} / \text{MeV(Bq/m³)}) \)
- \( R_2 = \) average beta energy per nuclear transformation
  - \( {}^{232}\text{Th} \): 1.37E+00 MeV
- \( CF_2 = \) dose equivalent rate on the skin within a cloud of 1 Bq/m³ per MeV beta energy
  - \( (2 \cdot 10^{-6} \text{ Sv/h} / \text{MeV(Bq/m³)}) \)
- \( w_{skin} = \) weighting factor for the skin (0.01)
- \( s = \) probability of exposure during one year (0.01)
- \( h = \) number of hours (8,760 h/a)

Calculation of activity per unit volume:

\[ X = \frac{(A \cdot c)}{VOL} \]

- \( c = \) Fraction of radiation source, combusted to ash (= 1E-3)
- \( VOL = \) volume of the location combustion take place (proposal = 32 m³)
- \( X = 20.25 \text{ Bq/m}^3 \)
- \( E = 0.025 \text{ nSv} \)

Assembly of lamps into luminaries as well as installation, servicing and repair activities

Dose rate of a single lamp (external gamma exposure, alpha and beta is completely shielded within the quartz glass bulb); Lamp with \( {}^{232}\text{Th} \) activity \( A = 4500 \text{ Bq} \) max. value only for special lamps;

- Exposure time \( t = 200 \text{ h/a} \) (10% of the annual working time (2,000h) is related to lamp handling);
- Distance \( d = 0.2 \text{ m} \); Quartz glass thickness, 4mm; Tungsten matrix cylinder 20mmx18mm diameter

\[ Dr = \text{effective Dose rate calculated by Software Micro Shield 8.0 here} = 0.0288 \mu \text{Sv/h} \]

\[ E = 200 \text{ h/a} \cdot 0.0288 \mu \text{Sv/h} \] (very special lamps, only few, maximal activity value)

\[ 5.76 \mu \text{Sv/a} \text{ for } 4500 \text{ Bq in } 0.2 \text{ m} \text{ distance or} \]

\[ 0.23 \mu \text{Sv/a} \text{ for } 4500 \text{ Bq in } 1.0 \text{ m} \text{ distance} \]

(Thoriated electrodes have distance to the lamp surface, additionally protection gloves are used)
Skin dose:

\[ D_{r} = \text{Effective Skin Dose rate calculated by Software Micro Shield 8.0 here} = 0.0246 \, \mu Sv/h \]

\[ E_{\text{skin}} = 200 \, h/a \cdot 0.0246 \, \mu Sv/h = 4.9 \, \mu Sv/a \text{ for } 4,500 \, Bq \text{ in } 0.2 \, m \text{ distance} \]

- End of Life - Treatment and Disposal

acc. to [EC RP 65] B 3.4: Ingestion of thoriated electrode (child swallows an electrode on a landfill, waste disposal)

\[ E = C \cdot M_1 \cdot f \cdot R_0 \cdot \text{decay} \cdot s \]

\[ C = \text{activity concentration of electrode material } 72 \, Bq/g \text{ max.} \]

\[ M_1 = \text{mass of electrode } = 100E-3 \, g \text{, only small electrodes can be swallowed} \]

\[ f = \text{swallowed part of electrode } = 100 \% \]

\[ R_0 = \text{effective dose coefficient for incorporation by ingestion } ^{232}\text{Th sec} = 4.93 \cdot E-6 \, Sv/Bq \]

\[ \text{including follow up dose} \]

\[ \text{decay} = \text{factor } 1 \]

\[ s = \text{probability of exposure during one year } (0.01) \]

\[ E = 0.36 \, \mu Sv \]

Ingestion of a thoriated electrode is considered as an exceptional case because the sharp glass scratches at first would avoid a person of a probable intake. Additionally the resorption of the Thorium in such form (bounded in the tungsten matrix) will not be completely implemented in the body.
### Annex 7  Thorium ($^{232}$Th) Decay Chain

<table>
<thead>
<tr>
<th>Nuclides</th>
<th>$\gamma$-Energies</th>
<th>Half life</th>
<th>Boiling point [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Th-232</td>
<td></td>
<td>1,4E10 a</td>
<td>4200</td>
</tr>
<tr>
<td>Ra-228</td>
<td>$\beta,\gamma$</td>
<td>5,75 a</td>
<td>1140</td>
</tr>
<tr>
<td>Ac-228</td>
<td>$\beta,\gamma$</td>
<td>6,13 h</td>
<td>3300</td>
</tr>
<tr>
<td>Th-228</td>
<td>$\alpha,\gamma$</td>
<td>1,91 a</td>
<td>4200</td>
</tr>
<tr>
<td>Ra-224</td>
<td>$\alpha,\gamma$</td>
<td>3,66 d</td>
<td>1140</td>
</tr>
<tr>
<td>Rn-220</td>
<td>$\alpha$</td>
<td>55,8 s</td>
<td>-62</td>
</tr>
<tr>
<td>Po-216</td>
<td>$\alpha$</td>
<td>0,15 s</td>
<td>962</td>
</tr>
<tr>
<td>Pb-212</td>
<td>$\beta,\gamma$</td>
<td>10,6 h</td>
<td>1751</td>
</tr>
<tr>
<td>Bi-212</td>
<td></td>
<td>60,6 min</td>
<td>1420</td>
</tr>
<tr>
<td>Ti-208</td>
<td>$\alpha$</td>
<td>3,1 min 3E-7 s</td>
<td>1475, 962</td>
</tr>
<tr>
<td>Po-212</td>
<td>$\beta,\gamma$</td>
<td>511, 583, 860, 2614</td>
<td></td>
</tr>
<tr>
<td>Pb-208</td>
<td>$\beta,\gamma$</td>
<td>stable</td>
<td>1751</td>
</tr>
</tbody>
</table>

35% $\alpha$  64% $\beta,\gamma$  40, 727, 1620
5. List of Contributors

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