A Survey into the Radiological Impact of the Normal Transport of Radioactive Material by Sea

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ABSTRACT

A survey has been carried out of the normal transport of radioactive material carried by sea to and from the UK. Information was obtained on these shipments, made during 2006 to 2008, and assessments were made of the resulting radiation doses to workers and members of the public. It was found that some 30,000 packages are transported annually by sea to and from the UK in about 1000 consignments. The radiological consequences of these shipments were found to be very low. The highest annual radiation dose to any dock worker or ships' crew member was found to be 0.2 mSv, and the majority receive annual doses of only a few microsieverts or less. Almost all of these annual consignments are made by cargo ship or ferry and only a small proportion of the total is made by passenger ferry. The annual dose to a general member of the public from the latter was found to be less than one microsievert. The annual collective dose arising from despatch, receipt and shipment of these materials to and from the UK was assessed to be around 2×10^{-3} man Sv.

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EXECUTIVE SUMMARY

A survey has been carried out of the normal transport of radioactive material carried by sea to and from the UK. Information was obtained on the nature and volumes of these shipments, made during 2006 to 2008, and assessments were made of the resulting radiation exposures of workers and members of the public. Data were collected on about 30,000 packages carried in almost 1000 consignments that are transported by sea to and from the UK annually. The radiological consequences of these shipments were found to be very low. The highest annual radiation dose to any dock worker or ships' crew member was found to be 0.2 mSv, and the majority receive annual doses of only a few microsieverts or less.

The annual collective dose arising from despatch, receipt and shipment of these materials to and from the UK was assessed to be around 2×10^{-3} man Sv. Almost all of this was from loading and unloading operations on cargo ships or freight ferries. The positioning of cargo and vehicles carrying packages is such that the doses received by crew during voyages are almost zero. The only exception to this was a single annual shipment of a large number of cylinders carrying depleted uranium hexafluoride, where the crew might receive small doses during the voyage.

Almost all of the shipments of radioactive material are made by cargo ship or ferry and only a small proportion of the total is made by passenger ferry. No evidence was found of any significant exposure of members of the public. However, drivers of lorries on freight ferries or car occupants on passenger ferries may receive very small annual doses from adjacent vehicles carrying radioactive material. For members of the public this annual dose was estimated to be less than one microsievert.

The survey showed that there have been a number of general trends since a previous survey was carried out more than a decade ago. There are currently no regular movements of irradiated fuel from the civil nuclear power industry, and the raw material for the manufacture of nuclear fuel is now imported as uranium trioxide (UO_3), rather than "yellow cake" (U_3O_8). Also, the UK's main supplier of radioactive materials for medical and industrial applications exports its products by air and, for the last several years, by the Channel Tunnel rail link rather than by cross-channel ferry. Overall, these changes will have resulted in a reduction in the radiological impact from the transport of radioactive material by sea to and from the UK.

CONTENTS

1 INTRODUCTION

1.1 Background to the study

A study has been carried out of the normal transport of radioactive materials by sea to and from the UK, during 2006 to 2008, and assessments have been carried out to determine the radiological impact of these movements in terms of the radiation doses to workers and members of the public. Also, comparisons have been made with a previous study carried out in the mid-1990s (Gelder, 1996), and the main trends identified.

The international safety standards for the transport of radioactive material are set by the International Atomic Energy Agency (IAEA), and published as model regulations (IAEA, 2005). These regulations require the relevant competent authority in Member States of the IAEA to arrange for periodic assessments of the radiation doses to persons due the transport of radioactive material. The Department for Transport (DfT) has therefore commissioned this study and, in recent years, similar studies on other modes of transport (Warner Jones, et al, 2003) (Watson, et al, 2005), as well as the previous study on sea transport (Gelder, 1996).

1.2 Regulatory requirements

The transport of radioactive material by sea must be carried out under the requirements of certain national and international legislation. Internationally, the relevant standards are published by the International Maritime Organisation (IMO). The IMO's International Maritime Dangerous Goods (IMDG) Code includes the detailed requirements for the safe transport of all dangerous goods by sea, including radioactive material. There are 9 classes of dangerous goods listed in the IMDG Code, of which radioactive material is Class 7. The standards embodied in the IMDG Code on the transport of radioactive material are derived from the safety requirements published by the IAEA (IAEA, 2005). This Code is updated every two years, as is the relevant international legislation for other modes of transport. For the period covered by this study the relevant edition of the IMDG Code was that published in 2006 (IMO, 2006). When packages containing radioactive material are stowed aboard a ship they must be segregated from areas occupied by the crew and passengers. The IMDG Code contains tables giving minimum segregation distances based on the total Transport Index[1] (TI) of the consignment, and the duration of the voyage. The IMO has also published guidance on the temporary storage of packages containing radioactive material in port areas (IMO, 2007).

Nationally, the main regulations are the Merchant Shipping (Dangerous Goods and Marine Pollutants) Regulations 1997 (GB Parliament, 1997), which require compliance with the IMDG Code. Those regulations are referred to the latest edition of the IMDG Code by the biennial publication of a Merchant Shipping Notice (MCA, 2006). Operators

[1] Some scientific and technical terms used in relation to radioactivity and the transport of radioactive material are described in the Glossary.

of vessels entering UK harbours must also comply with requirements for emergency planning and notification (GB Parliament, 1987). More generally, any work involving ionising radiation must be carried out in accordance with the Ionising Radiations Regulations 1999 (GB Parliament, 1999). Those regulations specify an annual limit on effective dose for workers of 20 mSv, and for members of the public, of 1 mSv.

This report contains references to the dose rates measured around packages during visits to ships, docksides and other premises. The maximum dose rate allowed at the surface of a package, under normal circumstances, is 2 mSv h^{-1} (2000 µSv h^{-1}) (IAEA, 2005).

1.3 Objectives and methods

The main objective of the study was to assess the radiation exposure of workers, and members of the public, from the normal transport of radioactive material by sea to and from the UK. The workers considered were those involved in the loading and unloading of ships as well as crews on board during the voyage.

The main tasks were to:

- identify the significant operations in terms of numbers of packages and/or people involved as well as any operations that could give rise to significant exposures;
- determine transport and working patterns as well as making measurements in and around ships transporting radioactive materials;
- assess the maximum individual and collective doses to workers and public using the quantities specified by the International Commission on Radiological Protection (ICRP, 1991);
- make comparisons with the previous survey (Gelder, 1996) to identify any trends.

The scope of the study covered all types of sea transport used to transport radioactive materials. All categories of radioactive materials were considered, including radioactive materials for medical and industrial use as well as materials associated with the civil nuclear fuel cycle. The transport of radioactive waste products was also considered. The survey was limited to the normal transport of radioactive materials, that is, under accident-free conditions, where the transport is carried out in compliance with the appropriate regulations (see Section 1.2).

Visits were made to the main consignors and consignees to discuss the objectives of the study and to obtain data on the volumes of shipment of the different types of material. Other data were obtained by correspondence. The types and volumes of materials transported by sea are discussed in Section 2.

During some of the visits to consignors' and consignees' premises dose rate measurements were made around packages that had been or were to be shipped by sea. Measurements were also made during visits to docksides and ships during loading or unloading operations. During those visits observations were made of the package handling procedures and worker doses were assessed from measured dose rates, and estimated exposure times. For some of these operations personal dosimeters were worn by a ship's crew and dockside workers, and information was obtained on those dose data by correspondence. The relevant information on dose rates, exposure times and assessed doses are given for each type of transport operation in Appendix A, and described in Section 3.

2 MATERIALS TRANSPORTED BY SEA

2.1 Types of material

Radioactive material is transported by sea to and from the UK, involving both long sea voyages and relatively short ferry crossings of the North Sea and English Channel. Almost all the materials transported fall into distinct types: materials associated with the nuclear industry, high-activity ^{60}Co sources, and materials used for industrial and medical applications. It is understood that the main UK producer of radiopharmaceuticals exports its materials either by air or by road using the Channel Tunnel rail link. There are imports of naturally occurring radioactive material, either packaged or unpackaged, for non-nuclear industries. However, these materials are outside the scope of the transport regulations due to their low activity concentration (Hughes and Harvey, 2008).

The following sections describe the types of shipments of radioactive material identified during the survey. Table 1 in Section 2.4 gives a summary of the main regular shipments of radioactive material made annually to and from the UK.

2.2 Nuclear industry materials

Figure 1 shows in schematic form the movement of materials associated with the production of nuclear fuel. Imported uranium trioxide (UO_3) is converted into uranium hexafluoride (UF_6), which is transported to an enrichment plant. In former years the feed material was U_3O_8, known as yellow cake, and which was then converted into UO_3. In the current process the conversion to UO_3 is carried out in the country of origin. The UF_6, following enrichment in ^{235}U, is transported to a fuel fabrication plant for conversion into uranium dioxide (UO_2) for the manufacture of nuclear fuel. Fuel made of natural un-enriched uranium, such as for Magnox reactors, can be made directly from uranium oxide without conversion into UF_6. Spent nuclear fuel from reactors is stored on-site for a period of time and then transported in flasks to storage, or reprocessing, sites. These movements can involve transport by sea. The descriptions of the transport methods in the following sections refer to those that were contemporary with the period of the study; that is, during 2006 to 2008.

2.2.1 Uranium trioxide

Uranium trioxide (UO_3) is imported into the UK by sea in drums carried within freight containers (Figure 2), as low specific activity material (LSA-I). The consignments typically consist of some 10 to 12 freight containers. Each container normally carries a single layer of 44 drums (Type IP-2) of volume 200 litres and each drum weighing about 300 kg. In 2006 there were 13 such consignments, and 6777 drums were imported in approximately 150 containers. These freight containers are transported in large container ships and the voyage time is between 5 to 10 days from the country of origin. The freight containers carrying the UO_3 are stowed in the central forward holds of the ship, about four levels down, and some 100 m from the accommodation areas of the ship. Also, during the voyage the holds are sealed so that there is no access to the areas close to the containers.

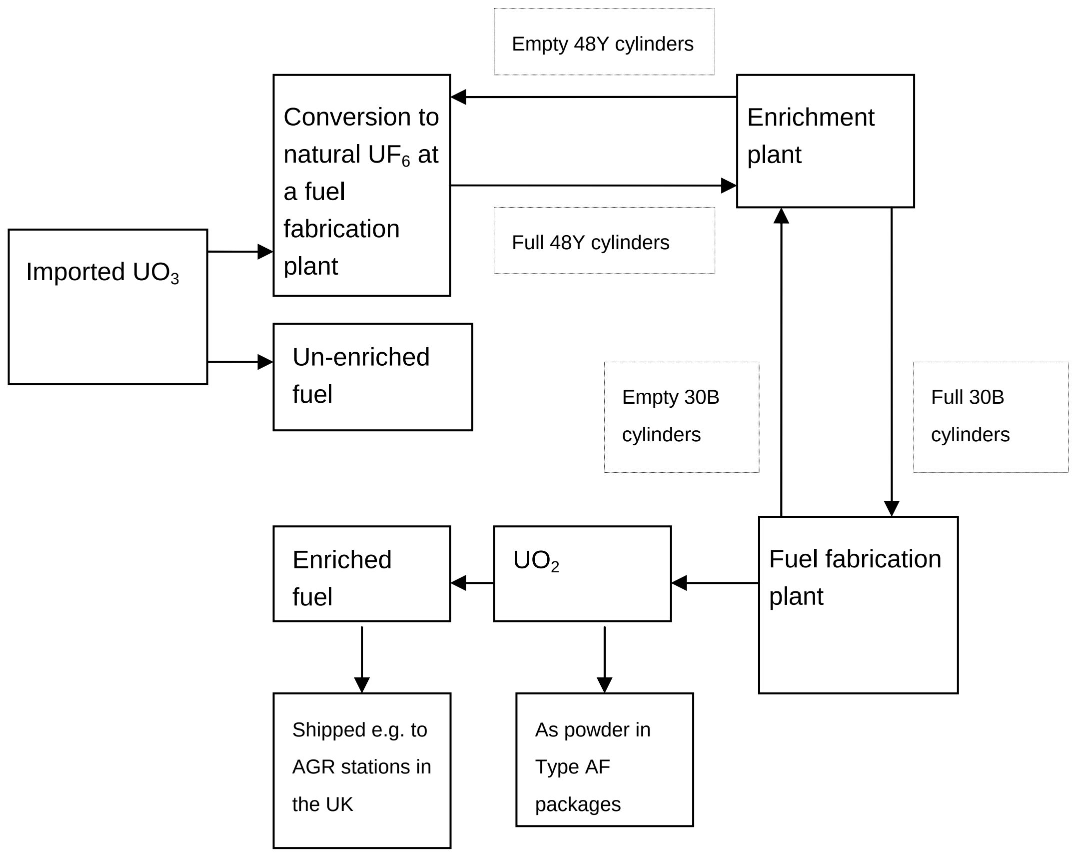

Figure 1. Enrichment and fuel fabrication process

Figure 2. Drums of UO_3 inside a freight container

On arrival in the UK, after being placed on the quayside, the containers are taken by mobile "straddle carrier" cranes to a marked area of the dockside designated for radioactive materials. The containers are subsequently transported from the port to the fuel fabrication plant by road.

2.2.2 Natural uranium hexafluoride

Natural un-enriched uranium hexafluoride is carried in steel cylinders (model 48Y), which are classified as Industrial Packages Type 2 (IP-2). These are about 3.8 m long, with a diameter of 1.2 m, and carry up to about 12 tonnes of UF_6. They have a covering material to provide thermal protection from fire. These cylinders are carried on lorry trailers, either fixed directly to the trailer or fixed within a steel frame called a "flatrack" (Figure 3). The surface dose rate is typically 10 µSv h^{-1} and, at 1 m, about 3 µSv h^{-1}. They are labelled category II-Yellow and nominally assigned a TI of 0.9.

Figure 3. Lorries carrying 48Y cylinders of natural UF_6 on the vehicle deck of a freight ferry

Empty cylinders are returned to the uranium oxide/ hexafluoride conversion plant which can contain deposits of UF_6 called “heels”. However, it should be noted that most of the cylinders encountered during this study were from facilities that periodically clean the internal surfaces. These “heeled” cylinders typically have dose rates at least an order of magnitude below those of full cylinders and are not considered further in this study, since their transport contributes a negligible dose to transport workers. Data on the number of these cylinders shipped by sea are included in Table 1.

Cylinders of natural UF_6 are carried by lorry and cargo ferry from the UK to enrichment plants in other European countries. These lorries are stowed in the middle deck of the ferry, in an area which is reserved for hazardous goods consignments, and which is at least 50 m from the areas occupied during the voyage. Before the ferry sails, a member of the crew attaches chains to the vehicles to secure them to the deck.

Figure 4. Manual removal of twist locks

Figure 5. Transport of flatracks and containers in a port area by straddle carrier

Imports of natural UF_6 in 48Y cylinders are also brought into UK ports from overseas, on large cargo ships. These are carried fixed within flatracks and are stowed in the forward areas of the ship, remote from the accommodation block. The flatracks are fixed to the deck or to another container by semi-automatic twist locks. Before the flatracks, or other containers, can be lifted off the ship port workers must unlock the twist locks manually. During the unloading of the flatracks by crane, and before being placed on the quayside, they are lowered so that the twist locks can be manually removed by stevedores (Figure 4).

The flatracks are then taken by straddle carriers (Figure 5) to a designated area of the dockside for temporary storage (Figure 6). They are then taken by straddle carrier to be loaded onto lorries for onward transport by road.

Figure 6. Natural UF_6 in 48Y cylinders fixed within flatracks in a dockside storage area

2.2.3 Enriched uranium hexafluoride

Enriched UF_6 is carried in steel cylinders (model 30B). These cylinders are some 2m long, about 0.8 m in diameter, and with a typical net content of about 1.5 tonnes. These packages are Type AF and are labelled category II-Yellow, fissile, UN2977, and typically have a TI of about 0.2 or 0.3. The dose rates at the surface of these packages are similar to those measured around the 48Y cylinders.

Up to four 30B cylinders can be fixed within a flatrack (Figure 7) and carried on a lorry trailer. The procedures for stowing lorries on cross-channel ferries, or unloading from a container ship, are very similar to those described in Section 2.2.2 for consignments of 48Y cylinders.

Figure 7. Four 30B cylinders containing enriched UF_6 fixed within a flatrack

2.2.4 Depleted uranium hexafluoride

The enrichment process results in large amounts of UF_6 depleted in ^{235}U. This material is shipped abroad to produce quantities of re-enriched material which can be used as feedstock for further enrichment and fuel fabrication. The consignments of depleted UF_6 are made in two ways. During 2007 9 consignments, each of 20 48Y cylinders carried on 10 lorries, were exported by road and freight ferry to a European site. Also, large numbers of 48Y cylinders containing depleted UF_6 are exported in the hold of a cargo ship, and in recent years one such consignment has been made annually from the UK. These Type IP-2 cylinders are labelled category II-Yellow, UN 2978, and the dose rates around a typical cylinder are very similar to those around cylinders of natural UF_6.

The shipments by road and ferry are made in a similar way to that described in Section 2.2.2 for cylinders of natural UF_6. For the large bulk shipment, cylinders are brought by road to the quayside and loaded by crane by about 5 quayside workers. Figure 8 shows the loading of one of 146 cylinders into the hold of a ship at a UK port during 2008. Figure 9 shows the stowage of the cylinders in the hold, and one of the 8 crew members engaged in fitting the lashings which secure the cylinders within the hold. During the voyage, which takes about 6 days, crew members may enter the hold and check that the lashings are secure, especially if the ship encounters rough weather.

Figure 8. Loading of cylinders of depleted UF_6 into the hold of a ship

Figure 9. Fixing cylinders of depleted UF_6 in the hold with steel supports and lashings

2.2.5 Material for new fuel

Exports of UO_2 are made from a nuclear site in the UK, via UK ports, where it is manufactured into nuclear fuel in the country of destination. This material is also exported by road and ferry to a port in Europe for onward shipment by sea. The UO_2 is contained within Type A packages carried inside standard "20-foot" or "40-foot" freight containers. During 2006 a total of 1879 packages in approximately 70 freight containers were exported. There were up to 2 freight containers for each consignment to Europe, and an average of 8 for shipments involving longer voyages. The freight containers are normally labelled as category III-Yellow, UN3327; the TI being typically about 2.8. For shipments of these containers by road and cross-channel ferry, the stowage procedures are similar to those described in Sections 2.2.2 and 2.2.3 for UF_6 shipments.

2.2.6 Irradiated nuclear fuel

The previous study on the transport of radioactive material by sea (Gelder, 1996) reported regular shipments of flasks containing irradiated fuel to a nuclear site in the UK. Since 2004, these shipments have virtually ceased as a result of changes in the nuclear industry business. However, during the period of the study two flasks carrying irradiated fuel from a research reactor were unloaded from a ship for temporary storage at a nuclear site. It is understood that the procedures observed on-board and during unloading were representative of the movement of other types of flasks carrying irradiated fuel.

The ship, certified to the INF3 standard, was specially designed to carry irradiated fuel. The two flasks were located in the forward hold some 45 m from the accommodation areas of the ship. The nearest regularly occupied area in the accommodation section is a room equipped with monitoring equipment, and instruments showing readings from radiation detectors installed in the holds. In addition to these installed monitors an engineer would enter the hold each day during the voyage to check equipment, and would also make dose rate measurements using a hand held instrument.

Before lifting the flasks from the hold by crane, about 4 workers attached the crane fittings to the flasks. The flasks were lifted from the hold and placed on rail wagons for onward transport, and the same workers were involved in securing the flask to the wagon.

2.2.7 Other shipments

In addition to the main regular shipments of materials described above, and listed in Table 1, a small annual number of movements of other materials are made by sea to and from nuclear sites in the UK. During 2007 the following shipments were reported:

- 18 Industrial Packages, Type IP-1, containing depleted uranium;
- 15 Type A packages containing plutonium/ uranium nitrate in an organic matrix from a research centre;
- 2 empty Type B(M) irradiated fuel flasks;

- one consignment of 2 flasks containing irradiated fuel from a research reactor (described in Section 2.2.6);
- 4 Type B(U) packages containing mixed oxide (MOX) fuel elements with a maximum TI per package of 2.2;
- 3 freight containers, each carrying 43 drums of thorium nitrate, the maximum TI per drum being 4.7;
- 4 freight containers, each carrying up to 60 Type IP-2 drums containing mineral oil, hydraulic oil and glycol, contaminated with radionuclides. This material was sent overseas for treatment and return. The TI for 3 drums was 0.3, and 0.1 for all the others;
- 2 freight containers, each carrying 5 Type IP-2 drums containing metallic lead, contaminated with radionuclides. This material was sent overseas for treatment and return. The TI for all the drums was 0.1.

The number of packages or freight containers involved in these shipments was small and the TI of each was low, typically 0.1 with a maximum of 4.7 for some of the thorium nitrate drums. The annual radiation doses to workers handling them would be much lower than for the regular shipments described in the preceding sections. Some of these small numbers of infrequent movements were “one-off” shipments. The last two shipments listed are of contaminated waste generated from decommissioning operations and sent abroad for treatment and return.

2.3 Industrial and medical materials

2.3.1 Irradiation plant sources

Some medical and surgical equipment are subjected to high doses of gamma radiation to sterilize them. This treatment is also applied to certain foodstuffs, including some spices and food packs for specialised uses. High activity ^{60}Co sources are used to provide the high intensity gamma radiation in these irradiation facilities. A company in the UK arranges the import and supply of these sources to irradiation facilities in the UK and overseas. Also, an overseas company supplies a number of these sources annually to UK facilities. These sources are produced by neutron irradiation inside nuclear reactors, and are currently imported by sea from three nuclear sites.

The ^{60}Co sources are carried within heavily shielded flasks, which typically contain around 10 sources with a total activity of about 5 PBq. Up to 4 flasks are carried within a flatrack similar to that described in Sections 2.2.2 and 2.2.3. The methods of transport and handling of those flatracks are also as described in those sections. Imports of new sources are by cargo ship to ports in the UK, where the flatracks are unloaded and carried by lorry to the supplier’s premises. Exports are either a reverse of these procedures, or by lorries travelling by cross-channel ferry and by road to European destinations. While loaded on a lorry these flatracks are fitted with a fabric covering.

When these lorries travel by cross-channel ferry, they are normally placed in the middle vehicle decks in the areas furthest from the occupied areas of the ship. Also these lorries, as with others carrying dangerous goods, are chained to the deck before the voyage.

2.3.2 Other industrial and medical materials

The company that distributes the ^{60}Co sources described in the previous section also supplies $^{241}Am/Be$ (americium/ beryllium) neutron sources and the transport methods are very similar to those described for ^{60}Co sources. Normally 4 freight containers, each carrying 14 Type A packages, are imported annually by sea through a port in the UK. They are held at the supplier's premises before being exported through a different port.

A European company supplies, by road and cross-channel ferry, radioactive material for medical uses to hospitals in the UK. One consignment is made each week of up to five Type A packages, with a total TI of about 4. The UK's main producer and supplier of radioactive materials for industrial and medical applications exports those materials by air or through the Channel tunnel rail link. Many of those packages supplied to hospitals contain technetium generators which are small units that produce a supply of ^{99m}Tc from the decay of ^{99}Mo. The ^{99m}Tc is used to image internal organs for a variety of diagnostic tests on patients. The ^{99}Mo has a relatively short half life (66 h) and the UK producer regularly imports consignments of used technetium generators from customers in other European countries by road and cross-channel ferry. These consignments can also include new radioactive materials for medical uses in the UK. Typically these would consist of 50 to 70 Type A packages containing ^{131}I, with a total TI of between 50 to 80.

Sealed radioactive sources are used in the oil production industry, mainly for carrying out well-logging and industrial radiography. The sources used for well-logging are lowered into the well for measurements of density and water content of rock. Typical activities used are 58 GBq of ^{137}Cs, and 296 GBq of $^{241}Am/Be$. These sources are typically transported to platforms in Type A packages labelled as category II-Yellow, and typically have a TI of 0.1. Information from the main port through which these packages are transported by supply vessel indicates that on average about one source per day is shipped through that port. The annual volume of these shipments is around 500 packages, as shown in Table 1. However, another main port was not able to supply data and this number may be an underestimate of the total number of such shipments through UK ports. The packages are always carried within a standard offshore container which is loaded as far aft as possible on the supply vessel. The low TI would give rise to a negligible dose during transport to and from platforms and no further assessment of exposure is carried out for these sources in this study.

Pipework and other equipment used on offshore oil platforms can become contaminated with scale containing naturally-occurring radioactive materials and are brought to an on-shore decaling facility. However the transport of these items results in only a trivial dose to the workers involved (Hughes and Harvey, 2008) and these materials are not considered further in this study.

There are occasional shipments of materials for non-nuclear industry uses, such as bulk shipments of ^{241}Am sources for smoke alarms. These and other such items are mainly transported as excepted packages and result in negligible doses to transport workers, and therefore these items are not considered further in this study.

2.4 Summary of shipments

The information on the shipments of radioactive materials to and from the UK is summarised in Table 1. The data in Table 1 are only for the main, regular, shipments. Some of the minor shipments noted in Sections 2.2.7 and 2.3.2 are not included. The annual numbers of packages carried by sea, listed in Table 1, are either from annual records held by the operators, or estimates based on typical weekly shipments. The data for the annual number of consignments represent annual totals for 2006 or 2007, or a 12 month period during 2007 - 2008, depending on what the operators could supply. These annual data are understood to be typical of recent years. The table covers a total of almost 1,000 consignments. Approximately 30% of these were of materials associated with the nuclear power industry and 70% were of materials for industrial and medical uses.

Table 1 Summary of main regular shipments by sea

Material	Annual number of consignments	Annual number of packages	Main package type	Report sections
Import of UO_3	13	6777	IP-2	2.2.1, 3.1.1
Import of UF_6 (enriched)	42	366	AF	2.2.3, 3.1.3
Import of UF_6 (natural, heels)	44	299	IP-2	2.2.2
Export of UO_2	39	1879	AF	2.2.5, 3.1.5
Export of UF_6 (natural)	50	260	IP-2	2.2.2, 3.1.2
Import of UF_6 (natural)	30	511	IP-2	2.2.2, 3.1.2
Export of UF_6 (enriched)	62	349	AF	2.2.3, 3.1.3
Export of UF_6 (depleted)	9	180	IP-2	2.2.4, 3.1.4
Export of UF_6 (depleted, bulk)	1	150	IP-2	2.2.4, 3.1.4
Import by a UK company of medical products and used technetium generators	52	3000 and 15000 used generators	A	2.3.2, 3.2.2
Import of medical products, from a European company	52	250	A	2.3.2, 3.2.2
Import of ^{60}Co from source A	6	120	B	2.3.1, 3.2.1
Import of ^{60}Co from source B	5	17	B	2.3.1, 3.2.1
Import of ^{60}Co from source C	5	8	B	2.3.1, 3.2.1
Import of $^{241}Am/Be$	4	56	A	2.3.2, 3.2.2
Export of ^{60}Co	26	104	B	2.3.1, 3.2.1
Export of $^{241}Am/Be$	4	56	A	2.3.2, 3.2.2
Sealed sources to/ from offshore installations from the main supply port	500	500	A	2.3.2

The consignments listed in Table 1 included some 30,000 packages, about 64% of which carried material for industrial and medical uses, and the remaining 36% carried materials associated with the nuclear industry.

3 DOSE ASSESSMENTS

3.1 Nuclear industry materials

3.1.1 Uranium trioxide

Consignments of UO_3 consist of several freight containers carrying IP-2 drums. The containers arrive at a UK port in the holds of large container ships, and are stowed several levels below the deck surface at least 50m from the accommodation areas of the ship. Measurements were made on such a ship after the hold had been opened and the dose rate in the walkway close to the ends of the freight containers was between 10 and 15 µSv h^{-1}. However, the holds are sealed during the voyage and so these areas are not accessible. The dose rate at the nearest access point on deck was at background level (i.e. less than 0.1 µSv h^{-1}) and therefore the dose to crew during the voyage is essentially zero.

Measurements were also made on a number of full containers at the consignee's premises and they were found to be almost identical in their characteristics. The typical dose rates at relevant distances are shown in Table A1. The main crane operator is at least 10 m from the containers as they are unloaded from the ship, for about 1 minute per container. The containers stowed in the holds are held in position by guide rails which are part of the structure of the hold, and therefore twist locks are not required. The containers are transferred to straddle carriers, the drivers of which are at a distance of about 3 m from the top of the container for the time it takes to move it to a storage area, assumed to be approximately 1 minute. A similar movement is required to take each container to a lorry for onward shipment by road.

The estimated annual doses from handling these containers at the dockside are shown in Table A1. The main crane operator would receive approximately 2.5 µSv y^{-1} from these shipments. In taking the containers to the storage area a straddle carrier driver would receive about 3.8 µSv y^{-1}, and a further dose of 3.8 µSv y^{-1} from transferring a container to a lorry. However, there are a number of such drivers and crane operators who would share these doses and so the annual dose to any individual driver or crane operator would be less than 1 µSv. The annual doses received by these workers from these operations are therefore extremely low.

3.1.2 Natural uranium hexafluoride

Tables A2 – A4 show estimates of the annual doses to transport workers from movements of natural uranium hexafluoride through UK ports. Table A2 contains data on shipments of this material in 48Y cylinders carried by lorry, and by freight ferry to nuclear sites in Europe. Normally about 3 lorries comprise a consignment, each carrying two cylinders (Figure 3). The dose rate at the surface of each cylinder is about 10 µSv h^{-1}, and about 3 µSv h^{-1} at 1 m. When the lorries are parked in the vehicle deck the typical dose rate at the sides of the vehicles is about 4 µSv h^{-1}. Within UF_6 alpha particles from the decay of uranium interact with fluorine nuclei to produce neutrons. However, the neutron dose rate measured at the surface of these cylinders was an order of magnitude or more less than the gamma dose rate.

The lorries are chained to the deck before the voyage by a crew member, who takes a few minutes to attach the chains to each lorry. This crew member is estimated to receive about 1 µSv for each consignment, and an annual dose of 27 µSv for the 27 consignments exported through that ferry port. A crew member also supervises the positioning of the lorries on the deck, which takes a few minutes at a distance of about 5m from the lorries. This may be done by the crew member who attaches the chains, and so would receive a further small additional dose (1.1 µSv y^{-1}), making an annual total of about 30 µSv. However during a year this dose is likely to be distributed over a number of such crew so that any individual would receive less than this dose. There were a further 23 similar consignments through another port, which would result in slightly lower doses than indicated in Table A2. Information from the main ferry companies indicated that the vehicle securing/ unchaining operations at the non-UK ports are carried out by workers from those ports.

The vehicle deck is not occupied during the voyage, and drivers are assumed to leave their vehicles immediately and return a few minutes before disembarking at the destination port. It is assumed that a driver in an adjacent lorry is waiting in the lorry cab for 15 minutes at a distance of 2 m. The dose received would be about 0.4 µSv, and it is assumed that this is not likely to be repeated during a year.

This material is also imported into the UK by a different company from that carrying out the above exports. The company imported an annual total of 60 cylinders in 3 consignments during 2007/8 (Table A3). For imports the procedures described above are reversed; that is, a crew member spends a few minutes releasing the chains from the vehicles so receiving an annual dose of about 6 µSv, including a small additional dose of 0.25 µSv from supervising the movement of the vehicles off the ferry. These doses will have been distributed among a number of such workers. A driver in an adjacent vehicle waiting to disembark might receive about 0.4 µSv.

Natural UF_6 is also imported in large container ships and off-loaded in a similar manner to that described for UO_3 shipments in Section 3.1.1. These consignments are also stowed well away from the accommodation areas and would give rise to essentially zero dose to the crew. The 48Y cylinders containing UF_6 are mounted lengthwise in flatracks (Figure 6) which are handled in the same way as freight containers. The unloading of a consignment of these flatracks was observed during a visit to a port. The flatracks were attached to the deck, or other containers with semi-automatic twist locks. These are unlocked on the ship by four dockworkers, before the main crane lifted each flatrack off the ship. While over the quayside the twist locks are removed by two stevedores (Figure 4). Table A4 shows the dose rates at distances relevant to the workers carrying out those operations. During 2007 there were 451 flatracks imported from a number of overseas consignors, resulting in annual doses of 7.5 µSv to each dock worker unlocking and removing the twist locks. The straddle carrier drivers are estimated to receive annual doses of 4.5 µSv, and the main crane operator, 3.7 µSv. However, individual annual doses would be lower as the indicated doses would be distributed among a number of such workers.

3.1.3 Enriched uranium hexafluoride

Enriched uranium hexafluoride is both imported and exported in a very similar manner to that described above for natural UF_6. However, the enriched UF_6 is carried within the smaller 30B cylinders which are mounted crosswise within flatracks; each flatrack carrying up to 4 cylinders. This arrangement results in lower dose rates from the sides of the flatracks, than for natural UF_6 cylinders. Table A5 shows the data for the import of 38 flatracks by cargo ship during 2006. The assessed annual doses to the workers involved are found to be extremely low, at less than 1 µSv.

Data for the imports of 19 consignments by ferry and road in 2006 are shown in Table A6. Each consignment consisted typically of 2 to 3 lorries each with a flatrack carrying 4 cylinders. The assessed doses are lower than for shipments of natural UF_6, and the most exposed worker is the crew member who releases the chains that fix the lorries to the deck. This annual dose is estimated to be approximately 3 µSv, but again this is likely to be shared among a number of such crew, so that individual annual doses would be less than this dose.

Table A7 shows data for exports during 2007 of 7 consignments of enriched UF_6 by road and ferry, which is the reverse of the operation described in the preceding paragraph. The resulting annual doses are very low, at about 1 µSv or less.

During 2007 there were 297 cylinders carried on approximately 84 flatracks containing enriched UF_6 exported through a port, and these were handled in a similar way to those imports of natural UF_6 described in Section 3.1.2, but as a reverse of those operations. The flatracks were loaded onto a cargo ship after being fitted with twist locks by stevedores. Semi-automatic twist locks are used that do not require manual locking on the ship. Table A8 shows the data for those operations, and the assessed annual doses are very low at less than 1 µSv from these shipments.

3.1.4 Depleted uranium hexafluoride

The enrichment process results in large quantities of depleted UF_6 and this material is exported in 48Y cylinders by two methods: by road and ferry, and as a large bulk shipment in a cargo vessel. During 2007 there were 9 consignments, of 20 cylinders each, taken by lorry and ferry to Europe, and Table A9 gives the data and dose estimates for those shipments. Each consignment would have involved some 10 lorries and it is assumed that a crew member would take about 30 minutes to chain them to the deck. For the 9 consignments this would result in an annual dose of about 18 µSv, assuming the same crew member carried out those operations. A small additional dose would also be received if that worker also supervised the positioning of the lorries in the deck area, giving an overall annual dose of less than 20 µSv. As with the other ferry shipments described above, it is assumed that a driver not involved with the shipment, was parked for about 15 minutes close to the consignment. This would result in a dose of about 0.4 µSv.

Cylinders containing depleted UF_6 are also exported from the UK in one large annual shipment. Measurements were made in 2008 while a cargo ship was being loaded with 146 cylinders of depleted UF_6, that were being shipped overseas (Figures 8 and 9), and a sample of the measurements made are shown in Table A10. The dose rates around a single cylinder are very similar to those around a cylinder of natural UF_6. The dose rate close to the surface is approximately 10 µSv h^{-1}.

The cylinders were placed into the hold and fixed in position with steel fittings and lashings. The dose rates in the areas of the hold close to the cylinders where workers were attaching these lashings was in the range 10 – 15 µSv h^{-1}, being typically about 13 µSv h^{-1}. The dose rates measured in the occupied areas of the ship such as the main living quarters, engine room and bridge were almost at background level on land; that is, 0.1 µSv h^{-1} or less. A measurement at 20 m from the ship on the dockside showed a dose rate at background level. Any workers at the port who were not involved with these operations were at a greater distance than this and therefore not subject to any significant dose. The dimensions of the site were such that any members of the public were at least 150 m away.

The dockside workers wear personal dosimeters for the duration of the operation and the crew wear similar dosimeters during the loading operations and during the voyage. The results recorded by those dosimeters for a similar operation during 2007 are shown in Table A11. The shipment involved 150 cylinders, as indicated in Table 1. The UF_6 cylinders arrive at the port by road, with each lorry carrying two cylinders. A worker from a small group of loading contractors who detached the fastenings and attached the crane slings, received 27 µSv during the whole operation. A deck operator who role was to signal to the crane operator to guide the cylinders into the hold received a smaller dose of 12 µSv. Contract workers in the hold, either positioning the cylinders or attaching the lashings received doses in the range 97 to 128 µSv. Members of the crew working in the hold received similar doses, the maximum being 210 µSv (i.e. 0.2 mSv). Those members of the crew may also check the integrity of the lashings during the voyage, which would be included in those doses.

3.1.5 Material for new fuel

Measurements were made around two freight containers carrying a number of packages containing UO_2 powder that were being exported for the manufacture of nuclear fuel. The dose rate at the surface of the containers was about 8 µSv h^{-1}, at 1 m 2 µSv h^{-1}, and at distances of between 5 to 10 m, 0.4 µSv h^{-1}. The freight containers were loaded onto the ship at a port in the UK and stowed just below deck level in a forward hold some 180 m away from the accommodation areas of the ship. The dose to the crew was therefore essentially zero. However, during the voyage of approximately 3 weeks the containers are monitored daily with a radiation dose rate meter, and the readings recorded. Such regular monitoring is understood to be a requirement of the shipping line. The dose to the crew member carrying out these measurements would be less than 1 µSv during the voyage. Doses to dockside workers, forklift truck drivers and crane drivers were estimated to be about 0.1 µSv or less, for this particular shipment.

The consignment described above was unusual in that very few of these freight containers are despatched on transoceanic voyages directly from a UK port. However, shipments are made on container ships to other European countries directly from a UK port. The doses assessed to dock workers from an annual total of 49 freight containers are shown in Table A12. The workers involved receive an annual dose of 0.4 µSv or less, and this dose is likely to be distributed among a number of such workers.

Freight containers carrying UO_2 powder are also carried on lorries by road and ferry, either to European destinations or to large ports in Europe for onward transoceanic shipment. The doses assessed for the ferry crossing are shown in Table A13, for an annual total of 8 consignments. The crew member attaching deck chains to the vehicles, and supervising the positioning of the lorries, would receive an annual dose of less than 5 µSv from these shipments. A driver not involved with this shipment, in an adjacent lorry would receive less than 0.2 µSv while waiting to disembark.

3.1.6 Irradiated fuel

As noted in Section 2.2.6, in recent years there have been very few international shipments of irradiated fuel. However, during the period of this study there was a shipment of two flasks containing irradiated fuel from a research reactor by sea to a nuclear site in the UK. Measurements were made on board the vessel before the flasks were unloaded and following unloading onto the quayside. The operations were observed and the occupancy times of the workers involved in the unloading were noted.

The maximum surface dose rate from the containers was 5 µSv h^{-1} and the dose rate at 1 m was less than 1 µSv h^{-1}. There was no detectable neutron dose rate. Dose rate measurements were made in the ship’s hold close to the flasks as the dose rates in the living quarters were at background level.

The maximum dose to the dockside crew from offloading both containers was assessed to be 0.7 µSv and for the crane driver less than 0.1 µSv. The dose to the ship’s crew in the living quarters was at background level and the only raised dose to the crew would be to the individual carrying out daily monitoring of the flasks, during the six week voyage. This dose was estimated to be 0.5 µSv for the whole voyage.

3.2 Industrial and medical materials

3.2.1 Irradiation plant sources

New ^{60}Co sources are brought from overseas to a UK port in heavily shielded flasks fixed to flatracks, with normally 4 flasks per flatrack. The flatracks are unloaded from the cargo ship using similar methods to other materials carried by flatrack described in previous sections. The approximate dose rates at relevant distances from the flatracks and assessed doses to dock workers are shown in Table A14. Some of these flasks can have a TI of 5.0, with a surface dose rate of up to 500 µSv h^{-1}. The doses were estimated using an average flask TI of 3.5. For the 30 flatracks imported through a UK port, it was estimated that the stevedores involved in close handling of the flatracks during unloading receive an annual dose of about 5 µSv. The other workers receive lower annual doses. As with other estimates of this type, these are maximum individual doses and the dose for each worker type will be shared among a number of workers.

These consignments are then taken by road to the supplier’s premises. After redistribution into batches for customers, the new sources are exported in flasks mounted on flatracks by two means: on transoceanic container ships and by road and cross-channel ferry to Europe. UK customers are supplied by road. The export of these sources through a UK port is essentially the reverse of the import procedures. However, the dose rates from the exported flasks are lower than from the flasks containing the new sources. The relevant data and assessed doses to the workers at the dockside are shown in Table A15. Annual doses to the workers involved are 1 µSv or less.

Visits were made to the premises of a supplier to obtain dose rate measurements from lorry trailers carrying flasks containing ^{60}Co sources. The maximum dose rates at 1 m from the sides of the lorries were found to be about ten times the TI for a single flask. The typical TI for flasks exported by ferry is about 1.2, which gives a dose rate of about 12 µSv h^{-1} at 1m from the lorry. This is approximately at the position occupied by the crew member during the operation to chain the vehicle before the ferry sailing. Assuming the same crew member is in the vicinity while supervising the positioning of this vehicle, and other vehicles, an annual dose of about 18 µSv would be received from 14 consignments (Table A16). However, it is likely that this annual dose would be distributed among a number of such crew. The driver of an adjacent vehicle might receive about 1.5 µSv while waiting to disembark.

3.2.2 Other industrial and medical materials

The main UK supplier of radioactive material for industrial and medical uses distributes this material including technetium generators to customers in Europe, either by air or through the Channel Tunnel. Used technetium generators are returned to the UK on lorries by freight or passenger ferry. The consignment also includes new material, typically 50 to 70 Type A packages containing ^{131}I with a typical total TI of 50 to 80. Measurements were made around the trailer of a lorry containing a typical load of this type. The maximum dose rate at one position on the side surfaces was 20 µSv h^{-1}, but more generally was less than 10 µSv h^{-1}. Due to the size of the lorry, and the positioning of the load, the dose rate in the cab was at background level. The maximum dose rate at 1 m and 2 m from the sides was 6 µSv h^{-1} and 3 µSv h^{-1} respectively. The dose rate was predominantly from the packages containing ^{131}I. The data are summarised in Table A17 and it should be noted that these were maximum doses and so the assessed doses are very conservative. The highest annual dose resulting from the weekly shipments is approximately 26 µSv to the crew member fixing deck chains to the lorry, but as noted for other operations of this type, this is likely to be distributed among a number of such crew members. On passenger ferries there may be members of the public in private vehicles adjacent to the lorry while waiting to disembark. The dose to the occupant of the vehicle would be less than 1 µSv, and it is assumed that this would be a one-off exposure.

A company in Europe exports radioactive material for medical uses by road and ferry to the UK. There is one shipment each week of up to five Type A packages. The maximum surface dose rate on the vehicle is in the range 20-80 µSv h^{-1} and the dose rate at 2 m is less than 3 µSv h^{-1}, which are therefore similar to the dose rates shown in Table A17. Therefore using the exposure scenarios assumed for Table A17, the annual doses from those shipments will be similar to those indicated in Table A17.

Neutron sources for industrial uses are imported by a company in the UK, and subsequently exported to various overseas customers. The ^{241}Am/Be sources are transported in Type A packages. Normally 14 of these packages are carried within a shipping container, and about 4 such containers are imported and exported annually.

These containers are held in temporary storage in the UK before shipment overseas. The Type A packages each contain 1.6 TBq of ^{241}Am, have TIs of 6.7 and surface dose rates of approximately 200 µSv h^{-1}. The dose rates around these packages are made up of very approximately equal levels of gamma and neutron radiation. Table A18 shows the dose rates from a container at various distances and the resulting annual doses to workers involved in either loading or unloading the containers at a port. Although the dose rates associated with these containers are among the highest reported in this study, since there are only 4 consignments a year the resulting doses to dock workers are low. The assessed annual doses are all less than 3 µSv. Different ports are used for importing and exporting the containers so that the same workers would not be involved in both operations.

3.3 Summary of dose assessments

In this study worker exposure was only considered in relation to the sea transport section of shipments of radioactive material, and not road or rail transport to and from ports. The IMDG Code (IMO, 2006) requires Class 7 material to be stowed on a ferry either at the bow or stern, furthest from the living quarters or regularly occupied work areas. During the visits made to ferry ports, this was observed to be the normal practice.

For the types of shipments covered in this study no consignment is likely to exceed a Transport Index (TI) of 200. For cargoes exceeding a TI of 100 but not exceeding 200 the IMDG Code requires a segregation of at least 4 container units (approximately 24 m total length). On the visits made to observe the stowage and unloading of containers and flatracks, it was noted that the Class 7 cargo was positioned on the cargo ship so as to be well separated from the areas normally occupied during the voyage, and which exceeded the required segregation.

In general, the observance of the IMDG segregation distances will minimise radiation exposures of crew and passengers. Measurements on cargo ships and ferries confirmed that dose rates were at background level in the areas normally occupied during a voyage. Therefore in this study, apart from those included in the tables in Appendix A, the exposures of other dock workers, the general crew and passengers, on cargo ships and ferries, are assumed to be at background levels.

Specific assessments of radiation exposures were only carried out for the regular and large scale movements of radioactive material. As discussed below the exposures associated with those shipments were found to be very low. The irregular shipments of mainly low TI materials from and to nuclear sites by sea, briefly noted in this report in Section 2.2.7, would result in even lower doses and were therefore not individually assessed. Also, those infrequent movements and shipments of sources to and from offshore platforms referred to in Section 2.3.2 would similarly result in trivial doses and are not separately assessed. Also, these shipments that were not separately assessed, would contribute a negligible additional collective dose.

The annual doses resulting from the types of shipments assessed are set out in Appendix A. The consignors and consignees making and receiving these regular and routine shipments tend to use specific ports. While there is some flexibility in the choice of port, from the information supplied by the main operators, it transpires that five main ports are used. A notable exception to this is the use of a sixth port solely for the bulk shipment of depleted UF_6 cylinders, described in Section 3.1.4. Therefore, for the purpose of analysis only these five main ports are considered for all the shipments apart from the bulk shipment of UF_6. A number of visits were made to three of these five ports to observe unloading, loading and stowage operations. The different workers and tasks listed in the tables of Appendix A reflect the observations made on the types of operations carried out. However, there may be variations in the types of operations at other ports so the tasks and stages of those operations that are identified in those tables are also used in a generic sense to represent similar operations at the ports that were not visited.

The workers at the five main ports are therefore assumed to handle the majority of radioactive material being imported into and exported from the UK. The workers identified in Appendix A would therefore accumulate annual doses from each type of shipment. Those accumulated doses are shown in Table 2. These doses could be interpreted as maximum annual individual doses but should in reality be regarded as collective doses to groups of workers carrying out each task. As these doses are shared among a group of workers, the annual dose to an individual worker would be about an order of magnitude below the doses indicated. The individual annual doses are therefore found to be very low. Under the most pessimistic assumptions the most exposed worker, at these five main ports, would be a member of a freight ferry crew who attaches and releases deck chains used to secure the vehicles carrying radioactive material. They would receive an annual dose of about 70 µSv. However, as noted previously, this dose would be shared by a small group of such workers, so that each would receive an annual dose in the order of 10 µSv. As noted in Section 3.1.2, the individual doses for ferry crew at the port of embarkation and at the destination port are not additional as different workers are involved.

The annual individual doses arising from the bulk shipment of cylinders of depleted UF_6 from a UK port are shown in Table A11. Those annual doses are higher than those assessed in Table 2 but are still low. The maximum individual dose for this operation in 2007 was 0.2 mSv.

For the shipments made by freight ferry it has been assumed that, just before the lorries depart, a driver in a lorry, not carrying radioactive material, is at a distance of 2 m from a lorry carrying Class 7 material for 15 minutes. Where the consignment involves a number of lorries a single adjacent driver is also assumed, as the Class 7 lorries tend to be parked together. The highest dose from this single exposure, 1.5 µSv, was found to be from a ^{60}Co shipment (Table A16). It is assumed that this would be a “one off” dose as it is unlikely to be repeated. The shipments of radioactive material for medical uses (Table A17) were the only transport operations that were identified where the adjacent driver could be a member of the public, rather than another worker. In that case the single dose would be 0.75 µSv; that is, less than one microsievert. These individual doses, accumulated for each shipment, are used below in the assessment of collective dose. In some cases there may be more than one person in an adjacent vehicle. However, the assumptions used to calculate a single dose are felt to be sufficiently pessimistic and a more complex calculation would be unjustified.

Table 2 Accumulated doses to workers at UK ports

Worker	Annual dose, µSv				
	Port A	Port B	Port C	Port D	Port E
Main crane operator	8.1	2.3	0	0	0.2
Stevedore unlocking twist locks on ship	9.4	6.9	0	0	0.7
Stevedore fitting/ removing twist locks on quayside	11	6.9	0	0	0.7
Straddle carrier/ fork lift truck driver to/ from storage area	13	6.9	0	0	0.6
Straddle carrier/ fork lift truck driver to/ from road vehicle	13	6.9	0	0	0.6
Crew fixing/ unfixing vehicle chains on freight ferry	0	24	56	70	0
Crew supervising vehicle positioning on freight ferry	0	1.0	3.3	6.9	0

The dose received by the drivers of lorries carrying radioactive material during a cross-channel voyage is much smaller than their dose from the complete journey from the consignor to the destination. Assuming their dose while on the ferry is similar to those assessed for the driver of an adjacent vehicle, the highest annual dose would be from the export of natural UF_6 (Table A2). A dose of 0.4 µSv for each of 50 consignments (through two ports) would result in an annual dose of 20 µSv (i.e. 0.02 mSv). Personal monitoring data from the operator shows that their drivers' average annual dose for the 3 years 2005 – 2007 was 0.58 mSv.

Table 3 shows the UK collective doses at all the ports, which consist of the summed annual collective doses derived from the data given in the tables of Appendix A. Table 3 also includes the contributions from the drivers of vehicles adjacent to the Class 7 (radioactive cargo) vehicles on freight ferries, and the doses received by the drivers of those Class 7 vehicles. The dose contributions from the dockside workers and ship's crew for the bulk shipment of depleted UF_6 at the sixth UK port are also included.

The annual collective dose received by the workers at ports from loading and unloading cargo ships is estimated to be about 1.6×10^{-4} man Sv, and 68% of this is received by the stevedores unlocking, inserting and removing twist locks. The remaining 32% is received by the straddle carrier drivers. The collective dose from freight ferry shipments is about 4.2×10^{-4} man Sv. The ferry crew receive 38% of this collective dose, 32% is received by the Class 7 drivers, and the remaining 30% by the drivers of adjacent vehicles. The collective dose from the bulk shipment of cylinders containing depleted UF_6 in 2007 was 1.2×10^{-3} man Sv and is the main contribution (67%) to the overall collective dose of 1.78×10^{-3} man Sv (or 1.8×10^{-3} man Sv).

It should be noted that the individual and collective doses assessed here are for the UK end of each shipment, and those received during a ferry voyage. When material is despatched or received at an overseas port and similar handling operations are used the overall annual collective dose for all these shipments would be very approximately doubled, resulting in a collective dose of about 3×10^{-3} man Sv. However, this value is very uncertain as the onward transport of these shipments could involve a number of transfer operations before reaching the consignee.

Table 3 UK collective doses from imports and exports of radioactive material

Type of operation	Workers	Annual collective dose, man Sv × 10^{-6}						
		Port A	Port B	Port C	Port D	Port E	Port F	Total
Cargo loading & unloading at ports	Main crane operators	8.1	2.3	0	0	0.2	0	11
	Stevedores on ship (4 per operation)	37	28	0	0	2.8	0	68
	Stevedores on quay (2 per operation)	23	14	0	0	1.4	0	38
	Straddle carrier/ fork lift truck drivers to/ from storage area	13	6.9	0	0	0.6	0	20
	Straddle carrier/ fork lift truck drivers to/ from road vehicle	13	6.9	0	0	0.6	0	20
Vehicles on ferries	Crew fixing/ removing vehicle chains on ferry	0	24	56	70	0	0	150
	Crew supervising vehicle positioning on ferry	0	1.0	3.3	6.9	0	0	11
	Drivers of adjacent vehicles	0	4.8	50	71	0	0	126
	Class 7 drivers	0	48	33	53	0	0	135
Bulk depleted UF_6 shipment	Loading contractors	0	0	0	0	0	490	490
	Ship's crew	0	0	0	0	0	710	710
Total		94	135	143	201	5.6	1200	1780

4 DISCUSSION AND CONCLUSIONS

Data were collected on the volumes of shipments of radioactive materials transported by sea and assessments were made of the radiation exposures resulting from these shipments. It was found that approximately 1000 consignments are transported by sea to and from the UK annually, involving the movement of some 30,000 individual packages. In this study only the main regular shipments were assessed.

The radiological consequences of the shipment of radioactive material to and from the UK by sea were found to be very low. The maximum individual annual dose to crew and dock workers was found to be 0.2 mSv, which is 1% of the annual dose limit for workers. Most of these workers receive annual doses of only a few microsieverts or less. The collective dose arising from despatch and receipt to and from the UK was assessed to be about 1.8 × 10^{-3} man Sv, which is rounded to 2 × 10^{-3} man Sv. Two thirds of this was from an annual bulk shipment of cylinders containing depleted UF_6.

The positioning of cargo and vehicles carrying packages is such that the doses received by crew during voyages are virtually zero. The only exception to this was a single annual shipment of a large number of cylinders carrying depleted UF_6, where the crew might receive small doses during the voyage from inspection of the lashings that secure the cylinders in the hold. Radiation monitoring of cargo during a voyage is not normally carried out, but during the visits to ports two examples were noted where daily monitoring is carried out, which was a requirement of the shipping companies' policies. Such monitoring could give rise to an unnecessary dose to the crew member carrying out the monitoring if there was no reason to suspect that the cargo had been disturbed. However, for the two cases noted the estimated dose to those crew members was extremely low, and did not warrant further comment.

No evidence was found of any significant exposure of members of the public. However, drivers of vehicles on ferries may receive very small doses from adjacent vehicles carrying radioactive material, but such a dose is unlikely to be repeated. The highest such dose was assessed as 1.5 μSv for drivers on freight ferries. Two types of shipments carrying radioactive material for medical uses could be carried on passenger ferries, depending on the availability of ferries at suitable sailing times. In these cases the driver incidentally exposed, including other occupants, could be members of the public in a private vehicle. In that case the maximum dose was found to be less than one microsievert and, as for the lorry drivers, the dose is trivial and unlikely to be repeated.

The findings of a previous study of marine transport of radioactive materials, (Gelder, 1996), carried out in the mid 1990's, differ from the results of this study due to changes in the types of materials being carried and methods of transport. The main qualitative trends observed from the two studies are:

- there are currently no regular movements of irradiated fuel to or from the UK;
- there are no longer any imports of uranium ore concentrate (U_3O_8) as the raw material for new fuel is now imported as UO_3;
- the main supplier of radioactive materials for medical and industrial applications no longer exports these products by ferry to Europe, these are now shipped by air, and by road and Channel Tunnel rail link.

Overall, these changes will have resulted in a reduction in the radiological impact from the transport of radioactive material by sea to and from the UK.

5 ACKNOWLEDGEMENTS

During this study visits were made to the premises of the main consignors and consignees of radioactive materials that are transported by sea. They also supplied details of those shipments. The authors are grateful for this cooperation, without which the study would not have been possible. Visits were also made to docksides to make measurements, and the cooperation of a number of shipping lines and port authorities is appreciated. The authors also appreciated the advice from the Health and Safety Executive's Office for Civil Nuclear Security and the Maritime and Coastguard Agency.

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7 GLOSSARY

Term	Description
Activity	The number of radioactive decays per unit time in a given material. Normally measured in disintegrations per second (Bq).
AGR	Advanced Gas-cooled Reactor. Used in the UK's second generation of gas-cooled nuclear power stations.
Alpha emitter	A radionuclide that decays emitting an alpha particle.
Alpha particle	A particle emitted by a radionuclide consisting of two protons and two neutrons (i.e. the nucleus of a helium atom).
Beta emitter	A radionuclide that decays emitting a beta particle.
Beta particle	An electron or positron emitted by a radionuclide.
Category	Packages other than excepted packages and overpacks must be assigned to either category I-White, II-Yellow or III-Yellow, depending on the maximum dose rate at the surface and at 1 m from the surface, and must be labelled accordingly.
Effective Dose	Measured in Sieverts (Sv), it is a measure of the overall exposure of an individual from ionising radiation. It is dependent on the absorbed dose, type of radiation and regions of the body affected. Since the Sievert is a large unit, doses are more commonly expressed in millisieverts (mSv) or microsieverts (µSv).
Effective dose rate (or "Dose rate")	The rate at which effective dose from external radiation is received, measured in units of Sv h^{-1}, or mSv h^{-1}, or µSv h^{-1}.
Irradiated Nuclear Fuel (INF) Flask	A Type B package used to transport irradiated nuclear fuel (see packages).
Ionising Radiation	Radiation capable of breaking chemical bonds, causing ionisation and damage to biological tissue.
Label	Apart from excepted packages all packages must be labelled with a diamond shaped warning label which gives information on the contents of the package.
Magnox	The first generation of the UK's gas-cooled nuclear power stations.
Nuclide	A species of atom characterised by a nucleus with a specific number of protons and neutrons.
Package	There are five main types of packages used to carry radioactive material: • Industrial Packages are industrial containers, such as drums, used to carry bulky low activity materials, or contaminated items. • Excepted packages are simple packages used to carry low activity materials and sources. They are mainly used to transport low activity diagnostic test materials to hospitals. • Type A packages are used to transport medium activity material such as medical or industrial isotopes. They must withstand normal conditions of transport including minor mishaps. • Type B packages are used to transport high activity sources and materials, such as Irradiated Nuclear Fuel (INF). They provide shielding from high radiation levels even under extreme circumstances. They must meet severe mechanical and thermal test requirements, which simulate accident conditions. • Type C packages are for the transport by air of greater quantities of radioactive material than is allowed to be transported by air in Type B packages. They must be designed to withstand very serious accidents such as aircraft crashes.
Radionuclide	A nuclide which spontaneously loses energy or disintegrates into another nuclide, resulting in the emission of ionising radiation.
Transport Index (TI)	A number equal to the maximum dose rate, at 1 m from the surface of the package, overpack or freight container, measured in mSv h^{-1} multiplied by 100. This number is used to control radiation exposure from a group of packages during transport.

APPENDIX A Exposure parameters and assessed doses

Table A1 Imports of uranium trioxide through Port A

Worker	Distance from container, m	Dose rate, µSv h^{-1}	Exposure time per container, mins	Dose per container, µSv	Annual number of containers	Annual dose, µSv
Main crane operator	10	1	1	0.017	149	2.5
Straddle carrier driver, to storage area	5	1.5	1	0.025	149	3.8
Straddle carrier driver, to lorry loading area	5	1.5	1	0.025	149	3.8

Table A2 Export of natural UF_6 to Europe through a ferry terminal at Port C

Worker	Distance from vehicles[1], m	Dose rate, µSv h^{-1}	Exposure time per consignment, mins	Dose per consignment, µSv	Annual number of consignments[2]	Annual dose, µSv
Crew member chaining vehicles to deck	1	4	15	1	27	27
Crew member supervising loading	5	0.5	5	0.04	27	1.1
Driver of an adjacent vehicle while waiting in cab on vehicle deck.	2	1.5	15	0.4	1 (for 1 consignment)	0.4

[1] Three vehicles per consignment on average.

[2] A further 23 consignments were despatched through Port D.

Table A3 Imports of natural UF_6 from Europe through a ferry terminal at Port B

Worker	Distance from vehicles, m	Dose rate, µSv h^{-1}	Exposure time per consignment, mins	Dose per consignment, µSv	Annual number of consignments[1]	Annual dose, µSv
Crew member releasing vehicle deck chains	1	4	30	2	3	6
Crew member supervising unloading	5	0.5	10	0.08	3	0.25
Driver of an adjacent vehicle while waiting in cab on vehicle deck.	2	1.5	15	0.4	1 (for 1 consignment)	0.4

1 Refers to three consignments of 20 cylinders, i.e. each consignment was 10 lorries carrying two 48Y cylinders each.

Table A4 Imports of natural UF_6 through Port A

Worker	Distance from flatrack, m	Dose rate, µSv h^{-1}	Exposure time per flatrack, mins	Dose per flatrack, µSv	Annual number of flatracks[1]	Annual dose, µSv
Main crane operator	10	0.5	1	0.008	451	3.7
Stevedore unlocking twist lock on ship	0.5 to 1.0	4	0.25	0.017	451	7.5
Stevedore removing twist locks	0.5 to 1.0	4	0.25	0.017	451	7.5
Straddle carrier driver, to storage area	5	0.6	1	0.01	451	4.5
Straddle carrier driver, to lorry loading area	5	0.6	1	0.01	451	4.5

[1]In 27 consignments, with one 48Y cylinder per flatrack.

Table A5 Imports of enriched UF_6 through Port B

Worker	Distance from flatrack, m	Dose rate, µSv h^{-1}	Exposure time per flatrack, mins	Dose per flatrack, µSv	Annual number of flatracks[1]	Annual dose, µSv
Main crane operator	10	<0.1	1	<0.002	38	0.06
Stevedore unlocking twist lock on ship	0.5 to 1.0	0.8	0.25	0.003	38	0.13
Stevedore removing twist locks	0.5 to 1.0	0.8	0.25	0.003	38	0.13
Straddle carrier driver, to storage area	5	0.1	1	0.002	38	0.06
Straddle carrier driver, to lorry loading area	5	0.1	1	0.002	38	0.06

[1] In 12 consignments with a maximum of 4 30B cylinders per flatrack. A further 8 flatracks were imported through Port A.

Table A6 Imports of enriched UF_6 from Europe through a ferry terminal at Port C

Worker	Distance from vehicles, m	Dose rate, µSv h^{-1}	Exposure time per consignment, mins	Dose per consignment, µSv	Annual number of consignments[1]	Annual dose, µSv
Crew member releasing vehicle chains	1	1	10[2]	0.17	19	3.2
Crew member supervising unloading	5	0.1	5	0.008	19	0.16
Driver of an adjacent vehicle while waiting in cab on vehicle deck.	2	0.2	15	0.05	1 (for 1 consignment)	0.05

[1] A further 9 consignments were made through Port D.

[2] Assumed average, as the number of vehicles vary between 1 and 4.

Table A7 Exports of enriched UF_6 to Europe through a ferry terminal at Port D

Worker	Distance from vehicles, m	Dose rate, µSv h^{-1}	Exposure time per consignment, mins	Dose per consignment, µSv	Annual number of consignments	Annual dose, µSv
Crew member chaining vehicles to deck	1	1	10[1]	0.17	7	1.2
Crew member supervising loading	5	0.1	5	0.008	7	0.06
Driver of an adjacent vehicle while waiting in cab on vehicle deck.	2	0.2	15	0.05	1 (for 1 consignment)	0.05

[1] Assumed average, as the number of vehicles varied between 1 and 4.

Table A8 Exports of enriched UF_6 through Port A

Worker	Distance from flatrack, m	Dose rate, µSv h^{-1}	Exposure time per flatrack, mins	Dose per flatrack, µSv	Annual number of flatracks[1]	Annual dose, µSv
Main crane operator	10	<0.1	1	<0.002	84	<0.2
Stevedore fitting twist locks	0.5 to 1.0	0.8	0.25	0.003	84	0.28
Straddle carrier driver, from storage area	5	0.1	1	0.002	84	0.14
Straddle carrier driver, from lorry loading area	5	0.1	1	0.002	84	0.14

[1] With a maximum of 4 cylinders per flatrack.

Table A9 Exports of depleted UF_6 to Europe through a ferry terminal at Port B

Worker	Distance from vehicles, m	Dose rate, µSv h^{-1}	Exposure time per consignment, mins	Dose per consignment, µSv	Annual number of consignments[1]	Annual dose, µSv
Crew member chaining vehicles to deck	1	4	30	2	9	18
Crew member supervising loading	5	0.5	10	0.08	9	0.75
Driver of an adjacent vehicle while waiting in cab on vehicle deck.	2	1.5	15	0.4	1 (for 1 consignment)	0.4

[1] Refers to 9 consignments of 20 cylinders, on 10 lorries.

Table A10 Dose rates from cylinders of depleted UF_6 during loading of a ship at Port F

Position	Dose rate, µSv h^{-1}
0.1 m from side of single cylinder	10
0.5 to 1 m from side of single cylinder	4
2 m from side of single cylinder	1.5
0.5 m from side of cylinders in hold	13
1 m from ends of cylinders in hold	4
Living areas, engine room and bridge	0.1
3 m from side of ship	0.3
20 m from side of ship	0.1 (background)

Table A11 Worker doses from loading and shipping a consignment of depleted UF_6 from Port F

Loading contractors		Ship crew	
Individual, role	Dose, µSv	Individual	Dose, µSv
Releasing lorry lashings and attaching crane sling	27	#1	50
Deck operator/ banksman to guide crane driver	12	#2	110
In hold positioning cylinders	112	#3	60
In hold positioning cylinders	97	#4	50
In hold fixing lashings	128	#5	210
In hold fixing lashings	114	#6	110
		#7	50
		#8	70
Collective dose, man Sv × 10^{-6}	*490*		*710*

Table A12 Exports of UO_2 powder through Port A

Worker	Distance from freight container, m	Dose rate, µSv h^{-1}	Exposure time per freight container, mins	Dose per freight container, µSv	Annual number of freight containers [1]	Annual dose, µSv
Main crane operator	10	0.4	1	0.007	49	0.3
Straddle carrier driver, from storage area	5	0.5	1	0.008	49	0.4
Straddle carrier driver, from lorry loading area	5	0.5	1	0.008	49	0.4

[1] A total of 49 freight containers in 31 consignments.

Table A13 Exports of UO_2 powder through a ferry terminal at Port D

Worker	Distance from vehicles, m	Dose rate, µSv h^{-1}	Exposure time per consignment, mins	Dose per consignment, µSv	Annual number of consignments[1]	Annual dose, µSv
Crew member chaining vehicles to deck	1	2	15	0.5	8	4
Crew member supervising loading	5	0.5	5	0.04	8	0.3
Driver of an adjacent vehicle while waiting in cab on vehicle deck.	2	0.7	15	0.18	1 (for 1 consignment)	0.18

[1] Refers to a total of 412 packages within freight containers.

Table A14 Imports of ^{60}Co sources through Port B

Worker	Distance from flatrack, m	Dose rate, µSv h^{-1}	Exposure time per flatrack, mins	Dose per flatrack, µSv	Annual number of flatracks[1, 2]	Annual dose, µSv
Main crane operator	10	3	1	0.05	30	1.5
Stevedore unlocking twist lock on ship	0.5 to 1	40	0.25	0.17	30	5
Stevedore removing twist locks	0.5 to 1	40	0.25	0.17	30	5
Straddle carrier driver, to storage area	5	9	1	0.15	30	4.5
Straddle carrier driver, to lorry loading area	5	9	1	0.15	30	4.5

[1] With 4 flasks per flatrack. A further 4 flatracks were imported through Port E.

[2]A further 5 containers each carrying 2 flasks were imported through Port A.

Table A15 Exports of ^{60}Co sources through Port A

Worker	Distance from flatrack, m	Dose rate, µSv h^{-1}	Exposure time per flatrack, mins	Dose per flatrack, µSv	Annual number of flatracks[1]	Annual dose, µSv
Main crane operator	10	2	1	0.03	12	0.4
Stevedore fitting twist locks	0.5 to 1	20	0.25	0.08	12	1
Straddle carrier driver, from storage area	5	5	1	0.08	12	1
Straddle carrier driver, from lorry loading area	5	5	1	0.08	12	1

[1] With up to 4 flasks per flatrack.

Table A16 Exports of ^{60}Co sources through a ferry terminal, Port D

Worker	Distance from vehicles, m	Dose rate, µSv h^{-1}	Exposure time per consignment, mins	Dose per consignment, µSv	Annual number of consignments	Annual dose, µSv
Crew member chaining vehicles to deck	1	12	5	1.0	14	14
Crew member supervising loading	5	3	5	0.25	14	3.5
Driver of an adjacent vehicle while waiting in cab on vehicle deck.	2	6	15	1.5	1 (for 1 consignment)	1.5

Table A17 Imports of used technetium generators and material for medical uses through a ferry terminal at Port D

Worker	Distance from vehicle, m	Dose rate, µSv h^{-1}	Exposure time per consignment[1], mins	Dose per consignment, µSv	Annual number of consignments[2]	Annual dose, µSv
Crew member releasing vehicle chains	1	6	5	0.5	52	26
Crew member supervising unloading	5	0.5	5	0.04	52	2
Driver of an adjacent vehicle while waiting in car on vehicle deck.	2	3	15	0.75	1 (for 1 consignment)	0.75

[1] One lorry per consignment.

[2]A weekly shipment of material for medical uses, with similar exposure parameters, is made through another port.

Table A18 Import of ^{241}Am/Be sources through Port B and export through Port A

Worker	Distance from container, m	Dose rate, µSv h^{-1}	Exposure time per container, mins	Dose per container, µSv	Annual number of containers[1]	Annual dose, µSv
Main crane operator	10	10	1	0.17	4	0.7
Stevedore unlocking twist lock on ship[2]	0.5 to 1	110	0.25	0.5	4	1.8
Stevedore fitting/ removing twist locks	0.5 to 1	110	0.25	0.5	4	1.8
Straddle carrier driver, to storage area	5	35	1	0.6	4	2.3
Straddle carrier driver, to lorry loading area	5	35	1	0.6	4	2.3

[1] With 14 Type A flasks per container.

[2] Locking does not occur when these flasks are exported.