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Survey into the Radiological Impact of the Normal Transport of Radioactive Material in the UK by Road and Rail

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Contents

1 Introduction

In the UK radioactive materials are routinely transported by road and rail for use by the civil nuclear industry, or for medical or industrial purposes. The majority of shipments are made by road, especially for radioactive materials and sources used for industrial and medical purposes. The number of consignments of radioactive material by rail is confined to the movement of material with high levels of radioactivity, such as irradiated nuclear fuel flasks (Watson et al., 2005).

The International Atomic Energy Agency (IAEA) has published regulations regarding the safe transport of radioactive materials (IAEA, 2009; IAEA, 2012) that requires national competent authorities to arrange for periodic assessments of the radiological impact due to the transport under normal conditions of radioactive material. Since 1983, the Office for Nuclear Regulation (ONR), which is the authority responsible for regulating the transport of Class 7* material in the UK, has commissioned Public Health England (PHE) and its predecessor organisations to undertake assessments of the radiological impact of the normal transport of radioactive material in the UK by different modes of transport (Harvey et al., 2014; Hughes and Harvey, 2009). This report describes the latest assessment in this series and looks at the radiological impact from the normal transport by road and rail. This study is an update of a previous assessment on the transport of radioactive material by road and rail which was published in 2005 (Watson et al., 2005).

2 Objectives and scope of the study

The main objectives of this study were to gather and analyse information on the types of radioactive materials transported by road and rail and to assess the radiation exposure of transport workers and members of the public from the normal transport of radioactive material by road and rail. This was achieved by gathering data on the number of consignments and packages and package types shipped by road and rail, as well as gaining an understanding of the working patterns of transport operations carried out in the UK. The assessment was mainly performed by carrying out dose rate measurements in and around conveyances transporting radioactive material.

The results of this study were compared with those of the previous study (Watson et al., 2005) to identify differences and trends. The scope covered all types of radioactive material categorised as Class 7 transported by road and rail, including radioactive materials for medical and industrial use as well as materials associated with the civil nuclear fuel cycle and the transport of radioactive waste products. The study was limited to the normal transport of radioactive materials carried out in compliance with the appropriate regulations and does not include exposures received as a result of accidents or other unplanned incidents.

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[*] The UN classifies dangerous goods for consignment depending on their predominant hazard: radioactive material is assigned Class 7.

The data used in this report are collected on an annual basis and are based on information mainly collected for 2014, but also in 2015. They are intended to provide a snapshot and capture the current situation in the UK. It should also be noted that the information gathered for this study may not be fully comprehensive and possible gaps have also been identified.

3 Methodology used in the study

The study considered separately the three main sectors that transport radioactive material (Class 7) in the UK: civil nuclear industry; radiopharmaceutical industry; and general industry and research. Information on movements of packages, package types, as well as transport patterns and working practices were collected directly from companies involved in the transport of radioactive materials. The military sector has been excluded from this study. A limited amount of information on annual doses received by transport workers was also collated in this way. In previous studies on the radiological impact of normal transport of radioactive material in the UK, ad hoc questionnaires were sent out to operators to gather the required data. However the response to the questionnaire prepared for the latest study on the transport of radioactive material by air (Harvey et al., 2014) was poor and therefore for the current study it was decided to follow a simpler approach and make contact directly with as many companies and organisations as possible with a request to supply all available data.

Visits were also made between September 2015 and March 2016 to a number of sites in both the nuclear and non-nuclear sector. The main purpose of these visits was to take measurements of dose rates in and around conveyances transporting radioactive material and use such measurements to estimate doses to workers. These visits offered the opportunity to observe directly the procedures adopted when loading and unloading packages, including taking note of the duration of tasks and to obtain further information from the company.

The information supplied by companies and organisations from the civil nuclear industry on movements of radioactive material by both road and rail was detailed and comprehensive. Complete data were also provided by the major companies involved in the manufacturing and provision of medical and industrial sources. A few companies involved in the movement of sources for industrial purposes also supplied data, but it should be noted that this represents only a small percentage of the companies in the UK that may transport radioactive sources on the road. Where possible, data have been anonymised so that the companies and organisations involved in this study cannot be easily recognised.

The doses assessed for this study were annual effective doses to workers involved in the transport operation (loading and unloading) and to drivers of the vehicles carrying the radioactive material. Doses were also calculated for members of the public who may be exposed to the radioactive material transported. In general these are people who may be present at the premises during loading and unloading but are not directly involved in the operations or they are residents of habitations on the route of a shipment. The estimates of doses to the transport workers were based on each of the tasks observed during the visits and take account of the time spent on each task, working hours, number of shipments, the Transport Index (TI) of the packages in the shipment and the annual TI of the packages. The Transport Index is a number assigned to a package or consignment and is used to provide control over radiation exposure. Doses to workers should be considered broadly representative of their exposure to radiation, rather than accurate estimates of the doses actually received by individual workers, which can only be made from their dose records.

Our estimate can be used to corroborate these records; it should also be noted that in general workers involved in transport operations are likely to receive doses when performing other non-transport related tasks and their dose records would reflect the total dose received.

4 Transport by road and rail in the UK civil nuclear industry

The collation of data from the nuclear industry required for this study was facilitated by the Radioactive Material Transport Users Committee (RAMTUC) (RAMTUC, 2015), which includes members from all areas of the civil nuclear industry. The committee encouraged its members to supply information using a proforma designed to collect the required data to determine the number of consignments and packages. The data collected included: date of the shipment; package type; exclusive use; UN number; Transport Index; activity; package contents; mode of transport; carrier; number of consignments; number of packages in consignment. The fuel enrichment facility at Capenhurst and fuel fabrication facility at Springfields returned data for the year 2014; the nuclear power stations returned data for a six month period September 2015 to March 2016; and the nuclear reprocessing facility at Sellafield returned data for the six month period April to September 2015. Personal dosimetry data was also obtained from Springfields.

In addition, visits were made to Capenhurst, a UK seaport, Sellafield and Springfields between September 2015 and March 2016.

4.1 Movements of radioactive material in the nuclear sector

A summary of the movement of radioactive packages by road and rail in the UK nuclear industry is given in Figure 1. The figure provides a summary of the number of packages transported and consignments carried out from different sectors of the nuclear industry by both road (black lines) and rail (red lines). Uranium ore that has been converted into uranium hexafluoride (UF_6) is imported into the UK by sea. It then travels by road first to the fuel enrichment plant at Capenhurst and then to the fuel fabrication facility at Springfields, before being transported as fuel for use in power generation or to ports for export overseas. Spent nuclear fuel is sent by road or rail for reprocessing at Sellafield to recover any reusable fuel and then either travels by road on to Springfields or for enrichment at Capenhurst. Low level waste is sent by road or rail to a waste repository for treatment and/or storage; Figure 2 provides a more detailed description of the treatment, storage and waste disposal part of the cycle. Each part of the nuclear fuel cycle is discussed in more detail in the following sections.

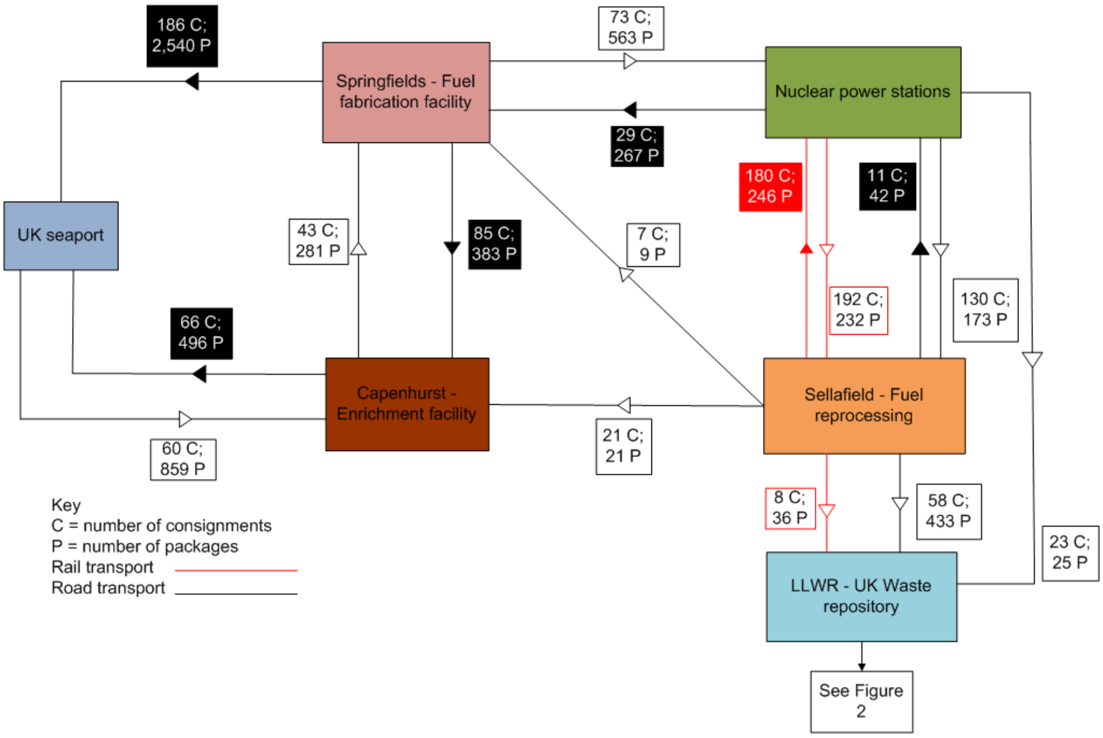

Figure 1 Schematic of the transport of radioactive packages by road and rail in the UK by the civil nuclear industry

4.1.1 Movements of radioactive material from and to the uranium enrichment facility

Natural uranium is imported to the UK as uranium hexafluoride (UF_6) by sea. It is then transported by road to the uranium enrichment facility at Capenhurst. Enriched uranium is then transported to the fuel fabrication plant at Springfields, as well as exported overseas. Uranium is transported from and to Capenhurst in two types of cylinders: natural uranium (UF_6 natural) and residue of UF_6 (known as 'heels') are transported in 48Y cylinders; and enriched uranium (UF_6 enriched) is shipped in 30B cylinders. Data on movements of 48Y from and to Capenhurst by road in 2014 are given in Table 1 and movements of 30B cylinders from Capenhurst in Table 2.

There were 38 consignments of natural uranium in 48Y cylinders from UK seaports to Capenhurst in 2014.The number of packages carried was 607 each with a typical TI of 0.6 making a total TI about 370. There were 20 consignments made in the opposite direction for transhipment overseas, mainly to Europe, carrying 245 packages containing heels each with a typical TI of 0.4 making a total TI of about 100. In addition 25 consignments carrying 190 48Y cylinders containing heels were made from Capenhurst to Springfields. A total of 1,042 packages containing different types of UF_6 were transported from Capenhurst in 2014. These journeys were all made by road.

Capenhurst also reported that there were 13 consignments made by road from Springfields to Capenhurst carrying 60 full 48Y cylinders. It has been assumed that these are in addition to the data on consignments provided by Springfields and given in Table 3.

Table 1: Numbers of consignments and packages of natural UF6 in 48Y cylinders transported from and to the enrichment plant at Capenhurst by road in 2014

Route	Number of consignments	Number of 48Y cylinders transported		
		Full	Heeled	Total
UK seaports to Capenhurst	38	427	180	607
Capenhurst to UK seaports	20	-	245	245
Capenhurst to Springfields	25	-	190	190
Springfields to Capenhurst	13	60	-	60
Total	96	487	615	1,102

The total number of 30B cylinders shipped from Capenhurst in 2014 was nearly 600 (see Table 2). There were 22 consignments of 252 30B cylinders from overseas to the enrichment plant and 251 cylinders were transported back to various UK seaports in 46 consignments. In addition, there were 18 consignments of 91 30B cylinders between Capenhurst and Springfields. No data was provided by Capenhurst on movements of 30B cylinders from Springfields.

Table 2: Numbers of consignments and packages of UF_6 in 30B cylinders transported from the UK enrichment plant by road in 2014

Route	Number of consignments	Number of 30B cylinders
UK seaports to Capenhurst	22	252
Capenhurst to UK seaports	46	251
Capenhurst to Springfields	18	91
Total	86	594

A number of shipments were also made from the enrichment facility to a landfill site to dispose of waste and to return cleaned cylinders. These shipments were not considered in this study since the waste transported was not classed as radioactive.

4.1.2 Movements of radioactive material from the fuel fabrication facility

In the UK the facility at Springfields manufactures nuclear fuel for both Advanced Gas-Cooled Reactors (AGR) and pressurised water reactors (PWR). Table 3 provides a breakdown of the consignments and packages transported from Springfields during 2014 by package type. The total number of packages shipped in 2014 was 3,421, transported in 326 consignments. Of these packages the largest number was represented by 1,520 Type A packages containing enriched UO_2 powder destined for other fuel fabrication plants in Europe; all transports to continental Europe were made by road to a seaport for onward shipment. The number of consignments of nuclear fuel for either AGR or PWR power stations was 79 containing just over 600 packages, each with a typical TI of 0.4.

Table 3: Summary of numbers of consignments, packages and TIs transported by road from the fuel fabrication facility in 2014

Package type	Contents	Destination	Consignments	Packages	Total TI
Type A	AGR fuel	Nuclear power stations	73	563	225.2
Type A	PWR fuel	Nuclear power stations in Europe	6	56	22.4
Type A - ISO containers	Enriched UO_2 powder	Fuel fabrication plants in Europe	26	1,520	912
Type B(U) - 48Y cylinders	Natural UF_6	Enrichment facilities in Europe and UK	121*	502	502
Type B(U) - 30B cylinders with overpacks	Enriched UF_6	Overseas	5	71	12.8
Type B(U) - 30B cylinders	Empty	Enrichment facilities in Europe and UK	33†	273	0
IP	Drums, drum samples, MED2000 and P25 samples of natural UF_6	Enrichment facility in UK	11	81	>1
Excepted	UX30 overpacks for 30B cylinders	Enrichment facilities in Europe and UK	51‡	355	0
Total			326	3,421	>1674.4

* This includes 26 consignments containing 54 packages delivered to Capenhurst; it was assumed that these are in addition to the consignments given in Table 1. The remainder were transported by road to seaports for onward shipment to enrichment facilities in Europe.

† This includes 8 consignments containing 55 packages delivered to Capenhurst; the remainder were transported by road to seaports for onward shipment to enrichment facilities in Europe.

‡ This includes 22 consignments containing 128 packages delivered to Capenhurst; the remainder were transported by road to seaports for onward shipment to enrichment facilities in Europe.

4.1.3 Movements of radioactive material from the nuclear power generation facilities

Data on the movements of radioactive material from the nuclear power generation facilities in the UK were provided by the two nuclear power generation companies. The data provided for AGR reactor stations and the PWR reactor site covered the year 2014; the data provided for the Magnox sites covered the six month period October 2015 to March 2016. For the purpose of the overall analysis carried out in this study the total numbers of consignments made and packages for a whole calendar year were estimated by doubling the figures provided as consignments are made fairly regularly throughout the year.

The number of consignments and packages by package type and contents transported by road during a six month period from October 2015 to March 2016 from different power stations are given in Table 4. The highest proportion of packages were excepted packages (48%) containing mostly low-level waste as well as laboratory samples and empty packages. The TI for these packages was generally 0; there were a few packages that were transported under exclusive use and had a TI greater than zero. Industrial Packages (IP) made up 42% of those consigned and also contained low-level waste, laboratory samples and empty packages being returned to the fuel fabrication at Springfields, the fuel reprocessing plant or to other nuclear power stations. The average TI was approximately 580 with a range of 0.1 to 6,534; the total TI for all packages was about 9,900. A small number of Type A packages were also transported from nuclear power plants containing items such as metal samples and contaminated material. One Type B package was transported by road from Wylfa to the reprocessing plant at Sellafield carrying irradiated enriched fuel although normally these packages are transported by rail.

Table 4: Number of consignments (C) and packages (P) by package type transported by road from nuclear power stations* in the UK

	No of consignments (C) and packages (P)									
	Excepted		**IP**		**Type A**		**Other**		**Total**	
Originating power station	**C**	**P**	**C**	**P**	**C**	**P**	**C**	**P**	**C**	**P**
AGR†										
Dungeness B	15	62	3	11	1	1	0	0	19	74
Hartlepool	31	69	6	13	3	3	1	1	41	86
Heysham 1	23	154	5	5	1	1	0	0	29	160
Heysham 2	22	70	2	11	1	1	0	0	25	82
Hinkley Point B	32	121	5	49	2	5	0	0	39	175
Hunterston B	32	92	11	306	0	0	1	1	44	399
Torness	34	78	6	51	1	1	0	0	41	130
PWR†										
Sizewell B	18	61	4	20	0	0	0	0	22	81
Magnox‡										
Berkeley	26	176	1	72	0	0	0	0	27	248
Bradwell	31	435	17	253	0	0	1	88	49	776
Chapelcross	20	136	4	11	0	0	0	0	24	147
Dungeness A	19	310	12	26	0	0	2	2	33	338
Hunterston A	26	236	0	0	1	3	0	0	27	239
Oldbury	20	107	2	2	0	0	0	0	22	109
Sizewell A	28	184	0	0	0	0	3	9	31	193
Trawsfynydd	3	4	6	270	0	0	4	404	13	678
Harwell	35	281	8	203	0	0	0	0	43	484
Winfrith	81	246	43	1,321	1	2	1	88	126	1,657
Wylfa	25	213	1	1	2	2	4	4	32	220
Total	521	3,035	136	2,625	13	19	17	597	687	6,276

*No data was provided for Hinkley Point A.

†Data presented is for the year 2014.

‡Data presented is for the six month period October 2015 to March 2016.

Table 5 gives details of the number of consignments and packages by package type transported by rail from different nuclear power stations. The data provided for AGR stations and the PWR station covered the year 2014; the data provided for the Magnox sites covered the six month period from October 2015 to March 2016. Type B packages containing irradiated fuel travelling from nuclear power stations to the fuel reprocessing plant made up 54% of the consignments with TIs of between 0 and 141 and a total of 821. Of the remaining packages, 44% were IP packages containing radioactive waste and 2% were excepted packages carrying empty drums to the fuel reprocessing plant.

Table 5: Number of consignments (C) and packages (P) by package type transported by rail from nuclear power stations* in the UK

	No of consignments (C) and packages (P)							
	Excepted		IP		Type B		Total	
Originating power station	C	P	C	P	C	P	C	P
AGR†								
Dungeness B	0	0	0	0	21	29	21	29
Hartlepool	0	0	0	0	17	22	17	22
Heysham 1	0	0	0	0	12	15	12	15
Heysham 2	0	0	0	0	20	25	20	25
Hinkley Point B	0	0	0	0	21	21	21	21
Hunterston B	0	0	0	0	21	32	21	32
Torness	0	0	0	0	15	23	15	23
PWR†								
Sizewell B	0	0	0	0	0	0	0	0
Magnox‡								
Berkeley	0	0	0	0	0	0	0	0
Bradwell	0	0	12	182	0	0	12	182
Chapelcross	0	0	0	0	0	0	0	0
Dungeness A	0	0	0	0	3	3	3	3
Hunterston A	0	0	0	0	0	0	0	0
Oldbury	0	0	0	0	50	50	50	50
Sizewell A	0	0	2	2	2	2	4	4
Trawsfynydd	0	0	0	0	0	0	0	0
Wylfa	0	0	0	0	20	20	20	20
Harwell	4	8	11	11	0	0	15	19
Winfrith	0	0	0	0	0	0	0	0
Total	4	8	25	195	202	242	231	445

*No data was provided for Hinkley Point A.

†Data presented is for the year 2014. ‡Data presented is for the six month period October 2015 to March 2016.

Taking into account that the Magnox data provided was for a six month period, the total number of packages currently transported over a year is estimated to be about 9,200 by road and 700 by rail.

4.1.4 Movements of radioactive material from the nuclear fuel reprocessing plant

Table 6 gives a summary of the transport of packages containing RAM from the fuel reprocessing plant at Sellafield in 2015. The data provided covered the six month period from April to September 2015 and as consignments are relatively regular a representative value for a full year would be double the figures reported in the table.

The total number of consignments or journeys made by road in a six month period was 346 carrying 1,517 packages. About 80% of the packages transported by road were excepted packages containing mainly samples for testing, laboratory equipment or very low level waste destined for waste management facilities. About 15% of the packages were IP packages and contained low-level radioactive waste for disposal at specialist facilities or contaminated metallic waste for decontamination or were empty flasks returned to nuclear power stations. IP packages were also used to transport uranium trioxide (UO_3) to the enrichment facility, while a small number of tankers were returned to the fuel fabrication facility. Type A packages containing either sealed sources for replacement, uranium sources for disposal or sludge debris represented 1% of the total. Less than 1% of the packages were Type B used to move plutonium sources for disposal. About 2% were packages containing combustible material for incineration transported under exclusive use, or empty flasks being returned to nuclear power stations; these are reported in Table 6 as 'other'.

Table 6: Number of consignments (C), packages (P) and destination transported from Sellafield by road during the period April to September 2015

	No of consignments (C) and packages (P)											
	Excepted		IP		Type A		Type B		Other		Total	
Destination	**C**	**P**	**C**	**P**	**C**	**P**	**C**	**P**	**C**	**P**	**C**	**P**
Capenhurst	0	0	21	21	0	0	0	0	0	0	21	21
Springfields	0	0	6	6	1	3	0	0	0	0	7	9
Nuclear power stations	8	26	2	12	0	0	0	0	1	4	11	42
LLWR	51	405	2	13	2	3	2	2	1	10	58	433
Contaminated metal recycling	3	10	35	29	0	0	0	0	3	3	41	42
Incineration	0	0	9	144	0	0	0	0	7	14	16	158
Laundry	1	10	0	0	0	0	0	0	0	0	1	10
Laboratories and others	189	798	0	0	2	4	0	0	0	0	191	802
Total	252	1,249	75	225	5	10	2	2	12	31	346	1,517

Table 7 gives details of the movements by rail of radioactive material from Sellafield. As shown by the table most of the shipments made by rail during the period from April to September 2015 were returning empty fuel flasks, transported as Type B(M) packages with a

TI of either 0.1 or 0.2, to nuclear power stations in the UK. In addition, there were 16 journeys made carrying excepted packages that were either empty containers or contained LSA-I non fissile or fissile-excepted radioactive material for disposal, some of which were transported under exclusive use; and 8 IP consignments containing 36 packages with a TI of 0.2 for disposal at the low-level waste facility at Drigg. No Type A packages were carried by rail. The total numbers of consignments and packages moved by road from the fuel reprocessing plan for the period from April to September 2014 were 188 and 282 respectively.

Table 7: Summary of consignments (C) and packages (P) moved by rail from Sellafield to destinations in the UK during the period April to September 2015

	Package type							
	Excepted		**IP**		**Type B**		**Total**	
Destination	**C**	**P**	**C**	**P**	**C**	**P**	**C**	**P**
Nuclear power stations	16	16	1	6	163	224	180	246
LLWR			8	36			8	36
Total	16	16	9	42	163	224	188	282

4.1.5 Transport of low level radioactive waste for recycling, storage and disposal

In addition to the movements of radioactive waste between nuclear facilities which have been included in the previous section of this report, low level radioactive waste from both the nuclear and non-nuclear sector is sent to a number radioactive waste repositories in the UK. Although a comprehensive set of data of all movements of radioactive waste in the UK could not be obtained for this study, data were collected on the movements of radioactive waste to and from the main waste UK repository site for low level radioactive waste (LLWR near Drigg in Cumbria).

Table 8 gives details of the consignments and packages sent to and from LLWR by road and rail during the period from April 2014 and March 2015. There were a total of 354 consignments containing 3,611 packages made by road: 58 consignments of 623 packages were made by road into LLWR while 296 consignments containing 2,988 packages left the LLWR site. Table 8 also shows the inbound consignments made by rail; there were no outbound consignments are sent by rail. There were also 195 consignments of 4,436 packages containing waste for landfill moved from LLWR that was not classed as radioactive and were not included in Table 8.

Table 8: Summary of the consignments (C) and packages (P) containing radioactive waste transported by road and rail to and from LLWR between April 2014 and March 2015

Transport mode	Description of material	Package type	C	P
Road – inbound	Empty packages or waste for disposal	Excepted	58	623
Road – outbound	VLLW, environmental samples, respirators, sealed sources.	Excepted	193	2,121
	Very low-level waste: bagged/drummed asbestos/rubble.	LSA-I	94	700
	Bagged compactable LLW	LSA-II	4	10
	VLLW for landfill	SCO	4	155
	Bitumen samples	Type A	1	2
Total by road			354	3,611
Rail – inbound	Empty packages, respirators, sources from Sellafield	Excepted or LSA-II	29	219
Total by rail			29	219

Information on movements of radioactive material was also obtained from a metal recycling facility which treats radioactively contaminated metal. Surface contaminated metal is treated at this UK site but activated metal is sent to an overseas facility for treatment. In 2014, 131 consignments containing 950 packages were made from the metal recycling company. About 20% of the total consignments were to UK air and sea ports and were subsequently shipped overseas. These consignments contained contaminated metal sent mainly as excepted packages with no TI; three consignments containing five packages were sent as IP-2 packages with TIs of between 0.1 and 0.3. The remaining 80% of packages were either excepted or IP and contained waste for incineration or laundry for decontamination with a range of TIs from 0 to 0.3. These data are summarised in Table 9.

Table 9: Summary of the number of consignments and packages transported by road from a metal recycling facility in the UK during 2014

Package type	Destination	Contents	Consignments	Packages
Excepted	Nuclear power stations	Empty packages	26*	92
	Waste facility overseas	Metal for decontamination	22†	373
	Waste facilities in UK	Low-level waste	58†	373
	Other non-nuclear industry	Samples for analysis	6	14
IP	Waste facility overseas	Metal for decontamination	3	5
	Waste facilities in UK	Laundry	15	92
Total			131	950

* Includes one delivery with a TI of 1.2 containing untreated waste.

† Includes deliveries carried under exclusive use.

4.1.6 Summary of the movements of low-level radioactive waste in the nuclear fuel cycle

Figure 2 provides a summary of all movements of low-level radioactive waste made from some of the facilities involved in the nuclear fuel cycle. There were around 2,500 packages transported to incineration sites with a total annual TI of 50. Just over 2,000 packages, with a total TI of less than 10, were consigned to landfill sites around the UK. Around 450 packages were transported to LLWR with a total TI of over 700 and around 400 packages with a total TI of approximately 150 were transported to the metal recycling facility, of which over 200 were exported to the metal recycling facility overseas. Over 1,000 packages containing contaminated personal protective equipment were transported to a laundry facility for washing with a total TI of <2. Consignments and packages from LLWR to other waste repositories licensed to dispose of radioactive waste are also shown. Information provided by LLWR showed that there were nearly 3,000 packages transported in almost 300 consignments, most containing very low level waste to landfill sites. It should be noted that not all movements of radioactive material to waste facilities are included in Figure 2.

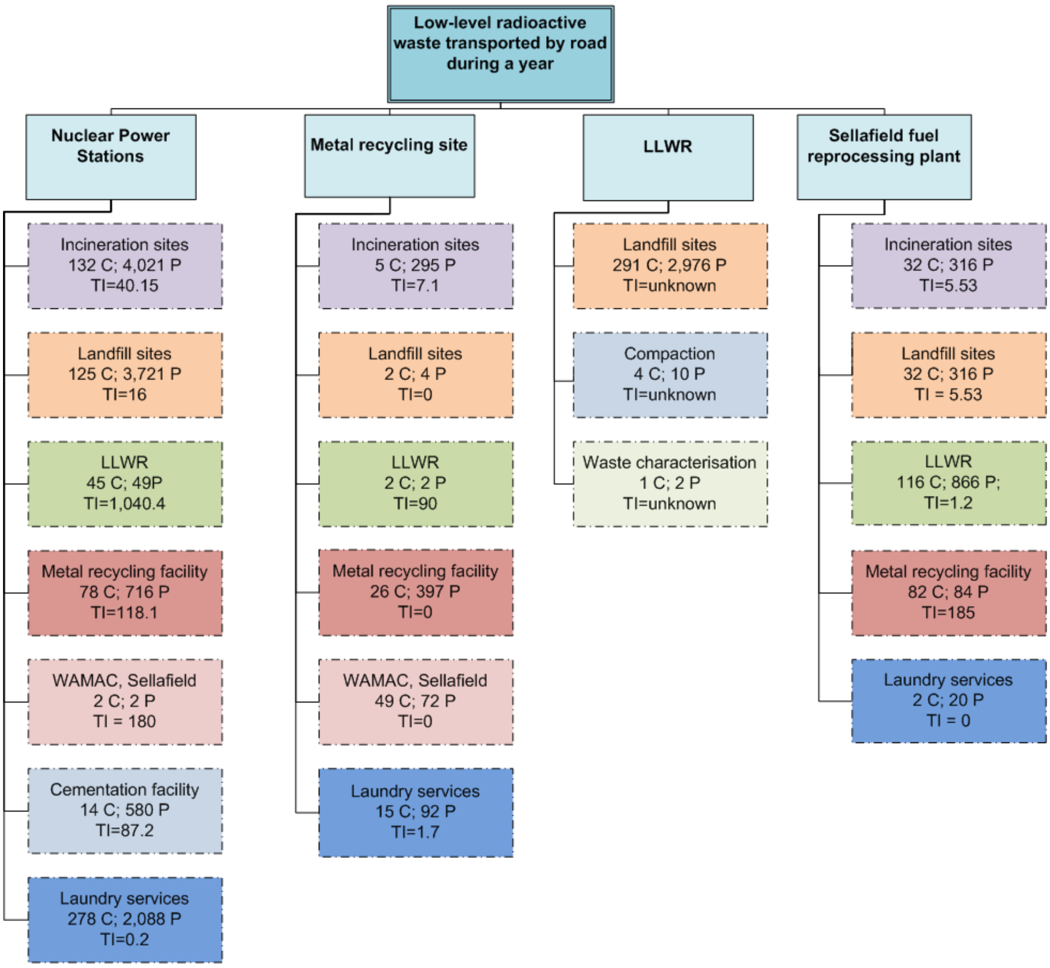

Figure 2: Summary of low-level radioactive waste transported in the UK during a year by road

4.1.7 Summary of number of packages moved annually for the nuclear fuel cycle

Figure 3 is a summary of the number of packages moved by road during the nuclear fuel cycle. An estimate of the number of packages that are currently transported annually throughout the nuclear cycle is about 25,000 in 3,000 consignments by road and about 1,500 packages in 750 consignments by rail; in some cases data were provided for a six month period and were multiplied by two. Data presented represent packages moved from each of the facilities considered with the exception of the low-level waste which also includes movements to the facilities. It should be noted that there may be some double-counting of consignments and packages, particularly between the enrichment and fuel fabrication facilities and also between Sellafield and LLWR, as it could not be verified if some of the data received referred to the same movements.

It can be estimated that 41% of the packages moved in the civil nuclear industry were from nuclear power stations, while 16% of packages transported were either to LLWR from Sellafield or from LLWR to other waste facilities in the UK. Movements from Springfields and Sellafield contributed 16% and 14% respectively; packages shipped from Capenhurst account for 9% of all packages while those from metal recycling waste represent 4% of all packages moved by road in the UK.

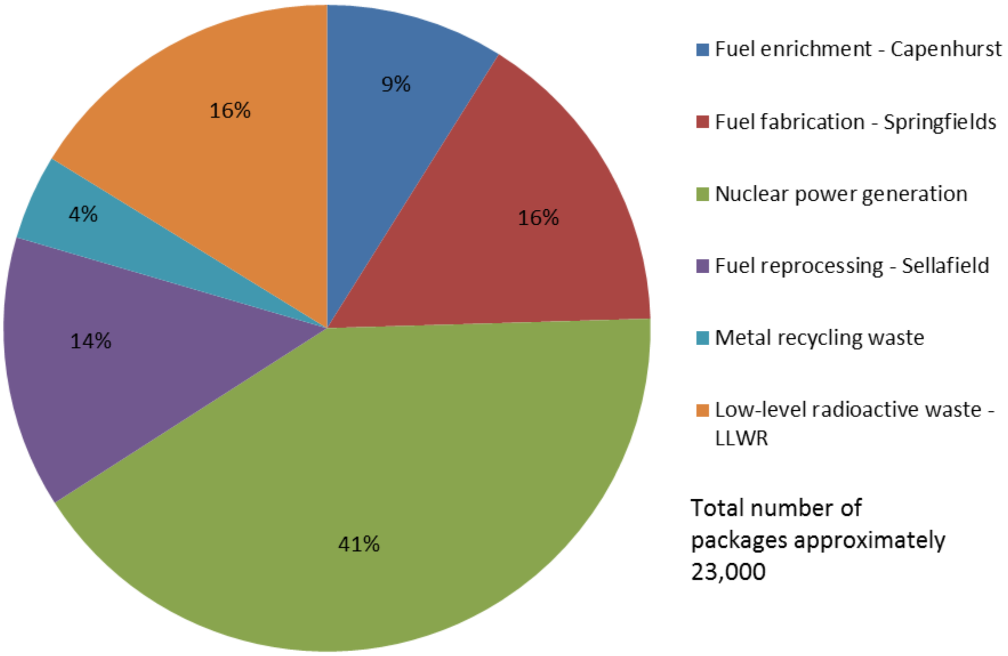

Figure 3: Summary of percentage of packages moved by road from different sectors of the nuclear industry during a year

Figure 4 is a summary of the annual number of packages currently moved by rail between nuclear industry facilities. There are no rail movements associated with the enrichment or fuel fabrication processes. The total number of consignments carried out in a year was estimated to be about 750 containing about 1,500 packages transported by rail. Most consignments and packages are from nuclear power stations or from Sellafield to mostly nuclear power stations; 17% of packages contain low-level radioactive waste from Sellafield to LLWR for disposal.

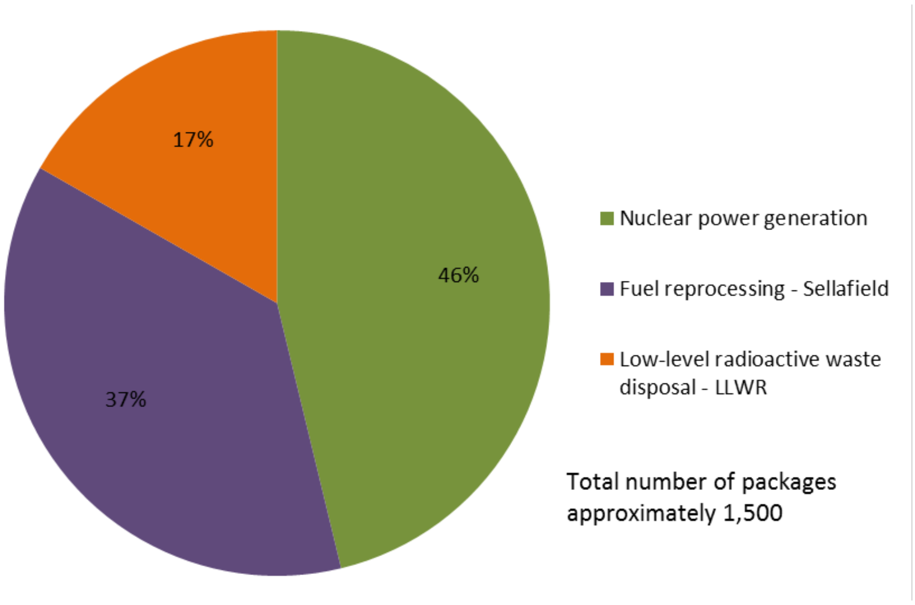

Figure 4: Summary of percentage of packages moved by rail from different sectors of the nuclear industry during a year

4.2 Estimated doses due to transport during the nuclear fuel cycle

This section describes the assessment of doses carried out for workers involved in the transport of RAM by road and rail and members of the public. This is not a comprehensive evaluation of doses received by all workers but only provides a snapshot and should be considered representative of the likely doses received by these workers. Doses were estimated for workers involved with the transport of radioactive material from the uranium enrichment process through to the delivery of radioactive waste, including train drivers, HGV drivers, people loading and unloading radioactive material in packages from trains and lorries, crane drivers, forklift drivers. Doses were also estimated for members of the public who may be exposed to the radioactive material transported. In general these are people who may be present at the premises during loading and unloading but are not directly involved in the operations or they are residents of habitations on the route of a shipment. The doses calculated were based on measurements taken during the visits, although we did not visit all facilities. Very little information was obtained on the dose records of workers.

4.2.1 Estimated doses due to transport during the uranium enrichment process

During a visit to the uranium enrichment facility at Capenhurst carried out in March 2016, measurements of dose rates were taken around a vehicle being loaded with three 30B cylinders full of enriched uranium destined for the fuel fabrication facility at Springfields. These measurements were used to estimate annual effective doses to workers loading the vehicle and to the driver of the vehicle (see Table 10).

The total time taken to load a vehicle was one hour, broken down into three tasks:

a loading 30B cylinders into the overpacks (35 minutes)
b closing the overpacks (15 minutes)
c taking dose rate measurements and contamination swabs (10 minutes)

Two people were involved in the operation and it was assumed that they worked on all 18 shipments that were sent from the enrichment facility to the fuel fabrication site during 2014. The total dose estimated to workers per loading operation was about 7 µSv leading to an estimated annual dose of about 20 µSv. The driver was not present during the loading of the vehicle and therefore it was assumed that he was only exposed for the journey which was estimated to take 1.5 hours. The dose to the driver for each consignment was estimated to be 0.3 µSv leading to an annual dose of 0.7 µSv.

Table 10: Estimated doses to workers during one shipment of 30B cylinders containing enriched UF_6 at uranium enrichment plant and annual dose

Person/task	Dose per task (µSv)	Annual dose (µSv)
Operative loading vehicle		
Loading 30B cylinders on HGV at Capenhurst	7	20
HGV driver		
Shipment from Capenhurst to Springfields	0.3	0.7

During a visit to the fuel fabrication facility at Springfields it was not possible to take dose rate measurements around a loaded vehicle as none were available. It has therefore not been possible to estimate doses to workers loading or unloading vehicles or doses to drivers transporting the different fuel types.

4.2.2 Estimated doses due to transport of radioactive material from the nuclear fuel reprocessing facility

During a visit to Sellafield carried out in March 2016, measurements were taken of dose rates on the surfaces of two empty flasks ready to be returned to nuclear power stations. These measurements were used to estimate the doses to the consignment officers that applied labels and placards to the flask. Only the doses to the consignment officers were calculated because these were the only people who spent time in the vicinity of these flasks once they had left the fuel handling building. They spent about five minutes applying labels and placards to the flasks before they left by rail to a nuclear power station. Their doses are given in the first two rows of Table 11.

A visit was also made in September 2015 to a seaport to take measurements around high-level waste flasks arriving by rail from Sellafield for onward shipment by sea. Dose rate measurements were taken at representative locations using a gamma dose rate monitor and a neutron dose monitor. Three flasks were delivered with TIs of 7.2, 9.0 and 11.0 giving a total TI of 27.2. One other shipment of high-level waste had taken place earlier in 2015 with a total TI of 23.1 giving a total TI for the year 2015 of 50.3. In 2014 only one shipment had taken place with a total TI of 17.9.

Doses were estimated for workers who carried out the main tasks at the dockside such as undoing bolts to remove flasks from the train, taking survey measurements on the surfaces and also at a distance of 2 m from the flasks and attaching the crane beam to the flasks at trunnions; times taken to complete tasks were noted and are reported in Table 11. Doses were also estimated for the crane and the train drivers. As is the norm for the rail transport of radioactive material, two drivers operated the train during the journey, one in the engine cab at the front of the train and the other in the engine cab at the rear of the train and therefore measurements were taken at both locations. Doses were also estimated for office staff working in offices at 5 m from the dockside for one hour; security guards at the site gate, estimated to be 100 m from the flasks; and members of the public walking outside the security fence about 20 m from the flasks. Exposure times and doses received by these people are given in Table 11.

Table 11: Estimated doses due to transport of high-level waste by rail from the fuel reprocessing facility to a seaport

Exposed individual	TI of flask(s)	Time of exposure (h)	Distance from flask(s)	Dose rate measured (μSv h^{-1})	Annual dose (μSv)
Operatives at Sellafield	0.5	0.08	Surface of empty AGR fuel flask	2.7	4
	2	0.08	Surface of empty Magnox fuel flask	7.2	10
Dock workers	11	0.5	Surface	16	20
		0.5	2 m	5	
Train drivers	11	2.5	Inside cab	0.2*	1
Crane driver	27.2	2.5	A few metres above flasks	0.05	0.2
Office workers	11	1	5	3	13
Members of the public	9	0.25	23	0.5	1
Security guards	27.2	3	100	0.03*	0.1

* Measurements are from neutron monitor only; only background dose rate was measured with the gamma dose rate monitor.

The main journeys by trains carrying radioactive material are between nuclear power stations and Sellafield. The doses to train drivers carrying high-level waste given in Table 11 represent very few journeys and may not be typical of train drivers involved in the transport of radioactive material. Therefore a further calculation was performed to estimate the dose to train drivers carrying fuel flasks to nuclear power stations based on the dose rate measurement taken at the seaport and data received from the nuclear power stations. According to this information, the most frequent journey was made from Oldbury nuclear power station to Sellafield. Typically the journey takes five hours to complete and carries one Type B package with a TI of 0.2. There were 50 consignments made from Oldbury in the six month period October 2015 to March 2016 carrying 50 packages with a TI on the day of 0.2

and an average annual TI of 0.2. Based on this information, the annual dose to a train driver was estimated to be typically of the order of 2 µSv y^{-1}.

4.2.3 Estimated doses due to transport of low level radioactive waste for recycling, storage and disposal

Dose rates measured during the visit to the contaminated metal recycling plant which took place in March 2016 are given in Table 12, while doses to drivers and workers involved in the transport of radioactive material at the metal recycling plant are given in Table 13. Table 13 also includes times taken to carry out a number of tasks at the plant which were used to estimate annual dose. On the day of the visit no deliveries were received and therefore dose rate measurements were taken from the surface of three different ISO containers with TIs of 6.4, 11.4 and 30.9 that had been delivered previously. These measurements were taken using a Mini 1000 gamma radiation monitor and a RADOS-RDS gamma monitor. The ISO containers were assumed to have been transported from either the reprocessing plant or from the waste repository site and the times of exposure of drivers were estimated based on the distances between the sites. Doses were also estimated to a forklift driver moving containers around the site; waste managers and health physicists inspecting the containers; and operations personnel cleaning and repacking containers.

Table 12: Data used to estimate doses to personnel involved in the transport of radioactive materials for metal recycling in 2014

Location of measurement	TI of ISO containers	Dose rate measurement (µSv h^{-1})
Surface of end of flask	6	20†
Surface of end of flask	11.4	6.5‡
1 m from end of flask	11.4	4‡
Surface of side of flask	30.9	40†

†Measurements taken using Mini 1000 gamma radiation monitor.
‡Measurements taken using RADOS-RDS gamma monitor.

Typical doses are reported in Table 13. Doses were calculated making cautious assumptions on the exposure times and using the highest dose rate measured at the surface of the flask with a TI of 30.9 even though not all workers would be exposed to the level of radiation measured on the surface of the flask. Doses given in Table 13 therefore have to be considered maximum potential doses received by these workers rather than actual doses. The operation personnel cleaning and repacking containers receive the highest dose as it was assumed they were exposed to the packages for an entire shift of 7.5 hours.

Table 13: Estimated doses to personnel involved in the transport of radioactive materials for metal recycling in 2014

Person/task	Time of exposure (h)	Annual dose (mSv y^{-1})
Transport driver carrying waste from Sellafield	0.75	0.05
Transport driver carrying waste from LLWR	0.83	0.06
Forklift driver moving containers around site	0.25	0.02
Waste manager inspecting containers	0.25	0.02
Health physicist inspecting containers	0.17	0.01
Operation personnel cleaning and repackaging containers	7.5	0.5

5 Transport of radioactive material in the medical sector

5.1 Movements of radiopharmaceuticals

In the UK there are approximately 200 nuclear medicine sites dispensing radiopharmaceuticals for either diagnostic or therapeutic treatment (ARSAC, 2010). There are three companies in the UK that manufacture or distribute radiopharmaceuticals; the information reported in this study was provided by one of these companies. Since many smaller hospitals do not have the facilities required to prepare the radiopharmaceuticals, radiopharmacies at larger hospitals prepare vials or syringes with the required doses and transport them to such hospitals within their vicinity.

The principal radionuclide for medical purposes transported by road and rail in the UK is ^{99m}Tc, which is used for diagnostic procedures (British Nuclear Medicine Society and Council, 2014). Technetium-99m generators are manufactured in the UK from the processing of bulk molybdenum ^{99}Mo, which is imported from other countries. Generally the technetium generators are delivered to central radiopharmacies and nuclear medicine departments of individual hospitals once or twice a week. The information reported in this study provided by one of the three main radiopharmaceutical companies represents a 40% share in the UK market for ^{99m}Tc generators (British Nuclear Medicine Society and Council, 2014)

Other radionuclides used in the medical sector are: ^{131}I, which is the principal radiopharmaceutical for the treatment of thyroid cancer and benign thyroid disease and neuroendocrine tumours; ^{123}I, which is used for imaging the endocrine system and the heart and the brain; ^{51}Cr, used for haematological investigations; ^{75}Se, used for investigations of the gut; ^{89}Sr used in the palliation of pain due to skeletal metastases; and ^{111}In, used in the imaging of the gastrointestinal tract as well as other areas of the body. Some data were also gathered on the movements of sources of ^{18}F, a radionuclide which is increasingly used with positron emission tomography (PET). Fluorine-18 has a short half-life (110 minutes) and is produced in cyclotrons usually close to a radiopharmacy, so that it is only transported for short distances. Other radionuclides, such as ^{60}Co and ^{137}Cs, are used in radiotherapy but no information on the transport of these radionuclides could be collected.

Figure 5 shows the transport routes for medical isotopes in the UK and the number of packages of radioactive material for medical use that are distributed within the UK and also exported overseas. Also included is information on waste movements: seven consignments of 1,268 packages containing 26 and 55 litre plastic kegs were delivered for incineration and one consignment of 72 200 litre drums were sent for super compaction, following which the compacted drums are loaded into ISO containers and delivered to LLWR for disposal.

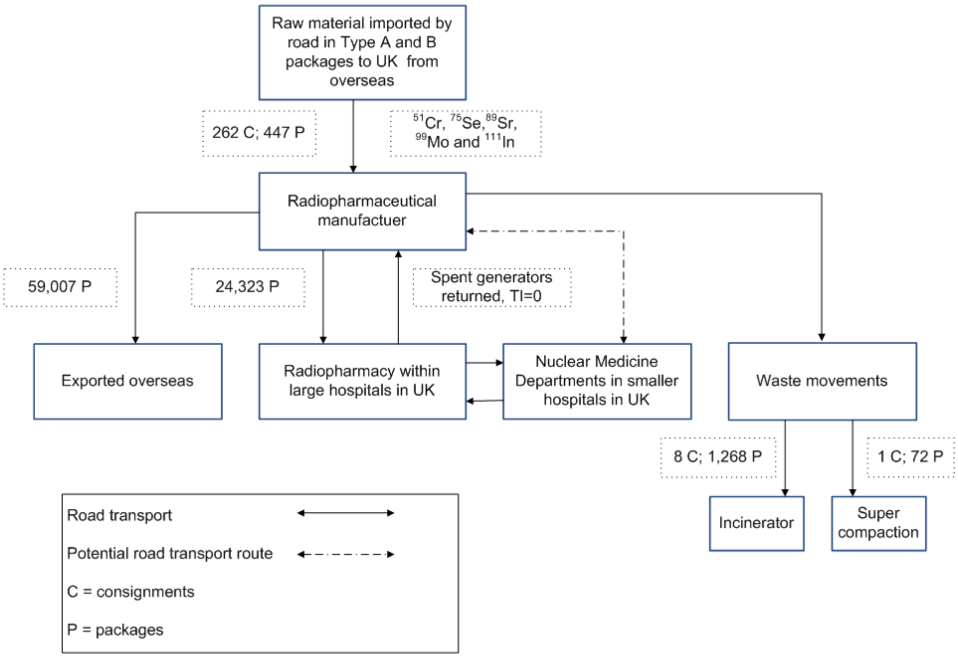

Figure 5: Summary of transport of radioactive material by the medical industry in the UK by road

The information on movements provided by a radiopharmaceutical manufacturer included the numbers of consignments and packages and package types delivered by road during 2014; the radionuclides imported into the UK by air or sea and the radionuclides distributed in the UK; as well as those transported to airports for onward shipment to countries in Europe and the rest of the World. In addition visits were made to both the radiopharmaceutical manufacturer and to their main carrier, since the radiopharmaceutical manufacturer has contracted out the delivery of their products rather than using in-house drivers. At both locations measurements of dose rates around several vehicles that were being loaded were taken and information was gathered on working patterns and procedures. Personal dosimetry data were also provided on annual doses received by operatives packing the radioisotopes in the warehouse and loading and unloading packages onto vehicles. Data were also collected from hospitals that act as hubs and re-package or transport radiopharmaceuticals on to nuclear medicine departments within smaller hospitals. Table 14 provides details of the consignments by road of raw material to a radiopharmaceutical manufacturer in 2014; the total packages delivered to the manufacturer by road were 447, most of which contained ^{99}Mo.

Table 14: Summary of shipments of raw material by road of to a UK radiopharmaceutical manufacturer in 2014

Radionuclide	Package type	Consignments	Packages	Total TI
^{51}Cr	A	10	10	Not known
^{75}Se	A	1	1	0.2
^{89}Sr	A	6	6	31.2
^{99}Mo	B	224	409	50.4
^{111}In	A	21	21	2.1
Total		262	447	>83.9

Table 15 provides a breakdown of the shipments by road of radiopharmaceuticals from the manufacturer visited. The total number of packages transported was 83,761, 70% of which were delivered to airports and seaports for shipment overseas. Most of the packages exported overseas consisted of technetium generators, while over half of the packages delivered in the UK contained ^{123}I. Table 15 also shows a breakdown of the numbers of packages by package type. It can be seen that the majority of packages consigned are Type A packages, of which 50% contain technetium generators and the remainder mainly contain either ^{123}I or ^{131}I. Most of the excepted packages contain ^{75}Se and all the Type B packages contain technetium generators exported from the UK by road via seaports (295 packages) or airports (84).

Table 15: Deliveries by road of radiopharmaceuticals from a manufacturer in 2014 (delivered within UK and exported overseas)

	Package type			No. of packages			Total TI	
Radionuclide	Excepted	Type A	Type B	Delivered in UK	Exported	Total	Delivered in UK	Exported
^{18}F	0	151	0	151	0	151	22.4	0
^{51}Cr	0	4,656	0	1,293	3,353	4,656	68	211.4
^{75}Se	4,436	1	0	3,195	1,241	4,437	0	0
^{89}Sr	16	721	0	42	673	737	0	0
^{99}Mo*	0	39,968	379	2,102	37,836	40,347	2,588.4	64,879.5
^{111}In	0	947	0	0	926	947	0	259.1
^{123}I	0	13,724	0	13,723	1	13,724	1,630.6	0.1
^{131}I	0	18,778	0	3,817	14,961	18,778	1,504.9	6,780.7
Total	4,452	78,946	379	24,323	58,991	83,761	5,814.3	72,130.8

* Technetium generators

Data in Table 15 includes movements of radiopharmaceuticals from a small number of veterinary hospitals, which use them for diagnostic imaging and radiotherapy, especially of horses. It is not known exactly how many veterinary practices in the UK use radiopharmaceuticals in the diagnosis or treatment of animals, but from the data received from the radiopharmaceutical manufacturer a total of 35 packages were delivered to a veterinary practice in the UK in 2014 each containing ^{131}I injections with a TI of 0.4. Information was also received from a veterinary practice which had taken delivery of a total of 38 packages in 2014 comprising three Type A packages containing ^{192}Ir each with a TI of approximately 0.6 and 35 packages of ^{131}I (sodium iodine injections) each with a TI of 0.4.

The majority of the hospitals that provided data on the movements of medical sources to smaller hospitals declared that the radioactive sources that they receive are mainly technetium generators. Occasionally sources of ^{111}In, ^{51}Cr and ^{123}I in Type A packages with TIs of about 0.1 were also delivered. Information received from one large hospital indicated that they typically made up to three deliveries per day, one to each of three other smaller hospitals and empty Type A packages were delivered back to the large hospital by return as excepted packages. Another large hospital re-distributed radioactive products to hospitals and veterinary units generally within a two-hour driving distance. They mainly transported ^{99m}Tc generators to smaller hospitals each day of the week with one driver per delivery route totalling up to seven drivers per day; they also transported ^{90}Y and occasionally ^{111}In with a typical TI of 0.1. A third hospital said that they delivered rubidium and technetium generators up to 10 times per year to local hospitals and departments within a few miles and the spent generators were subsequently returned to them.

Another hospital was visited and information on working practices and patterns was obtained but no dose rate measurements were taken as no deliveries were received during the visit. The hospital that was visited acts as a hub and delivers sources to one other hospital in its vicinity. Once a week they receive a delivery of a technetium generator that lasts up to one week from which injections or vials are prepared for use within the hospital or sent to the other hospital in the area. The vials are packaged and sent to the other hospital as Type A and returned as excepted packages. Other radionuclides handled are: ^{32}P, ^{89}Sr, ^{90}Y, ^{111}In, ^{123}I, ^{177}Lu and ^{223}Ra. They also receive pre-labelled radionuclides from the manufacturer which are either sent straight to the relevant department within the hospital or are transported on to the other hospital. In 2014, approximately 400 packages with a TI of 0 were transported from the main hospital to the other hospital. Information was also received from the hospital’s health physics department that showed the surface dose rates of the packages were generally <0.2 µSv/h. Personal dosimetry data was also provided that showed staff received annual doses between 1 and 2 mSv mainly from preparation work.

Figure 6 shows a breakdown of the number of packages containing radiopharmaceuticals that were imported, exported and delivered in the UK by one pharmaceutical manufacturer whose share of the UK market for ^{99m}Tc generator supply is in the region of 40% (British Nuclear Medicine Society and Council, 2014). It can be seen that nearly three quarters of all the packages were exported overseas.

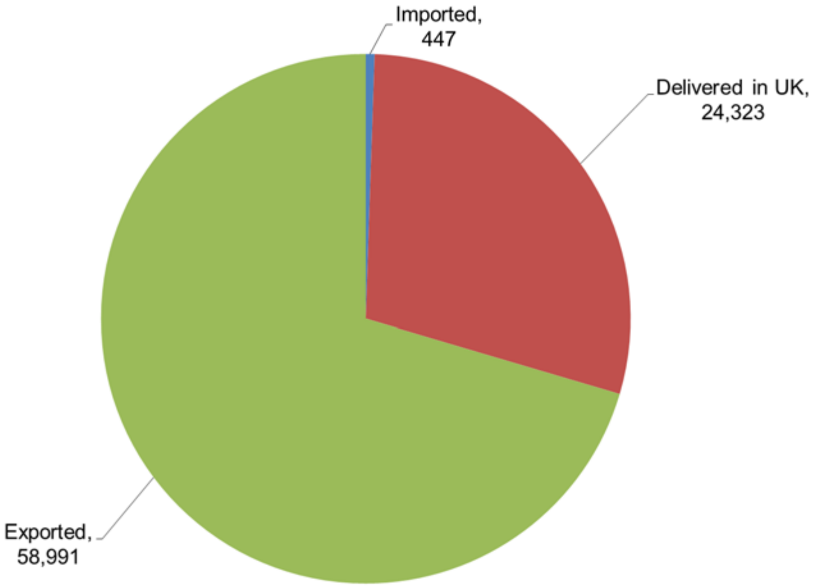

Figure 6: Summary of the number of packages transported by a radiopharmaceutical company by road in the UK during one year

5.2 Assessment of doses to workers involved in the transport of radiopharmaceuticals

A visit was carried out in August 2015 to one of the three manufacturers of radiopharmaceuticals in the UK. During the visit, dose rate measurements were taken around vehicles loaded for despatch and also a 7.5 tonne van carrying a conveyance of ^{99}Mo from an airport that was received on the day.

The consignment of ^{99}Mo consisted of three packages, all Type B, each with a TI of 0.3. Dose rate measurements were taken on the surface of the side of the van, at 1 m and 5 m from the van and on the van driver's seat; these are positions most likely to be occupied by a person loading and unloading the vehicle and representative of the distance at which members of the public could be exposed. Measurements were also taken on the surface of the packages after they were unloaded from the vehicle and on the forklift driver's seat. Molybdenum-99 was delivered once every two weeks by the courier company driver who worked for five days a week on a journey lasting on average 25 minutes up to a maximum of 1 hour, all other journeys contained empty packages.

Measurements were also taken around three other vehicles loaded with radiopharmaceuticals from the manufacturer's warehouse ready for delivery. The first was an HGV class 1, known as the 'Iron Horse', which is a specially designed lead-lined trailer used for 3 deliveries per week to UK airports; the remainder of the week the vehicle is used to transport radioactive material to Belgium and France. At the time of the visit the HGV was loaded with 140 Type A packages containing 89 technetium generators, 23 sources of ^{51}Cr , 4 sources of ^{75}Se, 9 sources of ^{131}I and 14 empty packages with a total TI of 157.7 destined for an airport. Dose rate measurements were taken on the driver's seat, on the surface of the side of the vehicle, at 1 m, 2 m and 5 m from the back door and the side of the vehicle. In the dose calculation it was assumed that the driver was exposed to the packages for an estimated 3.5 hours at the dose rate measured on the driver's seat.

The second vehicle was a small van transporting 10 packages to an airport. The consignment consisted of: five Type A packages containing ^{99}Mo with a total TI of 8.4; one Type A package containing ^{51}Cr with a TI of 0.2; one excepted package containing ^{75}Se; and three empty packages. Dose rate measurements were carried out at the same positions and distances as for the HGV class 1 vehicle described above. It was assumed that the driver was exposed to the radioactive material in the packages for one hour during the journey from the manufacturer to the airport and carried out this delivery four times a week.

Dose rate measurements were also taken around a 7.5 tonne vehicle loaded with 94 Type A packages and three empty packages with a total TI of 94 destined for a nearby airport. Measurements were taken at the surface of the back door of the van, the side of the van and at 1 m to simulate the exposure of workers hand-loading the packages into the back of the vehicle. It was assumed that the workers spent five minutes at each of the three measurement locations. Doses were estimated assuming that a driver was exposed for half an hour, which is roughly the journey time from the manufacturer to the airport and the journey was undertaken five times a week.

Annual doses were estimated for people that may be exposed to packages loaded onto each of the four vehicles and are given in Table 16. The total TI for each load is given in Table 16 along with the dose rate measurements taken around each of the vehicles. The doses for the loaders and unloaders were estimated based on the assumption that these workers spent a total of 15 minutes loading each vehicle divided equally between close contact with the back and the side of the vehicle and at 1 m from the back. The exception is the vehicles carrying ^{99}Mo as a measurement at the back door was not taken as the vehicle had already been opened before a measurement could be made; instead the measurement taken from the side of the vehicle was used in the dose calculation. The annual doses were calculated based on the number of deliveries per year, which was calculated from the number of deliveries per week and the number of working hours per year, and scaled by the average TI per year and the TI on the day. Estimates of doses to members of the public were calculated assuming that a person is living in a house 5 m from a set of traffic lights that the HGV and other vehicles pass by on every journey. It was assumed that these people are exposed to all journeys at a distance of 5 m from the side of vehicles transporting packages for one minute. This is a very unlikely scenario and the doses calculated are to be considered maximum theoretical doses; Table 16 shows that the annual dose to a member of the public would be approximately 0.001 mSv. However, doses are likely to be considerably lower due to shielding provided by building.

Table 16: Estimated doses to workers and members of the public exposed during the transport of radiopharmaceuticals by road from a radiopharmaceutical manufacturer

Exposed person	Position of measurement	TI of load	Dose rate (µSv/h)	Annual dose (mSv/y)
'Iron Horse' to airport				
HGV driver	Driver's seat	157.7	12	0.1
Operative loading vehicle	Surface of back door	157.7	60	0.05
	Surface of side of lorry		165	
	1 m from back door		30	
Member of the public	5 m from side of lorry	157.7	12	0.001
Small van to airport				
Van driver 1	Driver's seat	8.6	15	0.2
Operative loading vehicle	Surface of back door	8.6	250	0.6
	Surface of side of van		100	
	1 m from back door		50	
Member of the public	5 m from side of van	8.6	5	0.001
7.5 tonne van to airport				
Van driver 2	Driver's seat	94	20	0.1
Operative loading vehicle	Surface of back door	94	140	0.2
	Surface of side of van		300	
	1 m from back door		35	
Member of the public	5 m from side of van	94	25	0.002
7.5 tonne van delivering ^{99}Mo				
Van driver 3	Driver's seat	1.8	1.9	0.02
Operative loading vehicle	Surface of side of van	1.8	20	0.05
	1 m from side of van		10	
Member of the public	5 m from side of van	1.8	3.4	0.001

Annual doses to all six operatives working in the warehouse in 2014 were provided by the radiopharmaceutical manufacturer; the average dose received by these workers was 4 mSv, whilst the highest annual dose received was 7 mSv. The doses estimated and given in Table 16 are lower than those provided by the radiopharmaceutical manufacturer due to the assumptions made in the calculation. The estimated doses do not take into account the pattern of individual annual exposure of different warehouse operatives and undertaking operations other than transport.

In September 2015 a visit was also made to one of the transport companies contracted by the radiopharmaceutical manufacturer to collect, sort and deliver radioactive packages. Using information on working practices and dose rate measurements taken around vehicles, doses were estimated for drivers and warehouse operatives based on all deliveries carried out by the transport company in 2014. The drivers collect radioactive sources every day from the radiopharmaceutical manufacturer in lead-lined vehicles and return to the transport company's warehouse. At the warehouse packages that are not destined for the airport are unloaded by forklift truck and placed in a radioactive store to be sorted into destinations. Packages that are destined for the north of the UK are taken to Birmingham by one driver and then a second driver delivers the packages to various locations up to Newcastle.

Packages for the south of the UK are taken from the warehouse to Kent and a second driver then takes the packages to various locations around Kent and Surrey. Packages for London are taken to various hospitals throughout London. The vehicles are driven on regular routes by 14 different people. Table 17 gives details of the doses estimated to a driver travelling from the radiopharmaceutical manufacturer to the transport company's warehouse; a forklift driver that removes all the packages from the van and places them in the radioactive store; and warehouse operatives that are working near the vehicle. Doses were estimated using dose rates measured around vehicles with a load with a TI of 18.5 scaled by the total annual TI.

Table 17: Estimated doses to persons exposed during the transport of radiopharmaceuticals by road from a transport company

Exposed person	Position of measurement	Exposure time (h)	Dose rate (μSv h^{-1})	Annual dose (mSv y^{-1})
Van driver	Surface of side of van	0.08	400	
	1 m from side of van	0.08	100	
	2 m from side of van	0.08	45	
	5 m from side of van	0.08	10	
	Driver's seat	2.6	5	
	Total	3	560	0.2
Forklift driver	Surface of packages	0.04	320	
	Forklift cab	0.08	12	
	1 m from packages	0.04	32	
	Total	0.2	364	0.1
Operatives in the warehouse	Surface of van	0.08	240	
	1 m from van	0.08	35	
	2 m from van	0.08	15	
	5 m from van	0.08	10	
	Total	0.3	300	0.1

6 Transport of radioactive material for industrial use

Radioactive material is used in general industry in the UK for a number of purposes, such as industrial radiography, non-destructive testing, well-logging and gauging systems. In general, radiography sources make up approximately 70% of the industrial sources market. In the UK, there are many companies carrying out testing and measurements using radioactive sources, although the exact number is not known. Information on industrial source users proved very difficult to obtain and therefore a decision was made that the study should focus on the transport of radioactive sources for industrial radiography and the sterilisation of products, mainly medical equipment, because suppliers of radioactive sources and equipment for use in industrial radiography had already been identified as well as a company that sterilise products using ^{60}Co.

Visits were made to one of the main suppliers of radioactive sources in the UK for industrial, non-destructive testing and medical applications, and to a company that carries out irradiation for sterilisation purposes and acts as a consignor and consignee of ^{60}Co shipments. Data were collected on the number of consignments and packages of radioactive material in 2015 and on working practices; dose rate measurements were also taken to facilitate the estimation of doses to workers and the public.

Data on movements of equipment containing radioactive sources and some information on working practices was also collected from nine companies that carry out industrial radiography, non-destructive testing and well-logging.

6.1 Movements of industrial sources by road

In the UK there are two companies that import radioactive material for industrial sources. Information provided in this report was obtained from one of these companies. Table 18 provides a breakdown of the packages transported by road in 2014 by this company by radionuclide. A total of 2,383 packages were either imported or transported by road in the UK, with a total TI of 365.6. About 50% of the packages were Type A, half of which contained ^{192}Ir used for non-destructive testing; most of the remaining packages were excepted packages containing mainly ^{241}Am, ^{57}Co and ^{137}Cs. There were 204 Type B(U) and 20 IP packages delivered to and from the company.

Table 18: Summary of the numbers and types of packages and radionuclides involved in industrial source movements by road in the UK in 2014

Radionuclide	Excepted	IP	Type A	Type B	Total
^{241}Am/Be	1	-	3	-	4
^{241}Am	204	-	34	-	238
^{243}Am	2	-	-	-	2
^{133}Ba	9	-	1	-	10
^{207}Bi	4	-	-	-	4
^{14}C	25	-	-	-	25

Radionuclide	Excepted	IP	Type A	Type B	Total
^{109}Cd	28	-	-	-	28
^{252}Cf	2	-	24	-	26
^{36}Cl	61	-	-	-	61
^{57}Co	152	-	105	-	257
^{60}Co	30	-	32	6	68
^{134}Cs	-	-	1	-	1
^{137}Cs	126	-	82	5	213
^{152}Eu	1	-	15	-	16
^{55}Fe	33	-	-	-	33
^{153}Gd	25	-	2	-	27
^{68}Ge	14	-	76	-	90
^{3}H	14	-	-	-	14
^{129}I	7	-	-	-	7
^{131}I	2	-	-	-	2
^{192}Ir	-	-	612	179	791
^{85}Kr	-	-	7	-	7
^{22}Na	10	-	4	-	14
^{63}Ni	10	-	-	-	10
^{237}Np	2	-	-	-	2
^{147}Pm	2	-	-	-	2
^{238}Pu	6	-	-	-	6
^{239}Pu	4	-	2	-	6
^{241}Pu	1	-	-	-	1
^{226}Ra	2	-	-	-	2
^{106}Ru	1	-	-	-	1
^{35}S	4	-	-	-	4
^{75}Se	-	-	207	14	221
^{85}Sr	11	-	4	-	15
^{90}Sr	55	-	11	-	66
^{99}Tc	4	-	2	-	6
^{232}U	1	-	-	-	1
^{233}U	2	-	-	-	2
^{238}U	20	20	-	-	40
^{88}Y	4	-	-	-	4
^{90}Y	-	-	2	-	2
^{169}Yb	-	-	52	-	52
^{65}Zn	-	-	2	-	2
Total	879	20	1280	204	2,383

Figure 7 shows a breakdown of the data provided by package type. There were a total of 1,181 packages containing industrial sources dispatched from this company to either a UK airport or to companies in the UK in 2014. The majority of those despatched by the company were Type A (621) or excepted packages (420). There were also 122 Type B packages and 18 IP packages consigned. The TIs of these packages ranged from 0 to 4, and the total TI for packages despatched from the company in 2014 was 219.9. There were 1,208 packages received by the company: 660 were Type A; 460 were excepted; 82 were Type B and 6 were Type IP. Approximately 40% of all consignments were of radioactive sources for non-destructive testing.

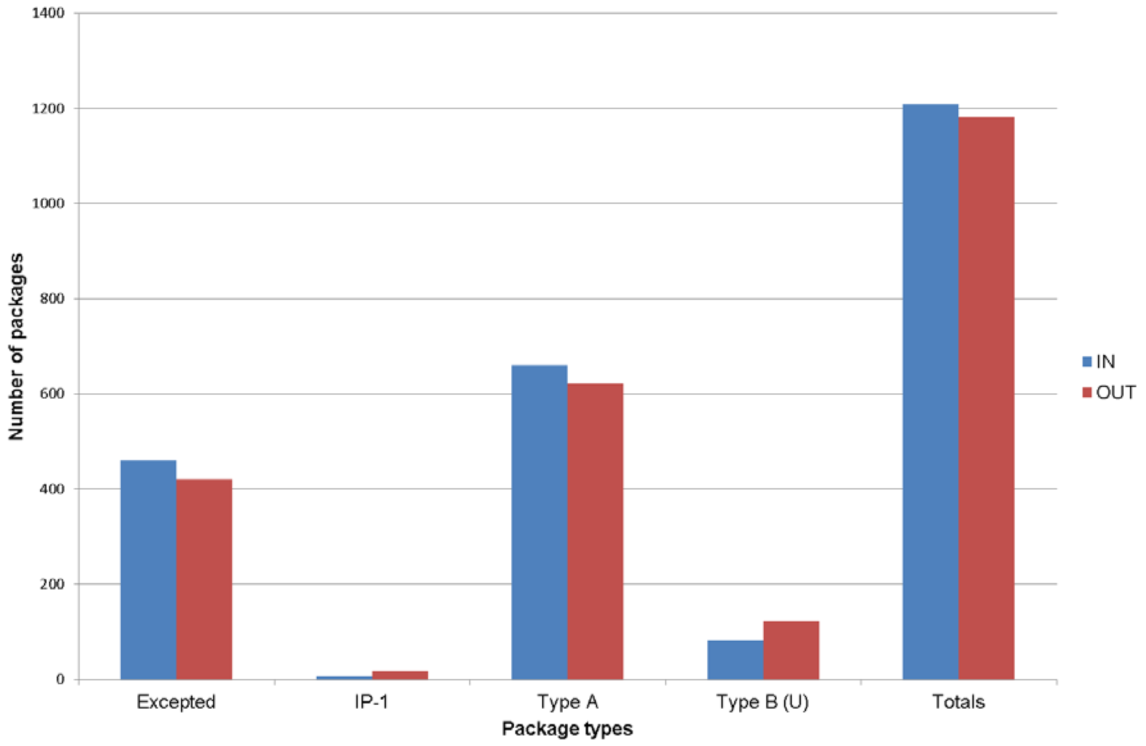

Figure 7: Summary of packages received by and despatched from an industrial source provider in 2014

A visit was made to a company that carry out irradiation for sterilisation purposes of medical equipment, cosmetics, packaging, and other products in December 2015. The company use ^{60}Co as the irradiation source, which is imported to the UK from either Canada or Russia and transported by road in the UK, and the visit was arranged to coincide with the delivery of a new ^{60}Co source to replace depleted sources. Table 19 gives details of the movement of sources of ^{60}Co transported by road for replacement purposes during 2014 to their four UK plants. During this year, there were six consignments of new ^{60}Co for replacement, one consignment of spent ^{60}Co from the company to a UK seaport and two consignments of empty flasks between two of the company's sites.

Table 19: Data on movement of ^{60}Co for industrial use in sterilisation of products in Type B(U) packages by road in the UK in 2014

Package contents	Journey	Activity (TBq)	Category	TI
New ^{60}Co	Seaport to company site	7.4 10^3	Yellow III	5.7
New ^{60}Co	Between company's sites	7.4 10^3	Yellow III	5.7
New ^{60}Co	Seaport to company site	7.4 10^3	Yellow III	5.6
New ^{60}Co	Seaport to company site	1.5 10^4	Yellow III	9.0
New ^{60}Co	Seaport to company site	9.3 10^3	Yellow III	18
New ^{60}Co	Between company sites	7.4 10^3	Yellow III	9
Spent ^{60}Co	From company site to seaport	3.2 10^3	Yellow III	3.8
Empty flasks	Between company's sites	7.8 10^3	Yellow III	0.2
Empty flasks	Between company's sites	1.1 10^3	Yellow II	0.02

Information was also received from a company that supplies radioactive sources for non-destructive testing. The company imports radioactive sources by air, which are then taken by van to the company's warehouse where they are separated out into different packages depending on customer requirements. The packages received normally contained around 20 sources. The main radionuclides are ^{60}Co, ^{192}Ir, ^{75}Se and ^{169}Y. The company normally ships 5 packages per month either to or from the airport and sends out around 400 packages per year to customers. About 80% of these packages are Type A and the remaining 20% are Type B packages labelled Yellow II with TIs of 0 to 1. The company employs six drivers in total and each of them normally carries out journeys two days per week. These data have been included in Table 20.

Information was also received via PHE's RPA service from nine companies that transport radioactive sources by road in their day to day work; this can be either well-logging, density gauges or non-destructive testing. The information collected has been summarised in Table 20. The TIs of the packages vary from a TI of 0 for ^{57}Co, ^{63}Ni and ^{241}Am sources transported as excepted packages to a TI of 2.4 for an Am-Be source used for well-logging, which was consigned 21 times in 2014. Due to the variety of uses of radioactive sources in the industrial sector and as the number of movements of sources is unknown, it would be extremely difficult to make any estimate of the number of packages or consignments of industrial sources moved by road in the UK.

Table 20: Summary of data collected on packages transported by road in 2014 from nine companies carrying out well-logging, density gauges, industrial radiography and non-destructive testing (NDT)

Package type	Sources	TI	Use	Consignments	Destination
Excepted	^{241}Am	0	Well-logging	6	Offshore platform
Excepted	^{57}Co	0	Well-logging	1	Airport
Excepted	^{241}Am	0	Instrumentation	573	Airport
Type A, Cat II yellow	^{63}Ni	0	Trace detection, security screening equipment or for ionising mass spectrometry	1-2*	No information on number of journeys
Excepted	^{137}Cs	N/A	Portable density gauges	20	Coal fired power stations to check coal stocks in UK
Excepted	^{137}Cs	0.1 0.2 0.3 0.4	Well-logging	25 37 30 1	Field-service operations
Type A	^{241}Am/Be	2.4	Well-logging	21	Field-service operations
Type A, Cat II	^{169}Yb, ^{75}Se	0.1	Radiography sources	288	Field-service operations
Type A, Yellow II	^{192}Ir ^{192}Ir	0.1 0.8	NDT	6 3	To oil platforms via road to heliports in <3.5 tonne vans. Company employs three radiographers.
Type A, Cat II yellow	^{137}Cs ^{137}Cs ^{241}Am-Be ^{137}Cs ^{241}Am-Be ^{241}Am-Be ^{241}Am-Be	0.3 0.1 1.5 0.1 1.5 0.4 0	Well-logging	4† 27† 4† 15 6 3 1	Field-service operations Field-service operations Field-service operations Airport Airport Airport Airport
Type A	^{192}Ir ^{75}Se ^{169}Y	0 - 1	Radioactive sources	320	Delivered to customers
Type B	^{60}Co	0 - 1	Radioactive sources	60	To/from airport
Type B	^{192}Ir ^{75}Se ^{169}Y	0 -1	Radioactive sources	80	Delivered to customers

*Packages per journey

† one-way journeys

Figure 8 summarises from the data collected the numbers of packages for each package type containing industrial sources moved by road in the UK. It should be noted that not all data from all industrial source suppliers or users were gathered for this study, and therefore the data presented in this report includes only known information. The data presented in the figure below represents packages moved taking into account that not all sources and movements are known, and also does not take account of the fact that the same source can be moved a number of times.

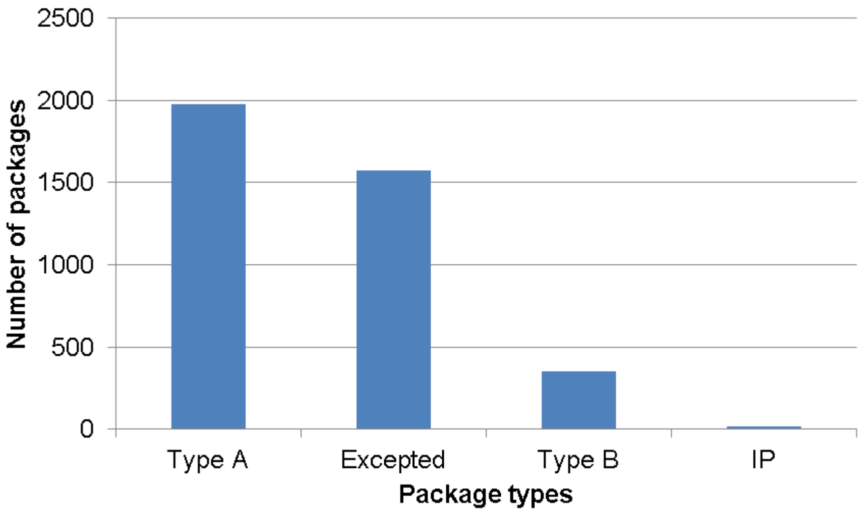

Figure 8: Summary of data collected on number of packages containing industrial sources for each package type transported in the UK in 2014

6.2 Estimate of doses due to the transport of radioactive sources for industrial purposes

Table 21 gives the estimated doses calculated using measurement data taken during a visit in December 2015 to a company that uses ^{60}Co to sterilise products. Doses were estimated for the workers involved in the delivery of flasks based on the TI of the packages received on the day of the visit. The tasks that the engineers undertook were observed during the unloading of the packages from the vehicle into a deep pool of water where the cobalt is stored when not in use: undoing straps, removing cages, carrying out surface contamination wipe tests from outside of flasks and assisting with lowering the flasks into the pool where they are near to the surface of the flask. Measurements were also taken at 1 m, 2 m and 5 m from the packages to simulate the positons occupied by engineers during the hour it was estimated it took to complete the tasks.

The annual dose to the engineer responsible for supervising the work was estimated to be 2 mSv assuming they are exposed to the packages for one hour and based on nine deliveries in 2015 with a total annual TI of 57; this value is higher than the dose of 1 mSv recorded by the company for the main engineer who attends all deliveries. The difference between the two values is most likely due to an overestimate of the time these workers are exposed to the packages. Annual doses to the HGV driver and the forklift driver are also given in Table 21. The HGV driver travels from a UK seaport to the first location where the flasks are delivered and then continues the journey to the second location, where the dose rate measurements used in estimating doses were carried out. The annual dose received by the driver was estimated to be 0.1 mSv. There is only one forklift driver who moves the packages from the lorry to the building whose annual dose was estimated to be 0.02 mSv.

Table 21: Summary of annual doses due to the movement of ^{60}Co by road in the UK

Person	Position of measurement	Time to carry out task (h)	Dose rates (μSv h^{-1})	Annual dose (mSv y^{-1})
Isotope Engineers	Surface of caged flask	1	250	2
	Surface of uncaged flask		600	
	1 m from flask		50	
	2 m from flask		15	
	5 m from flask		5	
HGV driver	Seat of driver's cab	9.5	2	0.1
Forklift driver	5 m from flask	0.5	5*	0.02

*This value has been assumed to be the same as the dose rate at 5 m from the package.

7 Conclusions

This report describes a study carried out by PHE to identify the number of packages and consignments for significant operations, determine transport and working patterns and assess the radiation doses to workers and members of the public from the normal transport of radioactive material by road and rail in the UK. The study was split into three different sections covering organisations and companies involved in the transport of radioactive materials by road and rail in the UK: civil nuclear industry; medical use of radioactivity; use of radioactive sources in general industry.

Information was collected by establishing direct contact with a number of companies known to transport radioactive material by road and rail rather than by using a specific questionnaire, since the use of questionnaires did not prove to be fruitful during the study on the consequences of the normal transport of radioactive materials by air (Harvey et al., 2014). Comprehensive information was collected for the nuclear industry, thanks to the collaboration established through RAMTUC, although there were gaps with regard to data about the transport of radioactive waste. It was not possible to establish contact with all the companies involved in the manufacture and distribution of medical radioisotopes; data used in this study came mainly from one of the main three radiopharmaceutical companies and covers approximately one third of the majority of movements in the medical sector. Also, incomplete information was collected on the movements of medical sources after they are shipped to nuclear medicine departments and radiopharmacies in hospitals. This aspect of the movements of medical sources should to be given careful attention in future studies as well as the transport of medical sources for particular sectors, such as PET and veterinary, although the number of sources used in these sectors is likely to be small.

As far as the uses of radioactive sources in general industry, this study focused on transport to and from companies importing and distributing sources for industrial radiography, non-destructive testing, well-logging and gauging systems. A large number of companies make use of these sources but it was not possible to establish contact with many of these companies to obtain a full picture of the movements of industrial sources within the UK. This particular topic should be the focus of future reviews.

Visits were made to companies within the civil nuclear industry, a radiopharmaceutical manufacturer, a courier carrying packages for the radiopharmaceutical manufacturer, and a company that carries out irradiation of packages for sterilisation. At each visit dose rate measurements were taken when it was possible to do so, information on working practices and patterns was obtained and data collected on numbers of consignments and packages.

Taking account of the uncertainties in the information collected described above, this study estimated that the number of packages consigned annually by road in the years 2014 to 2016 was about 110,000. This value should be treated with some caution and considered only a broad estimate. Since the information collected for this review from the medical sector and in particular the general industry sector is likely to be incomplete, the actual number of packages transported by road is likely to be somewhat higher, and therefore a figure of about 150,000 may be closer to the real value. It should also be borne in mind that medical and industrial sources may be moved more than once. In the previous study conducted by HPA (Watson et al., 2005), it was estimated that 500,000 packages were consigned by road in the UK in 2003; this information was obtained from a study supported by the European Commission on the transport of radioactive materials in Europe (EC, 2003).

Figure 9 provides an estimated breakdown of the number of packages containing radioactive material transported in the UK annually under normal conditions by road. The previous report on transport by road and rail (Watson et al., 2005) concluded that there was a continuing increase in the use of radioisotopes in medical procedures and this trend has been confirmed by this study. Figure 9 shows that roughly three quarters of the packages transported by road in the UK are medical sources, whilst 4% are industrial sources and the remaining 20% are packages in the nuclear industry. It should be borne in mind that these values are approximate.

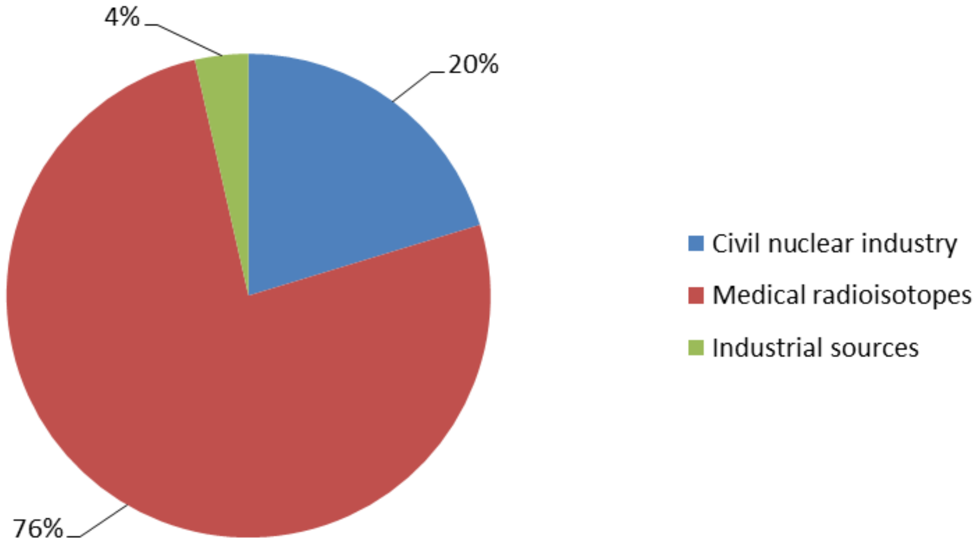

Figure 9: Summary of radioactive packages moved by road during one year

For transport by rail, it was found that only the civil nuclear industry move packages by this mode of transport. The total number of packages containing RAM transported by rail in a year between 2014 and 2016 was estimated to be about 1,500; the number of consignments was estimated to be about 750. The majority of these packages were Type B transported to nuclear power stations. For movements by rail, the previous HPA study on transport by road and rail (Watson et al., 2005) reported that in 2003 2,725 packages were moved by rail between major nuclear sites, consisting mainly of flasks containing both new and spent fuel. The data therefore suggest that there has been a reduction in the number of packages containing RAM transported within the civil nuclear industry over the last 10 to 12 years. The reason for this reduction in movements of fuel flasks by rail since 2003 is probably related to the fact that all Magnox power stations have ceased operating.

Working patterns remain very similar to those found in the 2005 HPA report (Watson et al., 2005), although it should be noted that companies do not use their employees to transport radioactive material as much as in the past, with a shift towards using specialist transport companies.

Doses to workers and members of the public in each of the three sectors covered by this study are given in the relevant sections of the report. Table 22 gives typical ranges of annual doses to different categories of workers and members of the public for the different sectors covered in this report. It should be noted that transport workers receive doses from other activities and tasks which they may carry out and not only from their involvement with transport operations. The wide range of doses to operatives loading/unloading vehicles reflects the different sectors of the nuclear and non-nuclear industry; the lowest doses are received by the operatives at Sellafield labelling nuclear fuel flasks and the highest doses are to the engineers involved in the movement of ^{60}Co sources for the purpose of irradiation. The drivers involved in transporting radiopharmaceuticals received the highest doses due to the large number of packages that are consigned each year compared to those consigned in the civil nuclear industry.

Table 22: Ranges of typical estimated annual doses to workers and members of the public due to the normal transport of radioactive material in the UK

Exposed person	Range of annual doses (mSv)
Operatives loading/unloading vehicles	~0.004 – 2
HGV drivers	~0.001 – 0.1
Van drivers	0.02 – 0.2
Train driver	0.0001 – 0.002
Forklift driver	0.02 – 0.1
Other workers	<0.001 – 0.5
Members of the public	<0.001

In the previous report (Watson et al., 2005) dosimetry data received from carriers of radioisotopes and hospitals showed that the average annual doses ranged from 0.2 mSv to 4.5 mSv and that the maximum dose received by a driver was 6.5 mSv. The annual doses calculated to van drivers in this report are considerably lower in the range of 0.02 to 0.2 mSv.

In the previous study, dosimetry results showed that the highest exposed workers were operatives involved in loading and unloading vehicles, who received annual doses in the range 3 to 6 mSv. The results from this study indicate that the doses to these workers are lower, up to a maximum of about 2 mSv per year. The doses presented in this study were estimated using dose rate measurements taken during visits carried out at specific sites. The previous study did estimate doses from measured dose rates but calculated daily doses rather than annual values.

Typical doses estimated in this study for HGV drivers and van drivers were of the order of 0.1 mSv. This value is lower than the mean doses to classified transport workers, assumed to be drivers, given in the previous report of between 0.6 and 0.9 mSv (Watson et al., 2005). It should be noted that doses for this study were estimated using dose rate measurements taken on visits whereas the previous study used personal dosimetry data from the Central Index of Dose Information and dosimetry data supplied by hospitals, carriers and suppliers of radioactive materials (CIDI, 2004). These dose records would also include doses received during other tasks as many of these people are not just involved in the transport of packages.

In this study it was estimated that the typical annual dose to the driver of a train moving fuel flasks to a nuclear power station would be approximately 2 µSv. In the previous study doses to train drivers were estimated to be 10 µSv due to the transport of fuel flasks; the difference is due to differences in the dose rate measurements and also a reduction in the number of fuel flasks being moved containing new fuel.

Table 22 also gives annual doses that have been estimated in this report to forklift drivers, 0.02 mSv at the metal recycling site and 0.1 mSv at the radiopharmaceutical manufacturer, and also other workers, such as crane drivers, 0.2 µSv, involved with the transport of radioactive materials that were not considered in the previous report and so no comparison can be carried out.

Doses to members of the public arising from the transport of radioactive materials are extremely low. In the previous study a dose to a person living in a building 5 m from a set of traffic lights by which a lorry carrying technetium generators passed each week was estimated to be less than 20 µSv. The dose estimated in this study using the same scenario was much lower (1 µSv).

In general doses to workers and members of the public from the normal transport of radioactive material in the UK by road and rail are low and well below the respective annual dose limits of 20 mSv for workers and 1 mSv for members of the public. In comparison the average annual dose for members of the UK population from all sources of natural radiation, medical exposure, nuclear weapons fallout, radioactive discharges and occupational exposure was 2.7 mSv in 2010 (Oatway et al., 2016).

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