Public Health England

Survey into the Radiological Impact of the Normal Transport of Radioactive Material by Air

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Published January 2014

PHE publications gateway number: 2013406

Survey into the Radiological impact of the Normal Transport of Radioactive Material by Air

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ABSTRACT

In 2012 the Centre for Radiation, Chemical and Environmental Hazards undertook a survey of the radiological impact of the transport of radioactive material by air at the request of the Office for Nuclear Regulation. This report describes the outcome of this, the third survey into the radiological impact of the transport of radioactive material by air and compares it with the outcomes of the two previous studies on the same topic.

In this study the main operations and working patterns related to the transport of radioactive materials by air from, to and within the UK were reviewed. Visits were carried out to three major passenger and cargo operators handling shipments of radioactive material to obtain relevant information and make measurements of dose rates to assess doses to workers at these companies, and for air crew and passengers.

The survey found that about 46,500 packages were transported by air from the UK on over 4,400 flights. The majority of these were medical sources sent by cargo or passenger flights from the UK; a small number of industrial sources were also shipped by air. Radioactive materials associated with the nuclear industry are exclusively transported by road and rail or ship. The highest annual dose to a worker of a cargo handling company was found to be around 7.0 mSv. Doses to air crew and passengers from exposure to radioactive material transported on aircraft were generally very low. The highest average annual doses to the flight and cabin crew were estimated to be 25 μSv y^{-1} and 73 μSv y^{-1}, respectively, while the highest average annual dose to passengers was 73 μSv y^{-1} on long haul flights. The total collective doses received by the flight and cabin crew were 0.0075 man Sv and 0.058 man Sv, respectively. The collective dose to the passengers from all types of flights was estimated to be about 4.4 man Sv. An increase in collective dose for short haul flights from the last study is due to inclusion of doses from onward flights from the hub. In this study collective doses are now included for onward flights from the international airports that UK operators use to transfer passengers to their intended destination (airport hub).

Packages of radioactive material are transported in holds underneath cabin areas or in the main deck cargo compartment at recommended segregation distances from passengers and crew. Another objective of this survey was to compare segregation distances used by operators with those recommended by the International Civil Aviation Organization and the values calculated using the International Atomic Energy Authority methodology. The survey found that segregation distances used by the operators were generally more cautious than those estimated using the IAEA methodology.

This study was funded by the Office for Nuclear Regulation.

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Approval: December 2013
Publication: January 2014
£15.00
ISBN 978-0-85951-749-2

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

CONTENTS

1 INTRODUCTION

Radioactive materials are commonly transported by air for medical and industrial purposes to, from and within the UK on both passenger and cargo-only aircraft. On passenger aircraft packages of radioactive material are transported in holds underneath cabin areas at recommended distances from passengers and crew; on cargo aircraft they may also be carried in the main deck cargo compartment.

The IAEA Transport Regulations (IAEA, 2012) form the basis for instructions governing the transport of radioactive materials issued by the International Civil Aviation Organization (ICAO). Regulations for the transport of radioactive materials by air in the UK are enforced by the Civil Aviation Authority (CAA).

The IAEA Transport Regulations require that the national competent authority for regulating transport of radioactive materials ‘shall arrange for the periodic assessments of the radiation doses to persons due to the transport of radioactive material, to ensure that the system of protection and safety complies with the Basic Safety Standards’ (IAEA,1996).

In the UK the Air Navigation (Fifth Amendment) Order 2009 (SI, 2009) requires information to be provided to aircraft crew on the health risks of their work, the assessment of exposures over 1 mSv per year, dose limitation for pregnant crew members and control for highly exposed crew.

In order to fulfil these responsibilities the Office for Nuclear Regulation (ONR) has periodically commissioned the Centre for Radiation, Chemical and Environmental Hazards of Public Health England to carry out studies to investigate transport practices and to assess the radiological consequences associated with the normal transport of radioactive material by air. Two studies have already been carried out on this topic, the first one was published in 1990 (Gelder, 1990) and the second one in 2003 (Warner Jones et al, 2003). In 2012 the ONR requested PHE to undertake a third survey into the radiological impact of the transport of radioactive material by air; this report describes the results of the survey and makes a comparison with those of the previous surveys to identify trends. The study is concerned only with the exposure to radiation from packages of radioactive materials during transport by air; exposure to natural sources of radiation during flights, such as cosmic radiation, was not considered.

In this study the airlines which carry packages containing radioactive material are referred to as ’operators’. Companies handling cargo in warehouses on behalf of the operators are referred to as ’cargo handling companies’.

2 OBJECTIVES AND SCOPE OF THE SURVEY

The main objectives of the survey were to identify significant operations carried out during the transport of radioactive material by air in terms of the numbers of packages and people involved as well as those operations that could give rise to the highest doses. In addition, measurements were to be taken at airport warehouses and on board aircraft transporting radioactive materials.

All types of airports and categories of aircraft were covered including both scheduled and charter flights and both passenger and cargo aircraft. All types of radioactive material were considered and, wherever possible, a distinction was made between medical and industrial sources and radioactive material used in the civil nuclear sector.

Data collected from major operators in the UK was used together with information and measurements from site visits to estimate annual individual and collective* doses to workers involved in the loading and unloading of packages at the airport warehouse, flight and cabin crew, passengers on board aircraft as well as any other people who might be exposed from these operations. In addition, the parameters used to derive the ICAO segregation tables (ICAO, 2013) were assessed using on-site measurements where possible.

3 COLLECTION OF INFORMATION FOR THE SURVEY – QUESTIONNAIRE AND VISITS

3.1 Questionnaires

Two questionnaires were sent out to the operators to gain information about the number of flights transporting radioactive materials. A first letter was sent by email to 194 operators who transport dangerous goods by air to identify which of them carry packages containing radioactive material. A list of all UK and non-EU operators approved to carry dangerous goods as cargo was supplied by the Civil Aviation Authority (CAA, 2012). There was, however, difficulty in obtaining a list of EU operators as there is no requirement for these operators to inform the CAA of what they transport. The letter contained questions similar to the one sent for the previous air study (Warner Jones et al, 2003). The information requested in the letter included:

a Details of contacts within the company

b Whether packages of radioactive material are transported

c Details of the number of packages transported in 2010/11

Only 13 responses were received from individual operators to confirm that they carry radioactive packages. A more detailed questionnaire was sent out to those operators who had confirmed that they transported radioactive material (RAM) in the first questionnaire.

The second questionnaire asked for more detailed information such as:

a Number of packages and number of consignments containing RAM transported in 2010 or 2011

b Number of short and long haul flights with and without RAM for both passenger and cargo aircraft

c Transport index (TI) in the last six months or longer in 2011

d Cabin crew and flight deck crew employees per operator in a year

* In this report the term individual dose is used to indicate the effective dose from exposure to external radiation received by a person over a defined period (either the whole year or the duration of a flight). The collective dose is the sum of all the individual doses received by the members of a particular group in a year. The individual dose is measured in sievert (Sv). The unit used for the collective dose is the man sievert (man Sv).

e Average and maximum cabin crew and flight crew per operator per flight

f Total number and average number of passengers carried in an aircraft in a year for short and long haul flights

g Maximum number of flights in a year for a courier or frequent flier for short and long haul flights

Responses to the second survey were very poor; only one operator provided the relevant information. Nevertheless operators indicated that the vast majority of radioactive packages transported by air from the UK were sources for medical use. Data collated in the survey was therefore supplemented with information on operators who export packages containing radioactive material from the UK and the number of packages transported in 2011, obtained from a major UK company that manufactures radiopharmaceuticals. The data provided by the manufacturer of radioactive medical sources was more detailed and more comprehensive than in the previous study and it was considered sufficient to enable PHE to produce a full analysis of the transport patterns and perform a robust assessment of doses associated with the transport of radioactive material by air.

Contacts with several operators and one manufacturer of radioactive material were made when the initial survey letters were sent, to investigate whether visits could be made to their premises to collect information relating to working practices and make measurements of dose rates on packages at the airport warehouse and on aircraft. Two of the operators were chosen because they were believed to transport most packages of radioactive material during 2011 and also because their aircraft transport both passengers and cargo; another operator was chosen because it transports most of its packages by long haul flight. The largest UK manufacturer and distributor of medical sources containing radioactive material and a UK company which distributes industrial radioactive sources, were also visited. A number of visits were then made to the premises of these companies between October 2012 and February 2013. During the visits dose rates on and around the packages were measured using two types of gamma dose rate meters: a Mini 1000 and a RADOS RDS-31. The background reading was measured at 0.5 µSv h^{-1}.

3.2 Visits to companies and operators

Figures 1 to 7 illustrate typical procedures in moving and loading packages at the companies visited.

3.2.1 A major manufacturing company of medical sources

The visit to the packaging facility of a company involved in the manufacture and distribution of medical sources occurred in November 2012. Dose rates on packages containing ^{131}I and ^{99}Mo medical sources were measured. Some of the packages containing these sources gave dose rates up to 500 µSv h^{-1} at the package surface. This company provided a large amount of data on consignments from, to and within the UK and on transit to the UK. The information formed the bulk of the data on which the analysis of transport patterns was based.

FIGURE 1 Packages sorted into destinations for cargo aircraft

FIGURE 2 Space for radioactive packages in a unit load device for cargo aircraft

FIGURE 3 Main deck cargo hold of a cargo aircraft

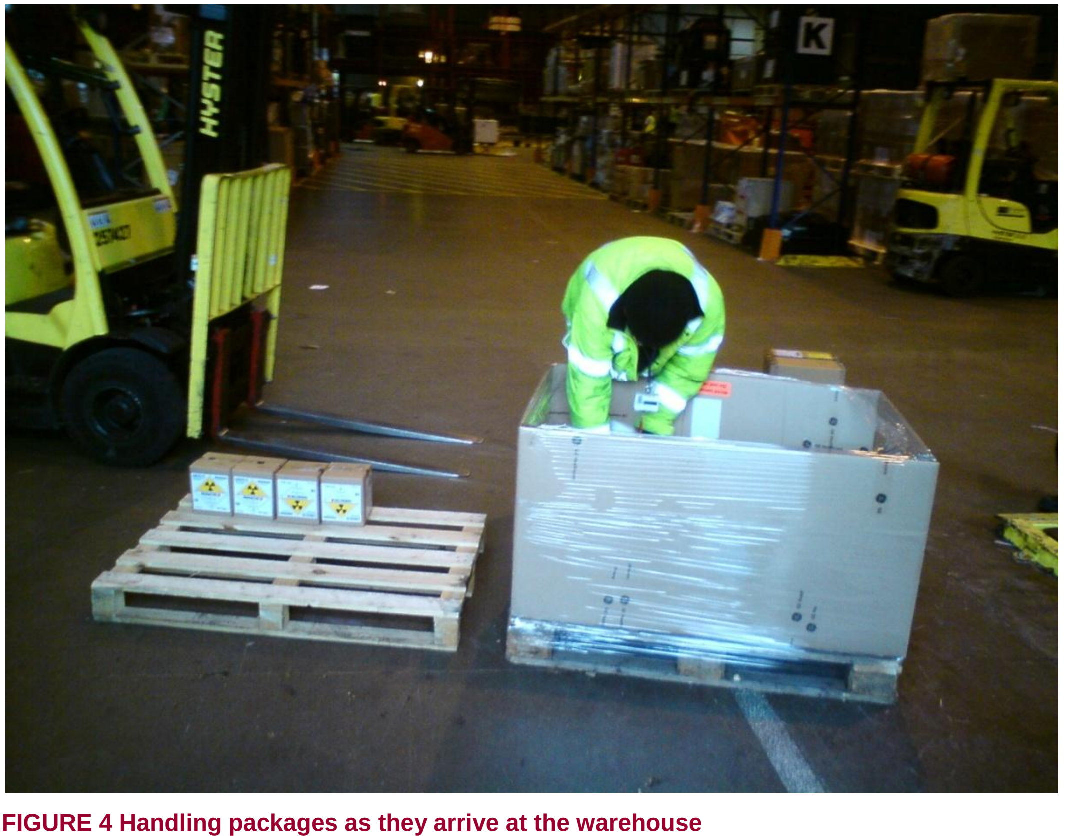

FIGURE 4 Handling packages as they arrive at the warehouse

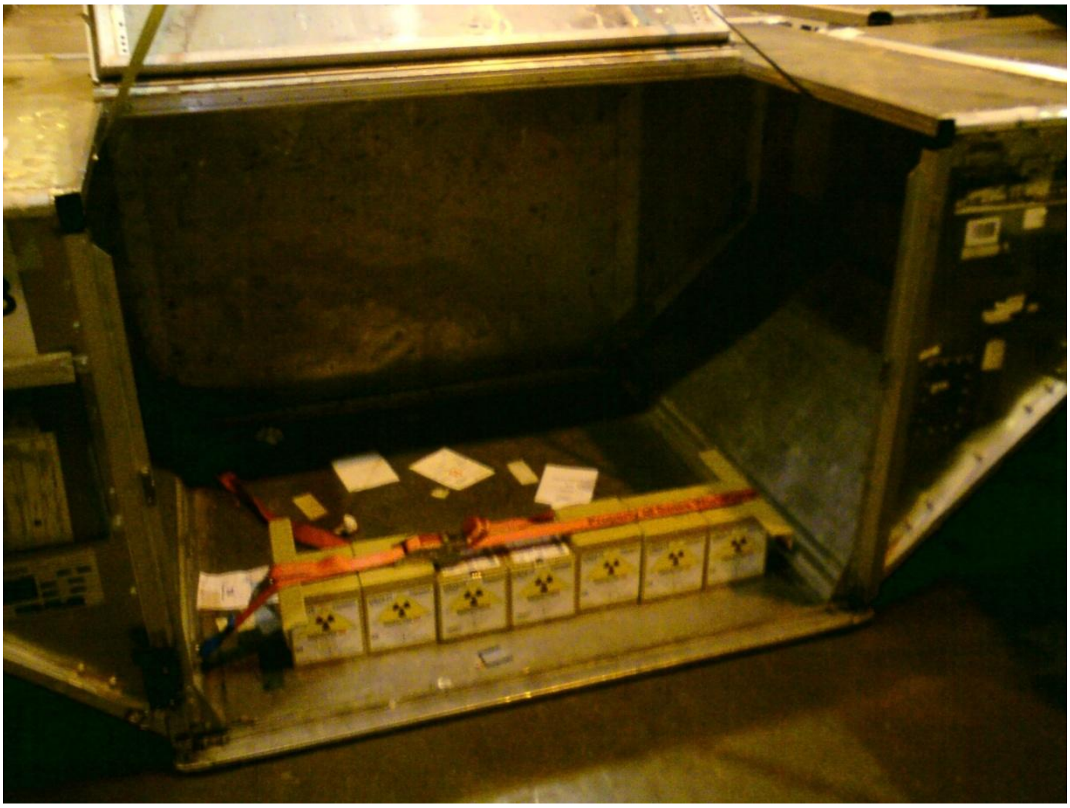

FIGURE 5 Packages arranged at the bottom of a unit load device

FIGURE 6 Measuring dose rates of packages before they are stored in the radiation store

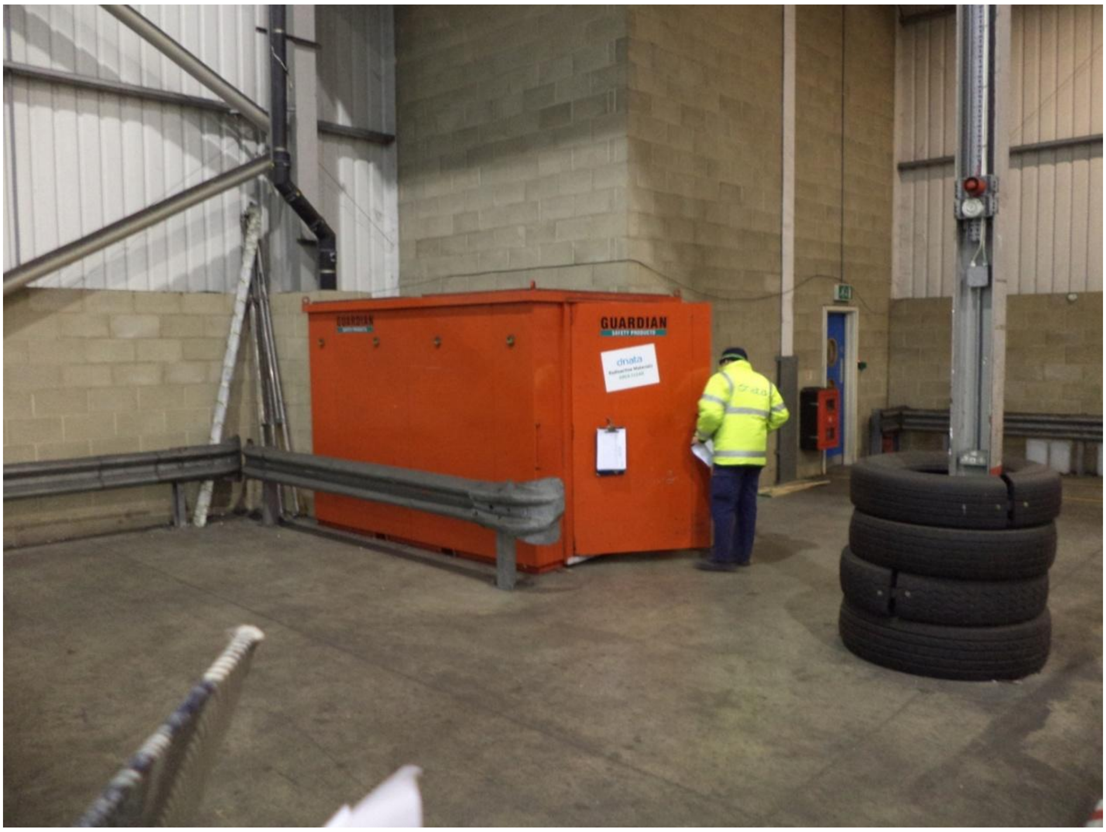

FIGURE 7 Radiation store containing packages

3.2.2 A company involved in the distribution of industrial and medical sources

The visit to the warehouse of a company involved in the distribution of industrial and medical sources was made in December 2012. The company is a distributor of a large number of medical sources (including ^{60}Co) and industrial radiography sources. The sources are transported as both Type A and B packages. Some dose rate measurements were made on the packages of these sources in the warehouse. The actual dose rates measured on the surface of Type A and B packages containing ^{192}Ir sources were 150 μSv h^{-1} and 80 μSv h^{-1}, respectively.

3.2.3 A major cargo handling company of a cargo airline

The visit to the depot of a major cargo handling company at a UK airport took place in October 2012. The company is the major operator in the UK for transporting packages containing radioactive material, primarily for the major distributor of medical sources in the UK described above. The packages are sent by cargo aircraft to different destinations, on both short and long haul flights. On the day the visit to the depot was made the packages had a total Transport Index (TI)* of about 300. Transport of medical packages by this operator normally occurs three times a week, usually with the highest TI on a Tuesday. The average TI for a week was estimated to be 700.

The depot was airside, which means that the packages were transported directly from the warehouse on to the aircraft, without transport on public roads. The packages containing

* The Transport Index is the dose rate in microsievert at 1 m divided by 10.

radioactive material were placed at the base of a unit load device (ULD) together with other packages. The ULDs were then transported on to the aircraft and those with the packages containing radioactive material were placed at the rear of the aircraft in front of a ULD containing no radioactive material. Measurements were taken in areas where workers were loading packages on to the aircraft and also in areas on the aircraft next to the flight crew, once the packages were in the aircraft. Measurements of dose rates were taken on a consignment that was bound for European destinations containing mostly ^{99}Mo sources, with a TI of about 150. The highest dose rates were measured in the warehouse where packages were being sorted by hand into different destinations. The personal dosemeter measurements taken by the operator indicated that in an evening when the packages with the highest TI are delivered, the individual doses to workers from all operations could be up to 150 µSv. The annual dose to an individual is reduced by rotating the staff to different tasks and the maximum individual dose is likely to be about 6 mSv. All staff are trained radiation protection advisers (RPAs).

3.2.4 A major cargo handling company for a passenger flight operator

The visit to the distribution warehouse of a major passenger operator was made in October 2012. This company transports radioactive material for the major distributor of medical sources in the UK, described above, from a depot at a major UK airport, which is also used by other operators. The warehouse was away from the airport and packages were required to be transported on public roads.

Three shipments of radioactive material are generally transported per week. On the day the visit took place the TI of the shipment was the highest of the week with a value of 14.7. The load was divided and the TI for the flight surveyed was about 8.4. The packages generally contained ^{131}I and ^{51}Cr sources for medical use. The packages were divided into three ULDs which were spread equally along the length of the hold of the aircraft. This consignment was bound for a non-European country, but the initial destination was the company's airport hub in Europe.

3.2.5 A cargo handling company of a long haul passenger operator

The visit to the freight handling company of a long haul passenger operator took place in February 2013. The company was located just outside a major UK airport and packages were transported airside by road from the warehouse to be loaded on to aircraft. The packages arrived on a van, mainly from a UK manufacturer of radiopharmaceuticals. The total TI of the two pallets in the warehouse on the day of the visit was 5.4.

Packages were unloaded from the van using a fork lift truck, checked and placed in a radiation storage unit. Typical doses recorded by the personal dosemeters carried by warehouse staff were 1 to 2 µSv over approximately a 15-minute period. Measurements of dose rates recorded during the visit were 30 µSv h^{-1} at 1 m from the pallet and 7 µSv h^{-1} at the seat of the fork lift truck driver.

The dangerous goods manager then rechecked the store where radioactive sources were kept when the packages were required to be transported to the aircraft. The check took between approximately 30 minutes and 1 hour to complete, and monitor readings were on average 30 µSv at the end of the process. The worker responsible for building a ULD then collected the packages from the store and placed them at the bottom of the ULD. On the day of the visit two ULDs were built and split between two flights: one with a TI of 3.1 and the other with a TI of 2.3. Each ULD was then loaded on to the back of a truck and transported airside to be loaded on to the aircraft.

The operators run four flights a day and radioactive packages are transported on one or two of these flights for four days a week. ULDs used to transport freight are 64 inches (about 160 cm) in height leaving a clear 12 inches (about 30 cm) to the floor of the passenger area of the aircraft. Each ULD can be loaded with radioactive material with a TI of up to 9 and there can be up to 4 ULDs on a passenger flight. The radioactive material typically carried includes sources of ^{51}Cr, ^{131}I, ^{111}In and ^{99}Mo, and intended for use in hospitals. During the visit it was not possible to follow the packages airside to record dose rates on the aircraft.

4 WORKING PATTERNS AND TRANSPORT OPERATIONS

The data obtained from the major distributor of medical sources indicated that there are 32 operators who transport radioactive material for medical use by aircraft, of which three operators transported radioactive material by cargo aircraft only; another operator was identified through the questionnaire sent out as part of this study. Table 1 gives the number of operators by airport in the UK and also shows which airports are exclusively used by the carriers. For example, there are 29 operators who transport radioactive materials out of Heathrow Airport, 28 of which use this airport as their sole terminal. Some of the operators transport the packages to an airport hub outside the UK, to be flown to non-European countries. Table 2 gives the cities where the operator hubs are located and the flight time from London Heathrow. Each company is identified by a code which indicates whether the operator flies short (S) or long haul (L) passenger flights or cargo (C) flights followed by a suffix (eg L1, S1, C1). This coding allows the company to be cross-referenced throughout the report without giving the actual company name.

4.1 Types of radioactive material transported by air

This section provides a summary of the main types of shipments of radioactive material by air identified during the survey. Most of the radioactive materials transported by air from, to and within the UK are sources and materials used for medical applications; a small number of industrial sources are also shipped by air. Materials associated with the nuclear industry are exclusively transported by road and rail or ship. The summary is based on data provided by the main producer of medical sources in UK, with some additional information collected through the questionnaires, and represents most of the shipments of radioactive material between the UK and other countries.

More than 46,500 packages containing radioactive sources for medical use were transported from the UK by air in 2011 on about 4,400 flights, with a total TI of about 49,000. About 8,600 packages were sent from the operator’s hub on 1,559 flights for a total TI of 2,058. About 63% of these packages were sent by cargo aircraft, although the number of flights by cargo aircraft transporting radioactive material was only about 36% of the total number of flights. This is because cargo aircraft can transport loads of radioactive material with a larger TI as there are no passengers who can be exposed. The average TI values per aircraft of packages containing radioactive material transported on cargo aircraft were 26 and 10 for

TABLE 1 Number of operators in the UK transporting radioactive material

Airport	Number of operators at airport	Number of sole use operators
Heathrow	29	28
Stansted	3	1
East Midlands	1	
Birmingham	1	
Luton	1	
Belfast	1	
Guernsey	1	
Manchester	1	
Aberdeen	1	

TABLE 2 Operators with airport hubs outside the UK

Operator*	City of hub	Flight time from Heathrow (hours)	Type of flight
L1	Toronto	7	Long haul
L2	Hong Kong	12.5	Long haul
C1	Leipzig	1.5	Short haul
L4	Dubai	7	Long haul
C3	Memphis	9	Long haul
S2	Luga	2.75	Short haul
S4	Helsinki	2.5	Short haul
S6	Madrid	2	Short haul
S8	Frankfurt	1.5	Short haul
L11	Doha	7	Long haul
S18	Zurich	2	Short haul
S19	Lisbon/Porto	2.3	Short haul
C2	Liege	0.5	Short haul
S21	Istanbul	3.25	Short haul

* S = short haul passenger flights; L = long haul passenger flights; C = cargo flights.

short and long haul flights, respectively, while the average TI values for short and long haul passenger flights were 3.5 and 4.2, respectively. The number of packages containing radioactive material for medical use transported on passenger aircraft within the UK and also transit through the UK on cargo aircraft was small compared to the number of packages containing radioactive material transported by air from the UK (see Table 3). Fewer than 700 flights into the UK carried radioactive packages containing medical sources (see Table 3).

Table 4 provides a breakdown by radionuclide and operator of the packages sent by the main producer of medical sources in the UK. About half of these packages contain technetium generators which are small units that produce a supply of ^{99m}Tc from the decay of ^{99}Mo. These

TABLE 3 Summary of main medical shipments by air

Route	Packages	Consignment	Flights with RAM	Total number of flights*	Total TI
Flights from the UK					
Short haul passenger	6,708	1,331	1,036	31,536	3,602
Long haul passenger	10,456	2,298	1,775	16,622	7,509
Short haul cargo	25,753	NA	1,322	7,807	34,573
Long haul cargo	3,601	NA	289	1,588	2,887
Total	46,518		4,422	57,554	48,571
Flights into the UK					
Short haul passenger	NA	NA	365	12,000	2,114
Long haul passenger	NA	NA	55	550	133
Short haul cargo	NA	NA	208	6,968	166
Long haul cargo	NA	NA	18	600	14
Total			646		2,428
Flights within the UK					
Short haul passenger	NA	NA	75	NA	49
Transit through the UK					
Short haul cargo	2,247	NA	493	NA	758

* These are the numbers of total outward flights for operators including those transporting radioactive packages.

are sent in Type A packages mainly on cargo aircraft as a higher TI can be transported on each flight. The raw material used to produce the radioactive source in the generators, molybdenum, is imported by air from South Africa and the Netherlands in Type B containers with a TI of about 0.8 per container. The empty Type B containers are flown back as Type A packages, while the spent ^{99}Mo containers are sent back to the UK as Excepted packages. Other sources include ^{51}Cr and ^{131}I, which are mainly transported by passenger aircraft because of the lower TI. The finished iodine product is manufactured in Germany, and is then transported back to the UK, mostly by road.

Radioactive sources are also supplied by another UK distributor to various companies worldwide for industrial and medical use. In 2011, 208 packages were sent to 20 overseas countries; about half of these contained sources for industrial use. The TI of individual packages varied between 0 and 1.5; the total TI for 2011 was 41. The sources were sent by air as Type A, Type B and Low Specific Activity Type 1 (LSA I) packages. The LSA packages were sent as three consignments, each with a TI of 0.1. The consignments were sent to both European and other countries by both cargo and passenger aircraft; the distributor did not provide details of the number of flights or a breakdown by type of aircraft. Table 5 gives a summary of the shipments of radioactive material made in 2011 from and to the UK. About 39% of the sources sent by this company are ^{192}Ir for use in industrial radiography. Other radionuclides sent by air include ^{241}Am (about 48% of all sources), ^{57}Co, ^{137}Cs, ^{68}Ge, ^{75}Se and ^{238}U.

TABLE 4 Medical packages exported in 2011 by a major UK medical source manufacturer

	Radionuclide									
Operator*	^{51}Cr	^{131}I	^{111}In	^{114m}In	^{99}Mo	^{24}Na	^{75}Se	^{89}Sr	Total	Total TI
S1		118							118	40
L1		783	1,278		16		24	22	2,123	1,055
S2		27							27	13
L2	178	1,026	186		250		9	75	1,724	967
S3		19			91				110	147
L3	1	202			98				301	202
C1	1,387	1,031	595		17,568	1	275	140	20,997	34,203
L4	4	513			201			1	719	483
C3	49	1,245	1,517	1	681			108	3,601	2,887
S4	4	273	47		41		6	2	373	187
S5, L5		198			61				259	185
S6		543			131			17	691	644
S7	7	20						1	28	7
L6		1	5					4	10	1
L7	59	45	28				1	26	159	30
S8	4	384			86			2	476	225
S9, L9	22	1,261	3		366				1,652	1,491
S10, L9		105	89					119	313	56
S11, L10	11	661			220			1	893	714
S12, L11	29	885	45		349				1,308	1,031
S13, L12		520			92				612	424
L13		2						4	6	1
S14	5	25	3		29		4		66	81
S15, L14	17	308			746				1,071	1,251
S16, L15	37	79	2					8	126	49
S17, L16		12							12	6
S18	69	3,071	28		342		3	40	3,553	1,372
S19		84			140				224	342
S20, L17		10			4				14	6
C2	460	118	3		137		268	27	1,013	370
S21	2	193			1				196	102
Total	2,345	13,762	3,829	1	21,650	1	590	597	42,775	48,572

∗ Operators flying both short and long haul flights are identified with two codes.

TABLE 5 Summary of shipments of medical and industrial sources by air supplied by a UK distributor

Route	Number of packages	Total TI
Short haul passenger/cargo	81	16
Long haul passenger/cargo	41	12
Long haul cargo only	86	13
Total	208	41

4.2 Transport by passenger aircraft

Consignments of radioactive material are transported on both short and long haul passenger flights. Generally consignments transported on short haul flights have a lower TI than those transported on long haul flights, because the size of the cargo hold is larger in a long haul flight and therefore the segregation distances between the packages and the passengers are larger. No evidence was found that combi aircraft* are now used to transport radioactive material; some small charter flights transport radioactive materials locally within the UK.

Consignments from the main UK producer of medical sources generally arrive at the warehouse of the operator three times a week. On arrival, the packages are sorted according to their destinations and then kept in a purpose built store for packages containing radioactive material awaiting transfer to the aircraft. The packages are then built into ULDs together with packages containing non-radioactive material and are subsequently loaded on to the aircraft before the passengers go on board.

As a rule, the maximum TI for narrow body aircraft, which generally fly to short haul destinations, is up to about 10, while for wide body aircraft, which generally fly long haul flights, the TI is up to about 18 (Reynolds, 2012). In general, packages destined for a non-European city are transferred to onward flights at an airport hub to other worldwide destinations.

4.3 Transport by cargo aircraft

Most of the consignments of the UK manufacturer of medical sources sent by cargo aircraft are transported by a single large cargo operator. Consignments typically arrive at the warehouse of the handling company three times a week in the evening to be loaded on to the aircraft departing either the same evening or the following morning. The consignments are sent generally as Type A packages divided according to their destination. Packages are built into the base of one or more ULD, depending on the TI, together with non-radioactive packages; the ULD is then loaded into the cargo hold from the side of the aircraft.

Approximately 50% of the packages are sent on direct flights to the final destination, with the rest being sent first to a European airport hub. Detailed information on the final destinations of the packages sent by cargo aircraft was not made available for this study and therefore for the purposes of estimating doses to passengers and crew it was assumed that all the packages that were sent to the airport hub were flown onward to other destinations by air.

* Combi aircraft can be used as either passenger or cargo aircraft and usually have a partition in the cabin to allow both uses at the same time.

Co-operation and communication between the manufacturers and the carriers are crucial to the continued safe handling and future growth of this sector. The major UK cargo carrier and medical supplier hold regular meetings to discuss any logistical issues.

4.4 Number of flight crew and passengers

The numbers of flights and passengers per operator in 2011 were used in this study for the calculation of collective doses. The numbers of flight crew on short and long haul flights, together with the numbers of seats on typical aircraft, were obtained from the site visits of two major operators that transport radioactive materials (see Table 6). The total number of flight crew for each operator was obtained by multiplying the number of flights by the number of crew on the aircraft given in Table 6.

For the operators who carried the majority of packages containing radioactive material the numbers of outward flights from the UK and passengers in 2011 were obtained from the CAA (CAA, 2012) and are reported in Table 7. For all other operators the number of passengers was estimated on the basis of the number of flights and the number of seats on the aircraft.

The data provided by CAA was also used to determine the radioactive traffic factor (RTF) for the same operators (see Table 7). The RTF is defined as the ratio of the annual number of journeys made transporting category Yellow II and category Yellow III* packages of radioactive material to the annual number of all journeys. From the information it was estimated that the RTFs for short and long haul passenger flights from the UK were 0.03 and

TABLE 6 Number of crew and passengers in aircraft used to carry radioactive material

Type of aircraft	Flight crew	Cabin crew	Passengers
Airbus 320	2	4	170
Boeing 747	4	17	379
Cargo aircraft (converted Boeing 757)	3	0	0

TABLE 7 Number of flights and passenger transported in 2011 by a selection of operators

Operator	Number of flights	Number of flights carrying RAM	Number of passengers	RTF
S18	9,100	300	900,000	0.03
L2	1,455	250	444,000	0.17
L4	5,350	220	1,750,000	0.04
L8	730	98	214,000	0.13
L10	1,359	246	349,000	0.18
L11	2,189	200	440,000	0.09
L14	649	258	116,000	0.4

* Yellow II packages have a TI of more than 0 but no more than 1 and a surface dose of more than 0.005 mSv h^{-1} but no more than 0.5 mSv h^{-1}; Yellow III packages have a TI of more than 1 but no more than 10 and a surface dose of more than 0.5 mSv h^{-1} but no more than 2 mSv h^{-1}.

0.1, respectively. An RTF of 0.18 for short haul cargo aircraft for flights from the UK was calculated from data for a single major carrier of radioactive material; it was assumed that the RTF for long haul cargo aircraft was the same. For flights into the UK the same RTFs for passenger flights were assumed, while a value of 0.03 was used for cargo aircraft. An RTF of 0.18 was also used for cargo aircraft in transit through the UK. The RTF values were used to calculate the number of flights carrying radioactive materials for operators where no such data was available.

5 ASSESSMENT OF THE RADIOLOGICAL CONSEQUENCES OF TRANSPORT OF RADIOACTIVE MATERIAL BY AIR

Individual and collective doses to workers involved in offloading and loading packages at the airport warehouse, to flight and cabin crew on both short and long haul flights, and to passengers were calculated for a selection of operations involving radioactive material transported by air. Doses to flight crew were calculated for both cargo and passenger aircraft, while doses to cabin crew were calculated only for passenger aircraft.

Doses were calculated only for the transport of medical sources, using information collected from the site visits and the data supplied by the CAA and the major UK manufacturer of medical sources. Doses from the transport of industrial sources were not calculated as these are likely to be smaller than those calculated for transporting medical sources – as the TI of a consignment of industrial sources is generally low and the number of consignments to overseas countries small.

The following sections give a general overview of the methodology used to calculate doses and an analysis of the results of the assessment. Details about the equations used to calculate the doses are given in Appendix A.

5.1 Doses to warehouse workers

Both individual and collective doses to warehouse workers employed by companies handling packages containing radioactive material for different operators were calculated for this survey. The doses were estimated for different phases of the process, from delivery of the packages to the warehouses, to their placement in the store used to keep the radioactive sources, to their uploading into the hold of the aircraft. Doses were calculated separately for each of the three companies visited during the study to include operations typical of transportation by different types of aircraft (cargo aircraft and short and long haul passenger aircraft). The doses were based on the dose rates measured during the visits or the doses recorded by dosemeters carried by workers and on information about working practices collected during such visits. The tables in this section summarise the annual individual doses and collective doses to workers; doses per delivery estimated using data collected during the visits are given in Appendix B.

Table 8 summarises annual doses estimated for workers at a cargo handling company for cargo aircraft. Doses were based on an average TI of about 230 per delivery to the warehouse and 150 deliveries of radioactive material to the warehouse over a year. The maximum annual dose to a warehouse worker was estimated to be 4.7 mSv y^{-1}, assuming that the same person

TABLE 8 Summary of annual individual and collective doses to workers at warehouse of a cargo handling company for cargo flights

Scenario		Individual dose (mSv)	Number of individuals per shift	Collective dose (man Sv)
Workers transporting packages from lorry to warehouse and sorting area∗		0.57	6	0.0103
Staff on gangways while packages are being sorted		0.19	2	0.0011
Warehouse workers	Sorting packages into different destinations	2.4	3	0.0214
	Moving boxes from bunker to ULD	2.0	3	0.018
	Moving ULDs ready for stacking on to aircraft	0.34	3	0.0031
	Total (warehouse worker)	4.7		
Driver moving ULDs from warehouse to aircraft		0.67	1	0.002
Worker moving four ULDs on to the hold of the aircraft		1.9	3	0.017
Total				0.073

∗ Based on measured doses from the Siemens EPD Mark 2 electronic personal dosemeter (EPD).

TABLE 9 Summary of annual individual and collective doses to workers at a warehouse of a cargo handling company for short haul passenger flights

Scenario	Individual dose (mSv)	Number of individuals per shift	Collective dose (man Sv)
Worker moving packages from van to warehouse	0.06	2	0.00025
Worker sorting packages from pallet (three loads)	0.47	1	0.00094
Worker carrying out dangerous goods checks∗	0.65	1	0.0013
Worker building ULD†	0.42	2	0.0017
Total	1.60		0.0042

∗ Based on measured doses from the Siemens EPD Mark 2 electronic personal dosemeter (EPD).
† Based on measured doses from the Appleford AI-1 personal integrating dosemeter (PID).

TABLE 10 Summary of annual individual and collective doses to workers at a warehouse for a cargo handling company for long haul passenger flights

Scenario	Individual dose (mSv)	Number of individuals per shift	Collective dose (man Sv)
Worker moving packages from van to warehouse	0.1	2	0.0004
Worker sorting packages from pallet	0.75	2	0.003
Worker doing dangerous goods checks	1.6	2	0.0065
Worker building ULD	0.45	2	0.0018
Total	2.9		0.012

performs all the different tasks required to sort packages and place them into a ULD. The annual collective dose for the workers at this company was estimated to be 0.073 man Sv, assuming that there are three shifts of workers. The doses were the highest of all the warehouses visited because of the larger number of packages, and hence TI, that is transported on cargo aircraft. It should be noted that the doses in Table 8 were estimated in this survey from dose rates measured at the warehouse; the maximum dose measured on a personal dosemeter for 2011 was around 7 mSv. The doses in Tables 9 and 10 give the estimated doses to workers at a warehouse for two cargo handling companies for operators which fly passenger aircraft. Doses are lower because fewer packages are transported on these types of flights. Doses to workers at the warehouse of an airline transporting radioactive material on short haul flights were based on an average TI per delivery to the warehouse of 4.6 and on 300 flights carrying radioactive material in a year and assuming that workers work two shifts. The maximum annual individual dose was estimated to be 1.6 mSv; the collective dose was estimated to be 0.0042 man Sv (see Table 9). For the company handling radioactive material for a long haul operator, doses were calculated on the basis of an average TI per delivery of 3.9 and 250 flights carrying radioactive material in a year and assuming that workers work two shifts. The maximum annual individual dose was estimated to be 2.9 mSv; the collective dose was estimated to be 0.012 man Sv (see Table 10).

5.2 Doses to crew and passengers on aircraft

5.2.1 Measurements of dose rates on board aircraft

Doses to flight and cabin crew and passengers calculated for this survey were based on dose rate measurements made on a narrow bodied Airbus 320 passenger aircraft used for short haul flights during one of the visits carried out in this survey. Dose rates measured on this aircraft are shown in Table 11 and Figure 8. On the day when the measurements were taken the aircraft was loaded with radioactive material with a TI of 8.4. The average dose rate for the location where passengers sit was estimated to be 3.6 μSv h^{-1}, while the average dose rate at the positions normally occupied by the cabin crew was estimated to be 1.5 μSv h^{-1}. The dose rate measured at the position normally occupied by the flight crew was 0.22 μSv h^{-1}.

Dose rates were also measured on a narrow bodied Boeing 757 converted to be used as a cargo aircraft. Packages containing radioactive material were stored towards the tail; the total TI on the cargo aircraft was 149. Dose rates were measured on the flight deck of the aircraft during and after loading. During loading the dose rate was measured at 10 μSv h^{-1}, while after loading the dose rate was 0.18 μSv h^{-1}.

It was not possible to take measurements on a wide bodied aircraft used for long haul flights and, therefore, for the purpose of the assessment of doses, it was assumed that dose rates on long flights were four times lower than the value measured on short haul flights for the same TI. This factor takes account of the greater distance between the packages containing radioactive material and the areas occupied by the flight and cabin crew on long haul flights. It was estimated from a comparison of dose rates calculated using Microshield computer program (v 9.05) (Negin, 1986) for the geometry of a narrow and a wide bodied aircraft for the same TI and is consistent with the ratio of dose rates measured on a narrow bodied aircraft (Boeing 757) and a wide bodied aircraft (Boeing 747) in the first study of the radiological impact of normal transport of radioactive material by air (Gelder, 1990).

TABLE 11 Dose rates measured on board an Airbus 320 passenger aircraft

Row number (business class)	Dose rate on seat (µSv h^{-1})	Row number (economy class)	Dose rate on seat (µSv h^{-1})
1	2	25	10
2	2	26	2
3	2	27	2
4	2	28	2
5	2	29	2
6	8	30	2
7	8	31	10
8	2	32	10
9	2	33	2
10	2	34	2
11	2	35	2
12	2	36	2
13	2		
14	2		
15	2		
16	2		
17	10		

5.2.2 Doses to flight and cabin crew

Individual and collective doses were assessed to flight crew for each of the 32 operators which transported medical sources in 2011. Doses to flight and cabin crew were calculated for both short and long haul flights. Flight crew were assumed to be on the flight deck for the duration of the flight; cabin crew were assumed to be located within the passenger cabin or at either end of the aircraft of passenger aircraft only. The method used to calculate the doses is described in detail in Appendix A.

Doses to flight crew for each airline were calculated using dose rate measurements made on the narrow bodied Airbus 320 aircraft and scaling them according to the average TI of the airline over the year, the number of flights per year and flight times. Annual average individual doses were calculated by multiplying the average dose for a single flight by the maximum number of flights which flight and cabin crew were assumed to fly and the RTF for the type of flight. Maximum doses received by the flight and cabin crew on a single flight were also calculated based on the flight times of the operators. An additional dose of 1.7 µSv was added to the dose received by the flight crew of cargo aircraft to take account of the fact that the flight crew were on the flight deck when the packages were loaded.

Data on the number of flights flown by each operator in a year and flight times was collected during the survey and is given in Appendix B, Tables B4 to B8. Default maximum numbers of flights per year in one direction assumed in the previous survey into the radiological impact of normal transport of radioactive material by air (Warner Jones et al, 2003) are reported in Table 12. These values were considered as an upper limit for the maximum number of flights of crew members in the calculation of doses if they were lower than the maximum number of flights specific to an operator.

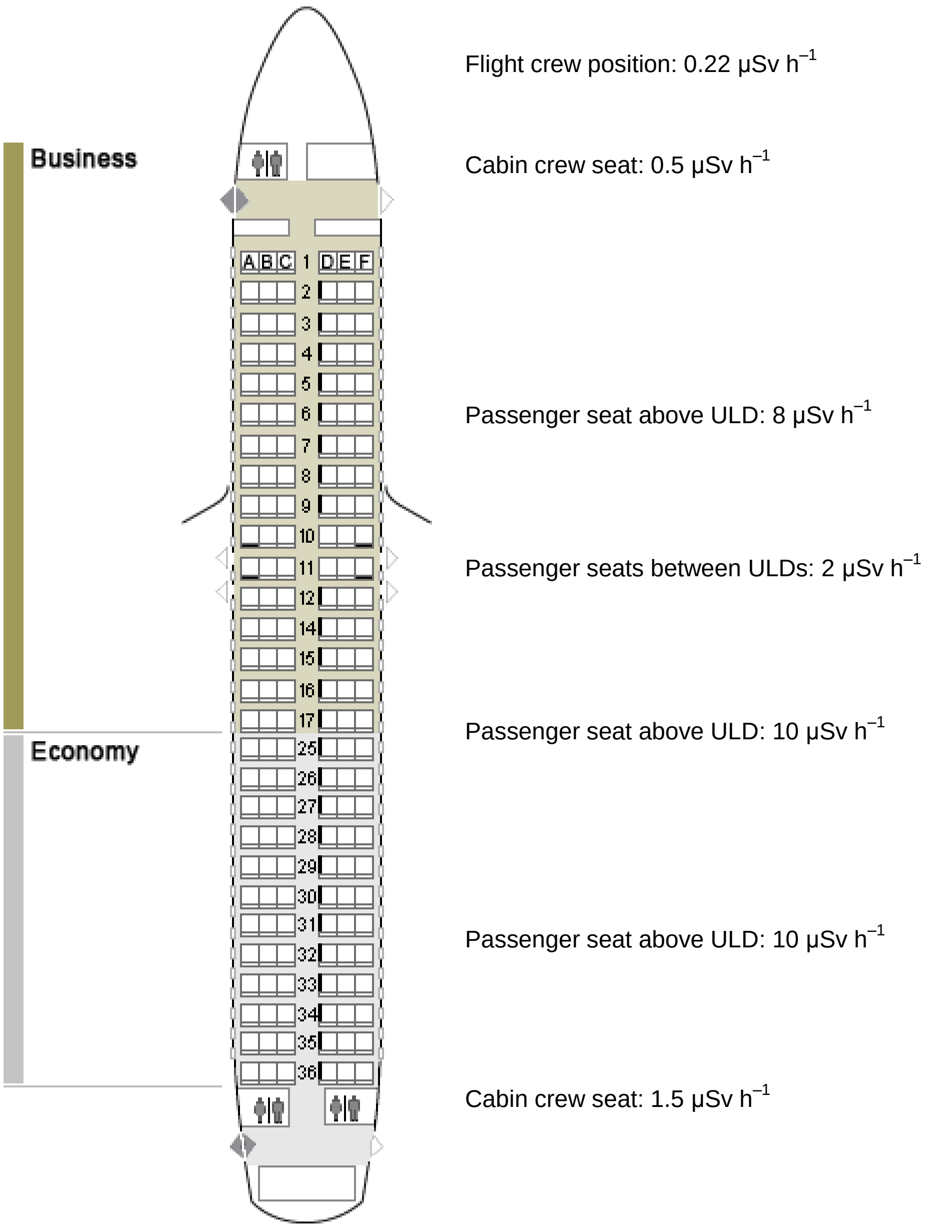

FIGURE 8 Dose rates measured on board an Airbus 320 passenger aircraft

TABLE 12 Maximum number of flights in a year per crew member (one way)

Route	Flight crew	Cabin crew
Short haul passenger	64	100
Long haul passenger	54	60
Short haul cargo	96	
Long haul cargo	18	

The collective doses for each operator were calculated by multiplying the number of cabin and flight crew for each operator by the average dose per flight and the RTF for the relevant type of aircraft. This was a different approach from the method used in the previous study (Warner Jones et al, 2003), in which collective doses were the product of the maximum annual individual dose and the number of flight and cabin crew members, based on the maximum annual number of flights as given in Table 12. Such an approach led to an overestimate of the collective dose because it did not take into account the actual number of flights carrying radioactive material.

Doses to flight and cabin crews are summarised in Tables 13 and 14. The average annual individual doses and the maximum doses for a single flight are the highest values over all the operators considered in the study; a distinction was made between flights from the UK and those into the UK or in transit through the UK.

TABLE 13 Summary of individual and collective doses to flight crew

Route	Average annual individual dose (μSv y^{-1})	Maximum individual dose for a single flight (μSv)	Collective dose (man Sv)
Flights from the UK			
Short haul passenger	0.9	0.4	0.0004
Long haul passenger	9.6	1.3	0.0018
Short haul cargo	25.0	1.4	0.0044
Long haul cargo	2.8	0.9	0.0008
Flights into the UK			
Short haul passenger	0.23	0.08	0.00006
Long haul passenger	1.70	0.17	0.00002
Short haul cargo	0.12	0.04	0.00002
Long haul cargo	0.04	0.07	0.000003
Flights in transit through the UK			
Short haul cargo	1.3	0.1	0.00008

TABLE 14 Summary of individual and collective doses to cabin crew

Route	Average annual individual dose (μSv y^{-1})	Maximum individual dose for a single flight (μSv)	Collective dose (man Sv)
Flights from the UK			
Short haul passenger	9.8	3.0	0.0055
Long haul passenger	73.0	9.0	0.051
Flights into the UK			
Short haul passenger	1.0	0.5	0.0008
Long haul passenger	6.1	1.1	0.0003

Doses for flights made from the UK were significantly higher than doses for flights into the UK or in transit through the UK because more packages containing radioactive material were transported from the UK rather than into the UK. The highest average annual individual dose received by members of the flight crew was calculated to be 25 μSv y^{-1} for a short haul cargo aircraft, while the maximum dose for a single flight was calculated to be 1.4 μSv for a short haul cargo aircraft. For the cabin crew the highest average annual individual dose was calculated to be 73 μSv y^{-1} for short haul passenger aircraft, while the maximum annual dose was calculated to be 9 μSv for long haul passenger flight.

The collective doses presented in Tables 13 and 14 are the sum over all relevant operators for a particular route (short or long haul) or type of aircraft (passenger or cargo aircraft) of the collective doses calculated for each operator. The total collective dose to flight crews was calculated to be 7.5 10^{-3} man Sv; the highest collective dose was calculated to be 4.4 10^{-3} man Sv for short haul cargo aircraft. The total collective dose to cabin crews was calculated to be 5.8 10^{-2} man Sv; the highest collective dose was calculated to be 5.1 10^{-2} man Sv for long haul passenger flights.

5.2.3 Doses to passengers

Average annual individual doses to passengers were calculated for each operator transporting radioactive material using a method similar to the one used to estimate doses to the cabin crew. Individuals considered in the assessment were passengers assumed to fly frequently. Doses for flights from the UK were calculated for both direct flights to the aircraft's final destination and flights to the operator's airport hub; for the latter types of flight doses from the airport hub onwards were also calculated. Flights from hubs to their final destinations were assumed to be short haul, if the distance between the hub and final destination was less than about 3,000 km.

Individual doses were based on dose rates measured at different positions in the aircraft and number of flights and flight times specific to the operator, given in Appendix B, Tables B9 to B14. Default maximum numbers of flights are given in Table 15. These values were considered as an upper limit for the maximum number of flights flown by passengers if they were lower than the maximum number of flights specific to an operator. They are based on the maximum annual travel period of 500 h y^{-1}, given in advisory material produced by the IAEA for the safe transport of radioactive materials (IAEA, 2008), assuming that aircraft carry radioactive material only in one direction and that flight times for short and long haul flights were 2.5 hours and 10 hours, respectively. For flights to an airport hub it was assumed that an individual would fly fewer flights if the onward flight from the airport hub was included. This number was assumed to be the same as for long haul flights.

Maximum doses for a single flight were calculated using the highest dose rate measured on board an Airbus 320 and operator-specific flight times. Collective doses were calculated by multiplying the annual average individual doses by the number of passengers carried by each operator in 2011 (see Section 4.4).

Doses to passengers are summarised in Table 16. The average annual individual doses and the maximum individual dose for a single flight given in the table are the highest values over all the operators considered in the study; detailed results for each operator are presented in Appendix B, Tables B9 to B14. Doses are given for flights from the UK, into the UK and in transit through the UK; for flights from the UK doses include the flights from the operator airport hub outside the UK to the final destination.

TABLE 15 Total annual flight times and average exposure hours per passenger

Type of flight	Number of flights per year
Short haul (direct flight)	100
Short haul (to hub for onward journey)	25
Long haul (direct flight)	25
Long haul (to hub for onward journey)	25

TABLE 16 Summary of individual and collective doses to passengers

Route	Average annual individual dose (μSv y^{-1})	Maximum individual dose for a single flight (μSv)	Collective dose (man Sv)
Flights from the UK			
Short haul	24	20	1.6
Long haul	73	60	2.7
Flights into the UK			
Short haul	3.8	3.6	0.078
Long haul	6.8	7.6	0.061
Flights within the UK			
Short haul	0.83	Not calculated	0.0004

The average annual individual doses to passengers on short and long haul flights were calculated to be 24 μSv and 73 μSv, respectively. The annual average doses for flights onward from the airport hub were lower than those for direct flights to the airport hub or final destination because of the lower frequency of flights from the airport hub. The maximum doses to a passenger on single short and long haul flights outbound from the UK were 20 μSv and 60 μSv, respectively. These doses were higher than those received by passengers on flights into the UK or in transit because more packages transporting radioactive material were transported from the UK.

The collective doses presented in Table 16 are the sum over all operators transporting radioactive material of the collective dose calculated for a particular operator. The total collective dose to flight crews was calculated to be 4.4 man Sv. The highest collective dose was calculated for long haul flights from the UK (2.7 man Sv), while the total collective dose for short haul flights was 1.6 man Sv.

6 SEGREGATION DISTANCES

Packages containing radioactive material transported by air must be separated from passengers, crew and photographic film. For this purpose tables containing distances which must be maintained between packages and passengers and flight and cabin crew members on board both cargo and passenger aircraft were developed. They are published in the International Civil Aviation Organization's (ICAO) Technical Instructions for the Safe Transport of Dangerous Goods by Air (ICAO, 2013). These distances, commonly referred to as segregation distances, are designed to ensure that the exposure to the crew members and passengers are controlled and make use of the TI of the load. The ICAO segregation distances are based on dose limits to workers and members of the public of 5 mSv y^{-1} and 1 mSv y^{-1}, respectively. During the site visits carried out for this survey it was found that operators estimated their own segregation distance, based on the ICAO tables, and had a set of tables for each type of aircraft they used.

In this study segregation distances were estimated based on the doses to frequent fliers on both short and long haul flights calculated using dose rates measured on various aircraft and the methodology described in detail in IAEA advisory material (IAEA, 2008). Segregation distances calculated were compared with those given in the ICAO segregation tables (ICAO).

6.1 Calculation of vertical segregation distance for passenger aircraft

The actual minimum distance (AMD) required between a source within a package or group of packages and the seat of a passenger or a flight crew on a typical aircraft is given by (IAEA, 2008):

$$\mathrm{AMD} = \mathrm{S} + \mathrm{h} + \mathrm{r} \qquad (1)$$

where S is the segregation distance between the top of the package and the top of the cabin floor (m), r is the radius of packages (m) and h is the height of seat taken to be 0.4 m. This equation assumes that all the packages are of the same size.

The segregation distance S is calculated using the equation:

$$\mathrm{S} = \left(\frac{\mathrm{TI} \times \mathrm{TF}}{100 \times \mathrm{RDR}}\right)^{\frac{1}{2}} (1 + \mathrm{r}) - (\mathrm{r} + \mathrm{h}) \qquad (2)$$

where TI is the transport index of the package, TF Is the transmission factor of gamma energy through the floor of the aircraft and RDR (mSv h^{-1}) is the reference dose rate. RDR is given by:

$$\mathrm{RDR} = \frac{\mathrm{DV}}{\mathrm{MAET}} = \frac{\mathrm{DV}}{\mathrm{MATP} \times \mathrm{RTF}} \qquad (3)$$

where DV is the annual dose limit for members of the public (1 mSv y^{-1}) or crew (5 mSv y^{-1}), MAET is the maximum annual exposure time (h y^{-1}), MATP is the maximum annual travel period (h y^{-1}) and RTF is the radioactive traffic factor. Default values for MATP for members of the public and the RTF given in the IAEA advisory material (IAEA, 2008) are 500 h y^{-1} and 0.1, respectively. Transmission factors are related to both the TI of the package or group of packages transported and their radius. The IAEA advisory material provides combinations of values for these three factors that are considered conservative but realistic; the values are reproduced in Table 17.

TABLE 17 Transmission factors and dimension of the package for different ranges of TI suggested by the IAEA advisory material (IAEA, 2008)

Transport index (TI)	Transmission factor (TF)	Package radius (r) (m)
0.0–1.0	1.0	0.05
1.1–2.0	0.8	0.1
2.1–50	0.7	0.4

6.2 Calculation of horizontal segregation distance for cargo aircraft

The approach used to calculate horizontal segregation distances for cargo aircraft is similar to that adopted to calculate vertical segregation distances for passenger aircraft. In this case the segregation distance, S, is the distance from the front of the package to the bulkhead separating the cargo hold from the flight deck, while h is the distance from the bulkhead to the flight deck seat for which the IAEA advisory material suggests a value of 0.4 m (IAEA, 2008). The same guide recommends a default value for the transmission factor of 0.8 for all TIs.

6.3 Comparison of segregation distances

The segregation distances used by different operators carrying consignments of radioactive material on passenger aircraft for both short and long haul flights and cargo aircraft were compared with the ICAO values and the segregation distances calculated using the method described in the IAEA advisory material (IAEA, 2008).

In the calculation of the segregation distances using the IAEA methodology, default values given in the IAEA advisory material were used for the seat height, transmission factor and the package radius. Values of the maximum annual travel period (MATP) adopted in the calculations were 250 hours for passenger aircraft and 240 hours for cargo planes. The MATP for passengers is the value in the IAEA advisory material divided by two and it is consistent with the general assumption made in this survey to assume that radioactive material is only transported in one direction. RTFs for different types of aircraft and flights were those derived in this survey. Table 18 provides a summary of the values used in the calculation of the segregation distances for a number of TIs on both passenger and cargo aircraft. The table also gives the maximum exposure time calculated using the RTF values derived in this study and the relevant radiation dose rates calculated using equation 3.

Segregation distances for different aircraft and TIs calculated using the IAEA methodology are given in Table 19 together with those from the ICAO tables (ICAO, 2013) and those used by some of the operators collated during the visits to cargo handling companies. Although the handling company for a cargo operator did not provide the actual segregation values that they used, they confirmed that the segregation distances are selected according to the ICAO tables and that radioactive packages are generally located to the rear of the aircraft, as far from the flight deck as possible. The cargo handling company for the operator of long haul passenger flights confirmed that the packages containing radioactive material were always placed at the base of the ULD, which meant that the segregation distance was the same irrespective of the TI.

TABLE 18 Parameters used for the calculation of segregation distance (S) for short and long haul passenger flight and cargo flight

Parameter	Passenger aircraft: Short haul	Passenger aircraft: Long haul	Cargo aircraft	Reference
Seat height (h) (m)*	0.4	0.4	0.4	IAEA (2008)
Package radius (r) (m)	0.4	0.4	0.4	IAEA (2008)
Transport index (TI)	2.9	5.4 (9)	38	This survey
Transmission factor (TF)	0.7	0.7	0.8	IAEA (2008)
Dose limit (mSv y^{-1})	1	1	5	
MATP (h y^{-1})	250	250	240	This survey
RTF	0.03	0.10	0.18	This survey
MAET (h y^{-1})	8.3	25	43	
RDR (mSv h^{-1})	0.12	0.04	0.12	

* Seat height is used for passenger aircraft. For cargo aircraft this is the distance between the bulkhead and the flight seat.

TABLE 19 Comparison of segregation distances for different TIs on passenger and cargo aircraft

Route	Segregation distance (m): ICAO tables	Segregation distance (m): IAEA methodology	Segregation distance (m): Used by operator	TI: Actual	TI: Based on segregation distance (S) used by operator
Short haul passenger	0.7*	0.00†	0.73	2.9	23
Long haul passenger	1.15‡	0.56	1.93	5.4	22
Long haul passenger	1.55	0.96	1.93	9§	22
Short haul cargo	3.75	1.47	NA¶	38	153#

* Based on a TI of 3.
† Actual value was negative.
‡ Based on a TI of 6.
§ Maximum TI allowed on aircraft in one ULD (based on limit for a long haul operator).
¶: It can be assumed that the segregation distance used is at least the same as the value given in the ICAO tables.
Calculated assuming that the segregation distance used is the same as the value given in the ICAO tables.

The segregation distances calculated using the IAEA methodology are significantly lower than those given in the ICAO tables for all types of aircraft. This is because the segregation distances calculated using the IAEA methodology are based on maximum annual travel periods which are broadly half of those given in the IAEA advisory material (IAEA, 2008) and on RTFs derived in this survey which are generally lower than the value of 0.1 assumed in the calculation of the segregation distances for the ICAO tables. The segregation distances used by the operators were generally greater than those recommended by the ICAO tables and those calculated using the IAEA methodology, even with the highest TI allowed by the operators, and could be relaxed. Table 19 also gives the TI for packages placed at the actual segregation distances used by the cargo handlers of operators for passenger flights visited during this survey that would meet the dose criterion for members of the public used to determine the segregation distances in the IAEA advisory material. The TIs thus calculated are much greater than the actual TIs normally transported on these flights.

It should also be noted that dose rates measured at seat level on short haul passenger aircraft directly above the location of the package containing radioactive material and on the flight deck of cargo aircraft (see Section 5.2) were significantly lower than the reference dose rates (RDR) assumed in the calculation of segregation distances given in Table 18.

7 COMPARISON WITH PREVIOUS STUDIES

The previous two surveys on the radiological impact of normal transport of radioactive material by air were published in 1990 (Gelder, 1990) and 2003 (Warner Jones et al, 2003). Most of the information used for the 2003 survey was obtained from questionnaires sent to the operators. For the current survey most of the information was obtained from a manufacturer of radioactive medical sources in the UK and a distributor of industrial radioactive sources and therefore the data for the current survey was more detailed and more comprehensive than in the previous study. However, both studies included information about the shipments carried by major cargo and passenger operators and therefore it should be possible to show a trend.

Table 3 shows that in 2011 about 46,500 packages containing radioactive material for medical use, were sent from the UK on about 4,400 flights, compared to about 62,000 packages on 3,700 flights in 2002 (Warner Jones et al, 2003). The numbers of cargo flights and short haul passenger flights transporting radioactive material were similar, but the number of long haul passenger flights transporting radioactive material has increased from about 1,300 to about 1,800. Data collected for the 2003 survey did not indicate the number of flights onward from the operator’s hub. For the current survey it was estimated that about 1,600 flights transport radioactive material from the operator’s hub to another destination.

The total annual TI has increased from 22,000 to over 48,500. This increase is mostly due to the increased TI for cargo aircraft, which has more than doubled. In this study specific RTFs were calculated for the operators who carried radioactive material and these values were used to derive RTFs for different types of aircraft. The RTF for cargo aircraft (0.18) agreed well with the value estimated in the previous study (Warner Jones et al, 2003); however, the RTFs estimated for short (0.03) and long haul passenger flights (0.1) were significantly higher than those estimated in the previous survey (0.002 and 0.017 for short and long haul passenger flights, respectively). The reason why the RTFs are different to those in the previous survey is because a different approach has been used to calculate them. In this study the RTFs were based on outward flights only for the major operators who transport radioactive packages. The RTFs calculated for the previous study were combined values which included all airlines for outward, inward and transit flights and flights within the UK (Warner Jones et al, 2003).

The maximum dose rates measured on passenger seats on an aircraft similar to that in the last study were comparable at 10 μSv h^{-1}. The dose rate measured on the flight deck on passenger aircraft was about half that measured in the last survey; however, the dose rates measured on the flight deck of cargo aircraft for this study were about four times higher.

Individual and collective doses calculated for warehouse workers were very similar to the doses calculated in the previous study (Warner Jones et al, 2003), with the exception of the doses for workers of the major cargo operator, for which thermoluminescent dosemeter (TLD) measurements showed doses up to 7 mSv y^{-1}. The increase in doses for these workers is related to the increase in the number of packages being transported and their TIs.

Sufficient information was collected in this survey to be able to calculate a dose to both flight and cabin crews and passengers for each separate operator, while in the previous study only doses for all operators were calculated. The individual doses to flight and cabin crews were generally similar to those estimated in the previous study. The highest annual average dose to the flight crew calculated in the current study was 25 µSv y^{-1} for short haul cargo flights, which is similar to the average annual dose calculated in the previous study for long haul cargo flights (36 µSv y^{-1}). The highest annual average dose to the cabin crew calculated in the current study was 73 µSv y^{-1} for long haul passenger flights, which is similar to the average annual dose calculated in the previous study for long haul passenger flights (64 µSv y^{-1}).

Average individual doses to passengers were not calculated in the 2003 study. The highest annual average dose to passengers calculated in the current study was 73 µSv y^{-1} for short haul flights. The maximum dose for a single flight was estimated to be 60 µSv; the previous study estimated that doses received by passengers during a flight could be up to around 20 µSv. In the 1990 survey it was estimated that the dose received by one group in particular – couriers – was 0.42 mSv y^{-1}, for an annual flying time of 1,200 hours.

The collective doses for flight and cabin crew in this study were generally lower than the collective dose calculated in the 2003 study by at least an order of magnitude. This is because in the previous study the doses were calculated making the cautious assumption that the flight crews flew the default maximum number of flights. For the current survey the calculation of collective doses took account of the actual flight times and number of flights of each operator and of more accurate RTF values. The collective doses for passengers calculated in this survey are comparable to those estimated in the last study for long haul flights but are four times higher for short haul flights. A significant contribution to this increase came from the inclusion of onward flights from the airport hub to other destinations.

8 CONCLUSIONS

This survey was based on data and information provided by a major UK company which manufactures radioactive medical sources and another UK company that exports industrial sources. Responses to two questionnaires sent to operators were poor and little information was collected from this source. Visits were made to three cargo handling companies that distribute a large number of these sources inside and outside Europe, using operators which fly both passenger and cargo aircraft. Measurements were made on both a cargo and short haul passenger aircraft.

The survey found that there were approximately 4,400 flights from the UK in 2011 which transported radioactive materials, with a total of over 46,500 packages with a total TI of about 48,500. In addition, around 650 flights were flown into the UK carrying packages containing radioactive material with a total TI of about 2,400.

The highest doses to warehouse workers were for a cargo handling company for cargo aircraft, mainly because of the high number and TI of the packages transported and the high frequency of the flights. The maximum annual dose estimated to an individual involved in moving and loading packages was around 4.7 mSv and the maximum personal dosemeter reading for an individual working for a major freight company in 2011 was 7 mSv. The total collective dose to warehouse workers for the three main carriers was estimated to be about 0.1 man Sv.

The highest average annual doses to flight and cabin crew were estimated to be 25 µSv y^{-1} and 73 µSv y^{-1}, respectively, while the highest maximum doses to flight and cabin crew for a single flight were estimated to be 1.4 µSv and 9 µSv, respectively. The highest average annual dose to passengers was estimated to be 73 µSv y^{-1} on long haul flights. The highest maximum dose to passengers for a single flight was estimated to be 60 µSv.

The total collective doses received by the flight and cabin crew were 0.0075 man Sv and 0.058 man Sv, respectively. The collective dose to the passengers from all types of flights was estimated to be about 4.4 man Sv. The increase in collective dose for short haul flights from the last study is due to inclusion of doses from onward flights from the airport hub.

The methodology of the calculation of segregation distances in the IAEA advisory material TS-G-1.1 (IAEA, 2008) was reviewed. Segregation distances calculated using the methodology and radioactive traffic factor determined in the survey were compared with the segregation distances used by some operators, which are based on tables of segregation distances produced by the ICAO (2013). Segregation distances used by the operators were generally more cautious than those estimated using the IAEA methodology.

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APPENDIX A Methodology for the Assessment of Doses

A1 Doses to warehouse workers

The annual individual dose to the warehouse workers, D_W (μSv), is calculated as follows:

$$D_W = N_d D_d$$

where N_d is the number of deliveries of radioactive consignments to which an individual is exposed and D_d is the dose per delivery (μSv).

For passenger aircraft the number of deliveries was the number of flights which carry radioactive packages divided by the number of shifts (two). For cargo aircraft the number of deliveries was assumed to be three per week or 150 per year and it was assumed that there were three shifts so that an individual is exposed for 50 deliveries.

The dose per delivery, D_d, is based on the dose measured for a given TI during the visits made and the average TI per delivery over the year:

$$D_d = D_m \frac{TI_{ave}}{TI_m}$$

where D_m is the dose per delivery determined during the visit (μSv), TI_{ave} is the average TI per delivery and TI_m is the TI for the delivery when measurements took place.

For passenger aircraft TI_{ave} is the total TI over a year divided by the number of flights. This assumes that each delivery goes on to each flight. For cargo aircraft the value of TI_{ave} is the total TI divided by the number of deliveries in a year.

The collective dose to the warehouse workers for a particular company, S_W, is:

$$S_W = \sum_{1}^{N_T} D_W(i)\ NW(i)$$

where $D_W(i)$ is the annual individual dose to carry out task i (Sv y^{-1}), NW(i) is the number of workers working on task i and N_T is the number of tasks carried out. NW(i) takes also account of the number of shifts.

A2 Doses to flight crew

The individual dose to a member of the flight crew over a single flight, D_{SF}, is given by:

$$D_{SF} = D_{mf}\ FT_a \frac{TI_{ave}}{TI_m}$$

where D_{mf} is the dose rate measured for short haul passenger and cargo flights at the position of the flight crew (μSv h^{-1}) (see Section 5.2), FT_a is the duration of the flight (h), TI_{ave} is the average annual TI for the operator and TI_m is the TI on aircraft when dose rates were measured.

The average annual individual dose to the flight crew on passenger and cargo aircraft, D_{F}, is calculated as follows:

$$D_F = D_{SF} N_F RTF$$

where D_{SF} is the dose received by a member of the flight crew on a single flight (μSv), N_F is the maximum number of flights for a member of the flight crew for each operator (see Section 5.2) and RTF is the radioactive traffic factor (see Section 4.4).

The collective dose to the flight crew, S_F, is the sum over all the operators who transport radioactive material of the collective dose to the flight crew calculated for a single operator:

$$S_F = \sum_{1}^{N_A} D_{SF}(i)\ NF(i)\ RTF$$

where $D_{SF}(i)$ is the dose to a member of the flight crew of the operator i for a single flight (Sv y^{-1}), NF(i) is the number of flight crew for operator i and N_A is the number of operators. The number of flight crew for each operator, $N_F(i)$, is the product of the number of flights of that operator in a year and the number of flight crew members on the flight deck for each aircraft.

A3 Doses to cabin crew

The dose from a single flight, D_{SC}, is given by:

$$D_{SC} = D_{mc}\ FT_a \frac{TI_{ave}}{TI_m}$$

where D_{mc} is the average dose rate measured for short haul passenger aircraft at the positions of the cabin crew (μSv h^{-1}), FT_a is the duration of the flight (h), TI_{ave} is the average annual TI for the operator and TI_m is the TI on aircraft when the measurements took place. For long haul passenger flights the dose rates were divided by four to allow for additional shielding and longer distances between packages and the cabin crew.

The average annual individual dose to the cabin crew for each operator on passenger flights, D_C, was calculated as follows:

$$D_C = D_{SC}\ N_C\ RTF$$

where D_{SC} is the dose received by a member of the cabin crew on a single flight (μSv), N_C is the maximum number of flights for a member of the cabin crew for each operator (see Section 5.2) and RTF is the radioactive traffic factor (see Section 4.4).

The collective dose to the cabin crew, S_C, is the sum over all the operators who transport radioactive material on passenger flights of the collective dose to the cabin crew calculated for a single operator:

$$S_C = \sum_{1}^{N_A} D_{SC}(i)\ NC(i)\ RTF$$

where $D_{SC}(i)$ is the dose to a member of the cabin crew of the operator i for a single flight (Sv y^{-1}), NC(i) is the number of cabin crew for operator i and N_A is the number of operators. The number of cabin crew for each operator, $N_F(i)$, is the product of the number of flights of that operator in a year and the number of cabin crew members on the flight deck for each aircraft.

A4 Doses to passengers

The dose from a single flight, D_{SP}, is given by:

$$D_{SP} = D_{mp}\, FT_a \frac{TI_{ave}}{TI_m}$$

where D_{mp} is the dose rate measured on short haul passenger flights (µSv h^{-1}) (see Section 5.2). Onward flights from the hub were assumed to be long haul except for operator S18, for which it was assumed that the onward flights were short haul. FT_a is the duration of the flight (h), TI_{ave}, is the average annual TI and TI_m is the TI on aircraft when measurements of dose rates were taken.

The average annual individual dose to the passengers for each operator on passenger flights was calculated separately for passengers flying directly to their destination and those flying to a European airport hub and from there to their final destination.

The annual dose to a passenger for a direct flight without changing at a hub, D_p, is given by:

$$D_P = D_{SP}\, N_P\, RTF$$

The annual dose to a passenger for a flight to a hub and a flight to a final destination, D_{ph}, is given by:

$$D_{Ph} = \left(D_{SP1}\, NP + D_{SP2}\, NP\right) RTF$$

where D_{SP} is the dose received by a passenger on a single direct flight (µSv); D_{SP1} and D_{SP2} are the doses received by a passenger on a single flight to the hub and from the hub onwards respectively (µSv), NP is the maximum number of flights for passengers, assumed to 25 hours for both flights to and onward from the hub (see Section 5.2) and RTF is the radioactive traffic factor (see Section 4.4). The RTF for the onward flights was assumed to be the same as for the first flight.

The collective dose to the passengers, S_P, is the sum over all the operators who transport radioactive material on passenger flights of the collective dose to the passengers for a direct flight calculated for a single operator:

$$S_P = \sum_{1}^{N_A} D_{SP}(i)\, NP(i)\, RTF$$

where $D_{SP}(i)$ is the dose to a passenger of the operator i for a single flight (Sv y^{-1}), NP(i) is the number of passengers for operator i and N_A is the number of operators. The number of passengers for each operator, $N_F(i)$, is the product of the number of flights of that operator in a year and the number of passengers on each aircraft. For some operators the number of passengers for 2011 was obtained from the CAA (see Table 7).

The collective dose to the passengers, S_{P2}, for flights from the hub is the sum over all the operators who transport radioactive material on passenger flights of the collective dose to the passengers calculated for a single operator:

$$S_{P2} = \sum_{1}^{N_A} D_{SP2}(i)\, NP(i)\, RTF$$

where $D_{SP}(i)$ is the dose to a member of the flight crew of operator i for a single flight (Sv y^{-1}).

APPENDIX B Individual and Collective Doses Calculated in the Survey

B1 Individual doses per delivery to warehouse workers

TABLE B1 Doses per delivery to warehouse workers for short haul cargo flight

Groups exposed and scenario	Exposure time (h)	Dose rate (μSv h^{-1})	Dose (μSv)	Measured dose (μSv)
Workers moving packages from lorry to warehouse and to sorting area				
In proximity of lorry	0.05	50	2.5	
In proximity of load	0.03	200	6.7	
Driving fork lift	0.25	10	2.5	
Total			12	15
Exposure to staff on gangways	0.33	15	5	
Workers sorting packages into different destination groups and moving groups into radioactive store				
Handling packages	0.03	750	25	
In proximity of package groups	0.33	100	33	
Covering pallets with shrink wrap	0.17	25	4.2	
Total			63	
Workers moving packages from radioactive store to ULDs				
Transporting packages to ULD	0.25	90	23	
Closing ULD	0.05	500	25	
Individual working on PC	0.25	20	5	
Total			53	
Driver transporting ULDs from warehouse to aircraft				
Transporting ULDs	0.03	90	3	
Individual working on PC	0.17	9	1.5	
Total			4.5	
Driver transporting ULDs from warehouse to aircraft				
Transporting ULDs	0.03	30	1	
Loading and unloading ULDs on the aircraft	0.42	40	17	
Total				
Workers moving ULDs (four) to the hold of the aircraft	0.33	150	50	

TABLE B2 Doses per delivery to warehouse workers for short haul passenger flight

Groups exposed band scenario	Exposure time (h)	Dose rate (μSv h^{-1})	Dose (μSv)	Measured dose (μSv)
Workers moving packages from van to warehouse (one load)				
In proximity of lorry	0.017	20	0.33	
Driving fork lift	0.017	55	0.92	
Total			1.3	
Workers sorting packages from pallet into three loads				
At1 m from packages	0.17	50	8.3	
At surface of packages	0.017	140	2.3	
Total			11	10*
Worker carrying out dangerous goods checks				
Worker sorting loads at 1 m	0.5	20	10	
At surface of packages	0.05	200	10	
Total			20	14†
Worker building ULDs	0.5	36	18	9
Exposure to drivers of the flatbed lorry while the three ULDs are loaded	1	2	2	3
Worker transferring the packages from the lorry to the aircraft	0.083	20	1.7	

* Based on measured doses from the Appleford AI-1 personal integrating dosemeter (PID).
† Based on measured doses from the Siemens EPD Mark 2 electronic personal dosemeter (EPD).

TABLE B3 Doses per delivery to warehouse workers for long haul passenger flight

Groups exposed and scenario	Exposure time (h)	Dose rate (μSv h^{-1})	Dose (μSv)
Worker moving packages from van to warehouse			
In proximity of lorry	0.083	6	0.5
Driving fork lift	0.083	7	0.58
Total			1.1
Worker sorting packages from pallet into three loads			
At 1 m	0.17	30	5
Close to surface of packages	0.017	200	3.3
Total			8.3
Worker carrying out dangerous goods checks			
At 1 m	0.25	30	7.5
Close to surface of packages	0.05	200	10
Total			18
Worker building ULDs	0.17	30	5

B2 Summary of individual and collective doses from a selection of operators

TABLE B4 Doses to flight and cabin crew from the transport of radioactive packages on short haul passenger flights from the UK

					Doses to flight crew			Doses to cabin crew		
					Individual dose			Individual dose		
Operator	Average annual TI	Average flight time (h)	Total number of flights	Number of flights transporting RAM	Single flight (µSv)	Average annual (µSv y^{-1})	Collective dose (man Sv)	Single flight (µSv)	Average annual (µSv y^{-1})	Collective dose (man Sv)
S1	1.9	2.3	550	18	1.2 10^{-1}	2.4 10^{-1}	4.2 10^{-6}	7.9 10^{-1}	2.6 10^{0}	5.7 10^{-5}
S2	4.3	2.8	91	3	3.2 10^{-1}	6.6 10^{-1}	1.9 10^{-6}	2.1 10^{0}	6.4 10^{0}	2.6 10^{-5}
S3	2.8	2.0	1,500	50	1.5 10^{-1}	3.1 10^{-1}	1.5 10^{-5}	1.0 10^{0}	3.3 10^{0}	2.0 10^{-4}
S4	1.2	2.5	4,900	160	7.7 10^{-2}	1.6 10^{-1}	2.5 10^{-5}	5.2 10^{-1}	1.7 10^{0}	3.3 10^{-4}
S5	2.8	2.5	270	9	1.9 10^{-1}	3.9 10^{-1}	3.3 10^{-6}	1.3 10^{0}	4.1 10^{0}	4.5 10^{-5}
S6	6.0	2.0	3,300	108	3.2 10^{-1}	6.6 10^{-1}	6.7 10^{-5}	2.1 10^{0}	7.0 10^{0}	9.2 10^{-4}
S7	0.3	2.6	490	16	2.0 10^{-2}	4.1 10^{-2}	6.2 10^{-7}	1.3 10^{-1}	4.3 10^{-1}	8.4 10^{-6}
S8	2.1	1.5	3,300	108	8.3 10^{-2}	1.7 10^{-1}	1.8 10^{-5}	5.6 10^{-1}	1.8 10^{0}	2.4 10^{-4}
S9	1.8	2.6	340	11	1.3 10^{-1}	2.6 10^{-1}	2.7 10^{-6}	8.4 10^{-1}	2.8 10^{0}	3.7 10^{-5}
S10	1.5	2.6	150	5	1.0 10^{-1}	2.1 10^{-1}	1.0 10^{-6}	7.0 10^{-1}	2.3 10^{0}	1.4 10^{-5}
S11	4.3	2.5	120	4	2.8 10^{-1}	5.8 10^{-1}	2.2 10^{-6}	1.9 10^{0}	6.2 10^{0}	3.0 10^{-5}
S12	2.9	2.5	300	10	1.9 10^{-1}	3.9 10^{-1}	3.7 10^{-6}	1.3 10^{0}	4.1 10^{0}	5.1 10^{-5}
S13	2.7	2.7	4,000	131	2.0 10^{-1}	4.1 10^{-1}	5.1 10^{-5}	1.3 10^{0}	4.3 10^{0}	6.9 10^{-4}
S14	3.9	1.6	550	18	1.7 10^{-1}	3.4 10^{-1}	5.9 10^{-6}	1.1 10^{0}	3.7 10^{0}	8.0 10^{-5}
S15	1.5	2.5	60	2	9.9 10^{-2}	2.0 10^{-1}	3.9 10^{-7}	6.7 10^{-1}	1.3 10^{0}	5.4 10^{-6}
S16	4.0	2.5	30	1	2.7 10^{-1}	2.6 10^{-1}	5.3 10^{-7}	1.8 10^{0}	1.8 10^{0}	7.1 10^{-6}
S17	3.8	2.5	30	1	2.5 10^{-1}	2.5 10^{-1}	5.2 10^{-7}	1.7 10^{0}	1.7 10^{0}	6.8 10^{-6}
S18	4.6	2.0	9,000	300	2.4 10^{-1}	5.0 10^{-1}	1.4 10^{-4}	1.6 10^{0}	5.4 10^{0}	2.0 10^{-3}
S19	7.4	2.3	1,400	46	4.4 10^{-1}	9.2 10^{-1}	4.0 10^{-5}	3.0 10^{0}	9.8 10^{0}	5.5 10^{-4}
S20	3.1	2.5	30	1	2.1 10^{-1}	2.0 10^{-1}	4.1 10^{-7}	1.4 10^{0}	1.4 10^{0}	5.5 10^{-6}
S21	3.1	3.3	1000	33	2.7 10^{-1}	5.5 10^{-1}	1.7 10^{-5}	1.8 10^{0}	5.9 10^{0}	2.4 10^{-4}

TABLE B5 Doses to flight and cabin crew from the transport of radioactive packages on long haul passenger flights from the UK

Operator	Average annual TI	Average flight time (h)	Total number of flights	Number of flights transporting RAM	Doses to flight crew: Individual dose, Single flight (μSv)	Doses to flight crew: Individual dose, Average annual (μSv y^{-1})	Doses to flight crew: Collective dose (man Sv)	Doses to cabin crew: Individual dose, Single flight (μSv)	Doses to cabin crew: Individual dose, Average annual (μSv y^{-1})	Doses to cabin crew: Collective dose (man Sv)
L1	9.6	7.0	1,000	110	$4.4\ 10^{-1}$	$2.4\ 10^{0}$	$1.9\ 10^{-4}$	$3.0\ 10^{0}$	$1.8\ 10^{1}$	$5.6\ 10^{-3}$
L2	3.9	12.5	1,500	250	$3.2\ 10^{-1}$	$2.9\ 10^{0}$	$3.2\ 10^{-4}$	$2.2\ 10^{0}$	$2.2\ 10^{1}$	$9.2\ 10^{-3}$
L3	2.1	4.0	940	94	$5.6\ 10^{-2}$	$3.0\ 10^{-1}$	$2.1\ 10^{-5}$	$3.8\ 10^{-1}$	$2.3\ 10^{0}$	$6.1\ 10^{-4}$
L4	2.2	7.0	5,400	220	$1.0\ 10^{-1}$	$2.2\ 10^{-1}$	$8.9\ 10^{-5}$	$6.9\ 10^{-1}$	$1.7\ 10^{0}$	$2.6\ 10^{-3}$
L5	3.2	6.7	500	50	$1.4\ 10^{-1}$	$7.6\ 10^{-1}$	$2.8\ 10^{-5}$	$9.6\ 10^{-1}$	$5.7\ 10^{0}$	$8.1\ 10^{-4}$
L6	0.0	12.3	30	3	$2.7\ 10^{-3}$	$8.1\ 10^{-3}$	$3.2\ 10^{-8}$	$1.8\ 10^{-2}$	$5.5\ 10^{-2}$	$9.3\ 10^{-7}$
L7	0.6	11.4	460	46	$4.8\ 10^{-2}$	$2.6\ 10^{-1}$	$8.9\ 10^{-6}$	$3.3\ 10^{-1}$	$2.0\ 10^{0}$	$2.6\ 10^{-4}$
L8	15.0	13.5	730	98	$1.3\ 10^{0}$	$9.6\ 10^{0}$	$5.2\ 10^{-4}$	$9.0\ 10^{0}$	$7.3\ 10^{1}$	$1.5\ 10^{-2}$
L9	0.4	12.0	1,000	108	$3.5\ 10^{-2}$	$1.9\ 10^{-1}$	$1.5\ 10^{-5}$	$2.4\ 10^{-1}$	$1.4\ 10^{0}$	$4.4\ 10^{-4}$
L10	2.8	8.3	1,400	246	$1.5\ 10^{-1}$	$1.5\ 10^{0}$	$1.5\ 10^{-4}$	$1.0\ 10^{0}$	$1.1\ 10^{1}$	$4.4\ 10^{-3}$
L11	5.0	6.7	2,200	200	$2.2\ 10^{-1}$	$1.1\ 10^{0}$	$1.8\ 10^{-4}$	$1.5\ 10^{0}$	$8.2\ 10^{0}$	$5.1\ 10^{-3}$
L12	3.5	11.4	200	20	$2.6\ 10^{-1}$	$1.4\ 10^{0}$	$2.1\ 10^{-5}$	$1.8\ 10^{0}$	$1.1\ 10^{1}$	$6.1\ 10^{-4}$
L13	0.2	4.8	60	6	$4.7\ 10^{-3}$	$2.5\ 10^{-2}$	$1.1\ 10^{-7}$	$3.2\ 10^{-2}$	$1.9\ 10^{-1}$	$3.2\ 10^{-6}$
L14	4.8	6.6	650	258	$2.1\ 10^{-1}$	$4.5\ 10^{0}$	$2.2\ 10^{-4}$	$1.4\ 10^{0}$	$3.4\ 10^{1}$	$6.3\ 10^{-3}$
L15	1.0	11.4	450	45	$7.4\ 10^{-2}$	$4.0\ 10^{-1}$	$1.3\ 10^{-5}$	$5.1\ 10^{-1}$	$3.0\ 10^{0}$	$3.9\ 10^{-4}$
L16	1.1	11.1	20	2	$8.0\ 10^{-2}$	$1.6\ 10^{-1}$	$6.4\ 10^{-7}$	$5.5\ 10^{-1}$	$1.1\ 10^{0}$	$1.9\ 10^{-5}$
L17	0.6	10.3	50	5	$4.0\ 10^{-2}$	$2.0\ 10^{-1}$	$8.1\ 10^{-7}$	$2.8\ 10^{-1}$	$1.4\ 10^{0}$	$2.3\ 10^{-5}$

TABLE B6 Doses to flight crew from the transport of radioactive packages on cargo aircraft from the UK (short and long haul flights)

Operator	Average annual TI	Average flight time (h)	Total number of flights	Number of flights transporting RAM	Individual dose		Collective dose (man Sv)
					Single flight (μSv)	Average annual (μSv y^{-1})	
C1	27	1.5	5,600	1,248	$1.4\ 10^{0}$	$2.5\ 10^{1}$	$4.4\ 10^{-3}$
C2	5	1	410	74	$2.0\ 10^{-1}$	$4.3\ 10^{0}$	$5.5\ 10^{-5}$
C3	10	9.0	1,600	289	$9.0\ 10^{-1}$	$2.8\ 10^{0}$	$7.6\ 10^{-4}$

TABLE B7 Doses to flight and cabin crew from the transport of radioactive packages on flights into the UK

Operator	Average annual TI	Average flight time (h)	Number of flights transporting RAM	Doses to flight crew			Doses to cabin crew		
				Individual dose		Collective dose (man Sv)	Individual dose		Collective dose (man Sv)
				Single flight (μSv)	Average annual (μSv y^{-1})		Single flight (μSv)	Average annual (μSv y^{-1})	
S22	5.9	0.5	360	$7.7\ 10^{-2}$	$2.3\ 10^{-1}$	$5.5\ 10^{-5}$	$5.2\ 10^{-1}$	$1.0\ 10^{0}$	$7.6\ 10^{-4}$
S23	0.8	2.0	5	$4.4\ 10^{-2}$	$1.3\ 10^{-1}$	$4.2\ 10^{-7}$	$2.9\ 10^{-1}$	$5.5\ 10^{-1}$	$5.7\ 10^{-6}$
L1	1.7	7.0	9	$7.8\ 10^{-2}$	$7.9\ 10^{-1}$	$1.5\ 10^{-6}$	$5.3\ 10^{-1}$	$2.9\ 10^{0}$	$2.0\ 10^{-5}$
L5	2.1	12.0	55	$1.7\ 10^{-1}$	$1.7\ 10^{0}$	$1.8\ 10^{-5}$	$1.1\ 10^{0}$	$6.1\ 10^{0}$	$2.5\ 10^{-4}$
C1	0.8	1.5	208	$4.1\ 10^{-2}$	$1.2\ 10^{-1}$	$1.7\ 10^{-5}$			
C3	0.8	9	18	$7.0\ 10^{-2}$	$3.8\ 10^{-2}$	$2.5\ 10^{-6}$			

TABLE B8 Doses to flight crew from the transport of radioactive packages on passenger flights in transit through the UK

Operator	Average annual TI	Average flight time (h)	Number of flights transporting RAM	Individual dose		Collective dose (man Sv)
				Single flight (μSv)	Average annual (μSv y^{-1})	
	1.5	1	493	0.1	1.3	$7.5\ 10^{-5}$

TABLE B9 Doses to passengers on short haul flights from the UK to the airport hub or final destination

Operator	Average annual TI	Average flight time (h)	Number of flights transporting RAM	Individual dose for single flight (μSv)		Average annual individual dose (μSv y^{-1})	Collective dose (man Sv)
				Maximum	Average		
S1	1.9	2.3	18	$5.3\ 10^{0}$	$1.9\ 10^{0}$	$6.2\ 10^{0}$	$5.8\ 10^{-3}$
S2	4.3	2.8	3	$1.4\ 10^{1}$	$5.2\ 10^{0}$	$1.5\ 10^{1}$	$2.6\ 10^{-3}$
S3	2.8	2.0	50	$6.7\ 10^{0}$	$2.4\ 10^{0}$	$7.9\ 10^{0}$	$2.0\ 10^{-2}$
S4	1.2	2.5	160	$3.5\ 10^{0}$	$1.3\ 10^{0}$	$4.1\ 10^{0}$	$3.4\ 10^{-2}$
S5	2.8	2.5	9	$8.4\ 10^{0}$	$3.0\ 10^{0}$	$9.9\ 10^{0}$	$4.6\ 10^{-3}$
S6	6.0	2.0	108	$1.4\ 10^{1}$	$5.1\ 10^{0}$	$1.7\ 10^{1}$	$9.4\ 10^{-2}$
S7	0.3	2.6	16	$8.8\ 10^{-1}$	$3.2\ 10^{-1}$	$1.0\ 10^{0}$	$8.6\ 10^{-4}$
S8	2.1	1.5	108	$3.7\ 10^{0}$	$1.3\ 10^{0}$	$4.4\ 10^{0}$	$2.5\ 10^{-2}$
S9	1.8	2.6	11	$5.6\ 10^{0}$	$2.0\ 10^{0}$	$6.6\ 10^{0}$	$3.8\ 10^{-3}$
S10	1.5	2.6	5	$4.6\ 10^{0}$	$1.7\ 10^{0}$	$5.5\ 10^{0}$	$1.4\ 10^{-3}$
S11	4.3	2.5	4	$1.3\ 10^{1}$	$4.6\ 10^{0}$	$1.5\ 10^{1}$	$3.1\ 10^{-3}$
S12	2.9	2.5	10	$8.4\ 10^{0}$	$3.0\ 10^{0}$	$1.0\ 10^{1}$	$5.2\ 10^{-3}$
S13	2.7	2.7	131	$8.8\ 10^{0}$	$3.0\ 10^{0}$	$1.0\ 10^{1}$	$7.1\ 10^{-2}$
S14	3.9	1.6	18	$7.4\ 10^{0}$	$2.7\ 10^{0}$	$8.8\ 10^{0}$	$8.2\ 10^{-3}$
S15	1.5	2.5	2	$4.5\ 10^{0}$	$1.6\ 10^{0}$	$3.2\ 10^{0}$	$5.5\ 10^{-4}$
S16	4.0	2.5	1	$1.2\ 10^{1}$	$4.3\ 10^{0}$	$4.3\ 10^{0}$	$7.3\ 10^{-4}$
S17	3.8	2.5	1	$1.1\ 10^{1}$	$4.1\ 10^{0}$	$4.1\ 10^{0}$	$6.9\ 10^{-4}$
S18	4.6	2.0	300	$1.1\ 10^{1}$	$3.9\ 10^{0}$	$1.3\ 10^{1}$	$1.1\ 10^{-1}$
S19	7.4	2.3	46	$2.0\ 10^{1}$	$7.2\ 10^{0}$	$2.4\ 10^{1}$	$5.6\ 10^{-2}$
S20	3.1	2.5	1	$9.2\ 10^{0}$	$3.3\ 10^{0}$	$3.3\ 10^{0}$	$5.6\ 10^{-4}$
S21	3.1	3.3	33	$1.2\ 10^{1}$	$4.3\ 10^{0}$	$1.4\ 10^{1}$	$2.4\ 10^{-2}$

TABLE B10 Doses to passengers on short haul flights including from the airport hub onwards

Operator	Average annual TI	Average flight time from hub (h)	Number of flights transporting RAM	Individual dose for single flight (μSv)	Average annual individual dose (μSv y^{-1})	Collective dose (man Sv)
S2	4.3	9.3	3	9.4 10^{0}	7.7 10^{0}	7.5 10^{-3}
S4	1.6	7.0	46	2.4 10^{0}	2.0 10^{0}	5.5 10^{-2}
S6	6.0	9.0	108	1.1 10^{1}	8.9 10^{0}	3.3 10^{-1}
S8	2.1	6.1	108	2.7 10^{0}	2.2 10^{0}	8.0 10^{-2}
S18	2.8	6.7	489	1.2 10^{1}	9.8 10^{0}	7.7 10^{-1}
S19	6.2	8.3	55	1.3 10^{1}	1.0 10^{1}	1.7 10^{-1}
S21	3.1	4.3	33	5.7 10^{0}	4.7 10^{0}	4.2 10^{-2}

TABLE B11 Doses to passengers on long haul flights from the UK to airport hub or final destination

Operator	Average annual TI	Average flight time (h)	Number of flights transporting RAM	Individual dose for single flight (µSv)		Average annual individual dose (µSv y^{-1})	Collective dose (man Sv)
				Maximum	Average		
L1	9.6	7.0	110	2.0 10^{1}	7.2 10^{0}	1.8 10^{1}	3.0 10^{-1}
L2	3.9	12.5	250	1.4 10^{1}	5.2 10^{0}	2.2 10^{1}	4.0 10^{-1}
L3	2.1	4.0	94	2.5 10^{0}	9.1 10^{-1}	2.3 10^{0}	3.2 10^{-2}
L4	2.2	7.0	220	4.6 10^{0}	1.6 10^{0}	1.7 10^{0}	1.2 10^{-1}
L5	3.2	6.7	50	6.4 10^{0}	2.3 10^{0}	5.7 10^{0}	4.4 10^{-2}
L6	0.0	12.3	3	1.2 10^{-1}	4.4 10^{-2}	1.1 10^{-1}	5.0 10^{-5}
L7	0.6	11.4	46	2.2 10^{0}	7.9 10^{-1}	2.0 10^{0}	1.4 10^{-2}
L8	15.0	13.5	98	6.0 10^{1}	2.2 10^{1}	7.3 10^{1}	6.2 10^{-1}
L9	0.4	12.0	108	1.6 10^{0}	5.7 10^{-1}	1.4 10^{0}	2.3 10^{-2}
L10	2.8	8.3	246	7.0 10^{0}	2.5 10^{0}	1.1 10^{1}	1.6 10^{-1}
L11	5.0	6.7	200	1.0 10^{1}	3.6 10^{0}	8.2 10^{0}	1.5 10^{-1}
L12	3.5	11.4	20	1.2 10^{1}	4.3 10^{0}	1.1 10^{1}	3.3 10^{-2}
L13	0.2	4.8	6	2.1 10^{-1}	7.6 10^{-2}	1.9 10^{-1}	1.7 10^{-4}
L14	4.8	6.6	258	9.5 10^{0}	3.4 10^{0}	3.4 10^{1}	1.6 10^{-1}
L15	1.0	11.4	45	3.4 10^{0}	1.2 10^{0}	3.0 10^{0}	2.1 10^{-2}
L16	1.1	11.1	2	3.6 10^{0}	1.3 10^{0}	2.6 10^{0}	9.9 10^{-4}
L17	0.6	10.3	5	1.8 10^{0}	6.6 10^{-1}	1.7 10^{0}	1.3 10^{-3}

TABLE B12 Doses to passengers on long haul flights including from the airport hub onwards

Operator	Average annual TI	Average flight time from hub (h)	Number of flights transporting RAM	Individual dose for single flight (μSv)	Average annual individual dose (μSv y^{-1})	Collective dose (man Sv)
L1	3.8	10.7	150	$1.1\ 10^{1}$	$2.9\ 10^{1}$	$5.4\ 10^{-1}$
L2	2.0	8.3	362	$7.0\ 10^{0}$	$3.0\ 10^{1}$	$6.4\ 10^{-1}$
L4	2.0	11.0	205	$4.0\ 10^{0}$	$4.1\ 10^{0}$	$2.6\ 10^{-1}$

TABLE B13 Doses to passengers on short and long haul flights into the UK

Operator	Average annual TI	Average flight time (h)	Number of flights transporting RAM	Individual dose for single flight (μSv)		Average annual individual dose (μSv y^{-1})	Collective dose (man Sv)
				Maximum	Average		
S22	5.9	0.5	360	$3.5\ 10^{0}$	$1.3\ 10^{0}$	$3.8\ 10^{0}$	$7.7\ 10^{-2}$
S23	0.8	2.0	5	$1.9\ 10^{0}$	$6.9\ 10^{-1}$	$2.1\ 10^{0}$	$5.8\ 10^{-4}$
L1	1.7	7.0	9	$3.5\ 10^{0}$	$1.3\ 10^{0}$	$3.2\ 10^{0}$	$4.5\ 10^{-3}$
L15	2.1	12.0	55	$7.6\ 10^{0}$	$2.7\ 10^{0}$	$6.8\ 10^{0}$	$5.7\ 10^{-2}$

TABLE B14 Doses to passengers on short haul flights within the UK

Operator	Average annual TI	Average flight time (h)	Number of flights transporting RAM	Average dose for single flight (μSv)	Average annual individual dose (μSv y^{-1})	Collective dose (man Sv)
S24	0.6	0.5	75	$5.6\ 10^{-1}$	$1.7\ 10^{-1}$	$8.4\ 10^{-4}$