

NATIONAL DOSE ASSESSMENT WORKING GROUP

PAPER 11-04:

THE USE AND CALCULATION OF COLLECTIVE DOSE

Rachel Smith (HPA)

1 INTRODUCTION

The collective dose is a measure of the radiation exposure in a population. In simple terms it is the integral of the distribution on individual doses within the population. Collective doses have been used since the 1970s both to indicate the radiation induced health detriments of sources of radiation exposure and as inputs to optimisation studies.

Over recent decades concerns have been expressed about the way collective doses have been used (ICRP, 2004). In particular, there is general agreement that using the fully aggregated collective dose masks a lot of useful information on levels of individual dose and their distribution over time and space, that decision makers may consider important.

The International Commission on Radiological Protection (ICRP) has recently published general guidance on the way to use collective doses for optimisation purposes (ICRP, 2006), following earlier publication of a consultation paper on this issue (ICRP, 2005). A group of experts established under Article 31 of the Euratom Treaty has also been considering the issue of collective doses in relation to radioactive discharges. HPA and CEPN carried out a study, funded by the European Commission (EC), to input to their deliberations. This document is a brief summary of the study, which is described in detail in Smith et al (2007).

ICRP recommends the separation of collective doses into various components, reflecting the attributes and the exposure characteristics of the exposed individuals, and the time and space distributions of exposures relevant for the decision making process. The disaggregating process results in a set of exposure characteristics and attributes that can be constructed on a case by case basis. The aim is to construct a dose 'matrix' as illustrated in Figure 1.

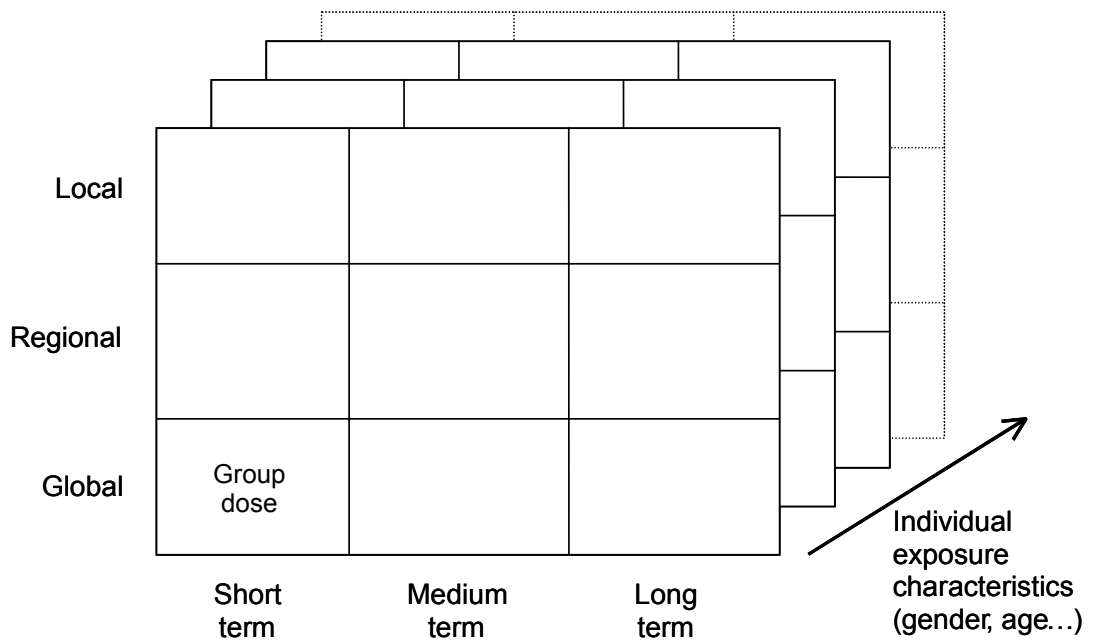


Figure 1 An example of a dose matrix (ICRP, 2005)

In the study some of the issues involved in the development and use of such 'matrices' were explored. In particular, practical issues regarding the disaggregation of collective doses in relation to individual dose rates and the temporal and spatial distribution of exposures were addressed and some preliminary suggestions are made of what can practically be achieved in the way of a 'dose matrix'. The scope of the study was restricted to the use of collective doses from routine discharges in optimisation and options comparison.

The objectives were accomplished primarily by carrying out a case study to estimate collective doses from discharges to the environment from a major nuclear site to various populations at various times and associated information on individual dose rates. The nuclear site chosen was Sellafield but additional calculations were also undertaken for Cap de La Hague for comparative purposes.

2 CALCULATIONS OF COLLECTIVE DOSE

2.1 General approach

The collective effective dose (generally referred to in this report as simply the collective dose) is defined as follows by the International Commission on Radiological Protection (ICRP)

$$S = \int_0^{\infty} E \cdot \frac{dN}{dE} dE \text{ or } \sum_i \bar{E}_i \cdot N_i$$

where $(dN/dE)dE$ is the number of individuals receiving an effective dose between E and $E + dE$, E_i is the mean effective dose to population subgroup i and N_i is the number of people in population subgroup i . Although the above equation appears superficially straightforward, in practice collective doses to members of the public are not estimated using it, primarily because, as will be discussed below, of issues regarding the determination of food doses. It should be noted that the linear no-threshold dose hypothesis is at the heart of the definition of collective dose. A small dose to a large number of people can be considered to imply the same overall population risk as a larger dose to a correspondingly smaller number of people, and, the integration and summation starts at zero. It is also possible to obtain doses per head of the population, known as per-caput doses. These per-caput doses are estimated by taking the estimated collective dose and dividing by the number of people. It can also be shown that the collective dose truncated at a particular time from one year's operation of a practice is numerically equal to the maximum annual collective dose-rate if the practice operated unchanged for that time period, provided all other factors remained the same.

In the literature a number of different methodologies for the determination of collective doses are presented. For atmospheric releases the general approach is to consider a radial grid around the release point. Atmospheric dispersion models are used to estimate the concentration of radionuclides in air for each of the radial grid elements (r, θ) , and deposition models to estimate the deposition rates onto the ground for each grid element. Using additional models for the movement of radionuclides within soil and agricultural systems, concentrations of radionuclides in soil and foods can be determined for each grid element. All these grid element specific data can be generated as a function of time. This grid element environmental concentration data is then used in combination with other information, including the population and agricultural production within each grid element to estimate the collective dose. Collective dose is defined as the summation of individual doses over time and space. In essence this basic approach is used in the majority of models to estimate collective doses from inhalation and external irradiation exposure pathways. For example, for inhalation doses the air concentration for a grid element is multiplied by a breathing rate and a dose coefficient(s) to generate an individual dose. This is then multiplied by the population within a grid element to get a collective dose. Summing this over all grid elements gives an estimate of total collective dose. Clearly this is a simplistic description of the process, ignoring as it does factors such as age groups, time variation and location factors, but these do not affect the basic structure of the approach.

Methods for the determination of collective doses from ingestion of foods, however, differ markedly from the above approach. For releases to atmosphere PC-CREAM (Mayall et al, 1997), for example, estimates collective doses from the ingestion of terrestrial foods as the product of the activity concentration in the food and the annual production of food in each element of a grid multiplied by the dose coefficient for ingestion and then summed over radionuclide and grid elements. It is assumed that someone eats the food but, as no information is available on who eats which food, it is stated that this approach is the only reasonable one.

In order to determine the distribution on individual doses from food consumption that make up the collective dose, estimated as above, additional data would be required. The most important would be information on the distribution of the affected food. In EU Member States and the EU as a whole there are significant movements of food from the points of production to the place of consumption. Whilst some information is available on imports and exports at a national level, information on food distribution within a country is not readily available. Unless the area affected by discharges is very small (eg a single farm which supplies a single shop) it would be extremely difficult and expensive to collect such information. For example, foods taken from farms to wholesale markets may be bought by a range of different food producers, shops, restaurants etc. spread over a wide region. Even when farms have long term supply contracts (eg with supermarkets), food is often taken to central distribution depots for distribution to particular shops on the basis of demand. Food distribution patterns can also vary over short periods of time (eg demand varies in different supermarkets and wholesalers sell to different customers at weekly markets). It would therefore be difficult to use any such information to predict patterns of exposures over the long time periods generally considered for collective doses. In general it is concluded, for the above reasons, that when doses from food consumption dominate it is not practicable to determine a distribution on individual doses.

Some other methodologies, although acknowledging the complicating factor of food distribution, have made the simplifying assumption that the food produced within a particular area is also consumed within that area. It is considered that given the wide distribution of foods this approach is inappropriate (Simmonds et al, 2006).

For aquatic releases the difficulty in determining collective dose as a summation of individual doses over time and space is even more apparent. For example, in the MARINA II study (EC, 2002) collective doses from the consumption of seafood were calculated as the product of the activity concentration in the edible fraction of seafood, the annual catch rate (also in terms of the edible fraction) and the dose coefficient for ingestion for each radionuclide, summed over radionuclide and marine compartment. This method uses data available on catches of different seafood and information on how much is consumed in the countries of the EU; it is assumed that someone eats the seafood but there is no information on who eats which food.

2.2 Methodology

For the study calculations were performed for discharges to the environment from the Sellafield nuclear site in the UK and the Cap de la Hague site in France based on published annual discharge data (see Smith et al (2007) for details) averaged over the period 1999 to 2003. The Sellafield and Cap de la Hague sites both contain nuclear fuel reprocessing plants and associated waste treatment facilities. They both discharge relatively significant quantities of longer lived radionuclides to the environment and have been considered in several past studies of collective doses. At both sites abatement technology has been introduced over the years they have been operating to significantly reduce discharges and hence doses so they are an interesting example to consider.

Collective doses were estimated at selected truncation times and the associated per-caput individual doses calculated. The general calculational approach was that adopted by Simmonds et al (2006). It should be noted that the results are presented to two significant figures for comparison purposes and should not be taken to imply this degree of accuracy. Techniques are available to assess numerically the uncertainties in estimated doses but they require more resources and information than were available for this study. However, the uncertainty associated with the estimated doses should be borne in mind.

For discharges to atmosphere, the PC-CREAM code system (Mayall et al, 1997) was used to calculate the collective doses. PC-CREAM implements the EC methodology for assessing the radiological impact of routine releases of radionuclides to the environment (Simmonds et al, 1995) in a package for personal computers. The default version of PC-CREAM only gives collective doses for a limited number of times and it was necessary to run the individual models making up PC-CREAM and to make manual adjustments to the system in order to obtain results for additional times. For discharges to the marine environment, the MARINA II model (Simmonds et al, 2002) was run to calculate activity concentrations in the marine environment which were subsequently used to estimate collective doses using the EC methodology (Simmonds et al, 1995).

For most radionuclides the collective dose is estimated only due to exposure to the original discharge; this exposure can continue for many years following its deposition onto the ground or dispersion in the marine environment even after the discharge has stopped. Some radionuclides, due to the length of their radioactive half-lives and their behaviour in the environment, can also become globally dispersed and act as a long term source of exposure to both regional and world populations. PC-CREAM includes models for the global dispersion of ^3H , ^{14}C , ^{85}Kr (for atmosphere only) and ^{129}I and these were included in the estimates of collective dose given here. It is possible to distinguish between the collective dose due to the initial discharge (referred to as the first pass dose) and that due to global circulation.

These calculational tools were used to estimate collective doses truncated at 1, 50, 100, 500, 1000, 5000, 10000, 50000 and 100000 years for the average annual discharges from Sellafield and collective doses truncated at 1, 50, 500, 10000 and 100000 years for discharges from La Hague. The populations considered were the UK or France, European Union (pre-2004 enlargement) or Europe¹ and the world. A full set of exposure pathways was considered for atmospheric discharges (eg, inhalation of radionuclides in the plume, external irradiation from radionuclides in the plume, external irradiation from deposited radionuclides and ingestion of various terrestrial foods). Also, the main exposure pathways due to marine discharges were included, namely, consumption of fish, crustaceans and molluscs and external doses due to radionuclides in beach sediments.

¹ For releases to atmosphere the population considered is that in Europe as a whole (7×10^8 people) while for discharge to the marine environment only the population of the European Union pre 2004 is considered (3.59×10^8 people).

As the truncation times for the estimates of collective dose are usually far in excess of the average lifetime, the truncated collective dose cannot simply be divided by the number of people in the chosen population group to obtain per-caput dose. However, the collective dose truncated at n years from a one-year discharge is numerically equivalent to the collective dose in year n following a continuous annual discharge, assuming all other factors remain constant (ICRP, 1999). Therefore for this study, the collective doses for a single year's discharge truncated at 50 and 100 years have been divided by the population number to obtain per-caput dose rates in the 50th and 100th year of a continuous discharge. In addition, the per-caput dose rate in the first year of discharge has been obtained by dividing the collective dose truncated at 1 year by the population number. Discharges are unlikely to continue for more than 100 years, therefore this approach is not used for longer times.

A further approach has been used to obtain indicative per-caput dose rates during selected time periods for the chosen population groups. This has been simplistically achieved by taking the collective dose truncated at time j and subtracting the collective dose truncated at time i and dividing this quantity by the time period considered ($j - i$) to obtain a representative annual collective dose rate. The resulting value can be divided by the number of population in the group of interest to obtain an indicative per-caput dose rate. This approach makes the crude assumption that collective doses increase linearly with time, which is generally not the case, particularly for the longer time periods. However, this approach does enable a broad estimate to be made of the levels of per-caput dose contributing to the collective dose.

2.3 Results

A selection of the results obtained is presented below. For a full summary of the results the reader is referred to Smith et al (2007).

2.3.1 Collective doses

Table 1 shows the collective dose truncated at various times due to the annual average discharges to atmosphere from Sellafield between 1999 and 2003. Results are given for the UK, Europe and world populations. The total collective dose is given together with the contribution due to the exposure following the release to atmosphere prior to global dispersion, referred to as the first pass. This includes exposure in subsequent years following deposition of radionuclides on land from the first pass. The difference between the total collective dose and the first pass is then due to the global circulation of radionuclides.

Table 1 Collective doses due to annual discharges to atmosphere from the Sellafield site (discharge is the average annual discharge between 1999 and 2003)

Integration period (y)	Collective dose (man Sv)					
	UK population (5.5 10 ⁷ people)		European population (7 10 ⁸ people)		World population (1 10 ¹⁰ people)	
	Total	(first pass*)	Total	(first pass*)	Total	(first pass*)
1	1.1	(1.0)	4.2	(4.1)	6.7	(4.1)
50	1.5	(1.3)	8.3	(5.7)	43	(5.7)
100	1.6	(1.4)	8.9	(6.0)	48	(6.0)
500	1.8	(1.5)	10	(6.2)	63	(6.2)
1000	1.9	(1.5)	11	(6.2)	74	(6.2)
5000	2.2	(1.5)	15	(6.2)	140	(6.2)
10000	2.4	(1.5)	18	(6.2)	180	(6.2)
50000	2.7	(1.5)	22	(6.2)	230	(6.2)
100000	2.7	(1.5)	22	(6.2)	230	(6.2)
Infinity	2.8	(1.5)	23	(6.2)	240	(6.2)

Notes:

* The first pass dose is that due to the initial discharge to the environment. The total also includes any contribution from the global circulation of relevant radionuclides.

Results presented to two significant figures.

Table 1 shows that the collective dose due to the first pass exposure is essentially all delivered in the first few hundred years following the discharge. The first pass dose is particularly important for the UK population while for the world population, it only makes a small contribution except in the first few years after the discharge. The contribution from the global circulation of long-lived radionuclides continues to increase for all times considered. Doses due to ingestion of terrestrial foods are the largest contributor to the first pass collective dose. For example, for the UK population about 80% of the collective dose truncated at 500 y is due to ingestion.

Even at short times the collective dose is mainly due to discharges of ³H, ¹⁴C, ⁸⁵Kr and ¹²⁹I, the four relatively long-lived, mobile radionuclides that also contribute to the dose from global circulation. Their relative contribution varies with time and is also different for the different population groups considered.

The contribution of ¹⁴C increases with time reflecting its long radioactive half-life (about 5700 y) and its high mobility in the environment (Simmonds et al, 1995). Although ¹²⁹I has a longer half-life (10⁷ y) than ¹⁴C, its contribution falls slightly at the very longest time; this is due to the importance of the first pass dose for ¹²⁹I, which affects the overall change in collective dose with time. The use of a specific activity approach (Simmonds et al, 1995) for ¹⁴C means that the estimated first pass collective dose is all delivered in the year of deposition.

The collective doses due to averaged annual discharges into the marine environment from the Sellafield site between 1999 and 2003 are shown in Table 2.

Table 2 Collective doses due to annual marine discharges from the Sellafield site (discharge is the average annual discharge between 1999 and 2003)

Truncation time (y)	Collective dose to population (man Sv)					
	UK (5.5 10 ⁷ people)		European Union* (3.59 10 ⁸ people)		World (1 10 ¹⁰ people)	
	<i>Total</i>	<i>(first pass[†])</i>	<i>Total</i>	<i>(first pass[†])</i>	<i>Total</i>	<i>(first pass[†])</i>
1	0.44	(0.44)	1.0	(1.0)	1.3	(1.2)
50	2.3	(2.2)	6.4	(5.7)	29	(8.7)
100	2.4	(2.2)	7.1	(5.9)	45	(9.0)
500	2.9	(2.3)	9.9	(6.1)	120	(9.4)
1000	3.2	(2.3)	12	(6.1)	180	(9.5)
5000	5.2	(2.3)	24	(6.2)	540	(9.8)
10000	6.6	(2.4)	34	(6.3)	800	(10)
50000	8.3	(2.4)	44	(6.5)	1100	(10)
100000	8.4	(2.4)	45	(6.6)	1100	(11)

Notes:

* Pre-2004 enlargement.

† The first pass dose is that due to the initial discharge to the environment. The total also includes any contribution from the global circulation of relevant radionuclides.

Results presented to 2 significant figures.

Table 2 shows that the dose due to the first pass is mainly delivered in the first 50 years after discharge. Over time, the globally circulating component increasingly becomes the majority contributor to the total dose. Carbon-14 is the highest contributor to the collective dose to the UK population at all truncation times. As with discharges to atmosphere, carbon-14 delivers a long-term dose due to global circulation. Other important contributors to collective dose in the first year are technetium-99, ruthenium-106, caesium-137 and plutonium-239. Long-lived radionuclides can continue to contribute to the collective dose over long time periods whether from the first pass or global circulation.

The above tables of collective doses from both atmospheric and marine discharges can be considered as examples of 'dose matrices', where the total collective dose is disaggregated according to time and space scales only, the first part of the matrix illustrated in Figure 1.

2.3.2 Per-caput doses

It is possible to obtain estimates of individual, per-caput doses from the collective doses. Table 3 shows the annual per-caput doses to the UK, European and world populations in the 1st, 50th and 100th year of continuous discharge from Sellafield.

Table 3 Maximum annual per-caput doses assuming continuous discharge to atmosphere from the Sellafield site

Years of discharge	Per-caput dose (Sv) to different populations		
	UK	Europe	World
1	1.9×10^{-8}	6.1×10^{-9}	6.7×10^{-10}
50	2.8×10^{-8}	1.2×10^{-8}	4.3×10^{-9}
100	2.9×10^{-8}	1.3×10^{-8}	4.8×10^{-9}

Notes:

Discharges are assumed to be at an annual rate obtained as an average value of the discharges between 1999 and 2003.

Results presented to two significant figures.

The per-caput doses are very small and, as expected, increasing the number of years of discharge increases the per-caput dose in the final year of discharge, although the differences in dose are relatively small. The per-caput doses are highest for the UK population.

It is important to note that these are the average doses for the population and higher doses would be received by people living closest to the site.

For marine discharges the per-caput doses are estimated by dividing the collective doses truncated at the appropriate times by the population number of interest, thus representing the per-caput dose for these populations in the selected year. The results of these calculations for the Sellafield site are presented in Table 4.

Table 4 Maximum annual per-caput doses due to a continuous discharge to the marine environment from Sellafield

Years of discharge (y)	Per-caput dose in population (Sv)		
	UK	European Union*	World
1	8.0×10^{-9}	2.9×10^{-9}	1.3×10^{-10}
50	4.1×10^{-8}	1.8×10^{-8}	2.9×10^{-9}
100	4.4×10^{-8}	2.0×10^{-8}	4.5×10^{-9}

Notes:

* Pre-2004 enlargement.

Presented to 2 significant figures.

Discharges are assumed to be at an annual rate obtained as an average value for discharges between 1999 and 2003.

The collective doses are determined using net seafood catches, ie, the seafood caught by a country less the seafood exported. When both of these numbers are very similar (ie the majority of the fish caught is exported) uncertainties in each, arising from incomplete data collection or rounding, could result in significant uncertainty in the net seafood catch. Therefore, under these circumstances the net catch may not be a true representation of the actual amount consumed in the country and there will be similar uncertainties associated with the collective and per caput doses generated using it (Simmonds et al, 2002).

Increasing the number of years of discharge results in higher estimates of per-caput doses showing the tendency of marine discharges to take some years to build up in the environment dependent on the rates of transfer of radioactive material away from the originating site. This is especially true for European Union and world per-caput doses due to the longer travel distance from the discharge sites. For Sellafield discharges, as the discharges occur from a UK based site, the per-caput doses in the UK population are the highest, representing an average dose to a member of the UK population. Higher doses would be received by individuals closer to the site should a full dose assessment be performed (eg, Environment Agency *et al.*, 2004). Conversely, individuals at greatest distances from the site may be expected to receive lower than average doses.

2.3.3 Indicative per-caput annual dose rates

Indicative per-caput dose rates are obtained by finding an average collective dose rate for the period of interest and dividing it by the total population. These together with the maximum annual per-caput annual doses can provide information on individual doses to contribute to the matrix shown in Figure 1.

Table 5 shows indicative per-caput dose rates for the 3 population groups for different time periods following annual discharges to atmosphere from the Sellafield site obtained as an average of discharges between 1999 and 2003.

Table 5 Indicative per-caput dose rates at different time periods following one year's discharge to atmosphere from the Sellafield site (discharge is the average annual discharge between 1999 and 2003)

Time period Y	Per-caput dose rate (Sv/y) for different populations		
	UK	Europe	World
1-50	$1.8 \cdot 10^{-10}$	$1.2 \cdot 10^{-10}$	$7.3 \cdot 10^{-11}$
50-100	$3.1 \cdot 10^{-11}$	$1.7 \cdot 10^{-11}$	$1.0 \cdot 10^{-11}$
100-500	$8.6 \cdot 10^{-12}$	$4.5 \cdot 10^{-12}$	$3.7 \cdot 10^{-12}$
500-1000	$2.2 \cdot 10^{-12}$	$2.2 \cdot 10^{-12}$	$2.3 \cdot 10^{-12}$
1000-5000	$1.5 \cdot 10^{-12}$	$1.5 \cdot 10^{-12}$	$1.5 \cdot 10^{-12}$
5000-10000	$8.8 \cdot 10^{-13}$	$8.7 \cdot 10^{-13}$	$8.7 \cdot 10^{-13}$
10000-50000	$1.3 \cdot 10^{-13}$	$1.3 \cdot 10^{-13}$	$1.3 \cdot 10^{-13}$

Note:

Results presented to 2 significant figures.

Beyond approximately 500-1000 years per caput dose rates are expected to be the same for all populations. The differences in the above table are a result of minor differences in the models used for the different populations and possible rounding errors.

The per-caput dose rates show the expected trend of decreasing levels with time, with the UK receiving the highest per-caput doses in the first period following the discharge. However, from 500y on there are no differences (except rounding errors) in the estimated per-caput doses between the three population groups as by this time the dose is dominated by that due to global circulation. All of the estimated annual per-caput dose rates are extremely small. The

results presented are for a single year's discharge if the discharge continues for n years then the results can be multiplied by n to obtain the indicative per-caput dose rates for the total discharge, except for times less than n where a specific calculation would be required.

Indicative per-caput dose rates for marine discharges were derived for selected time periods using the three population groups previously considered for the same average annual discharges (1999 to 2003). The results of these calculations for the Sellafield are presented in Table 6.

The indicative per-caput dose rates decrease over time with the highest per-caput doses received by individuals in the UK. The per-caput dose rates converge to similar values across population groups (ignoring rounding errors) by 500 years indicating that the majority of the dose after this time is due to globally dispersed radionuclides. Differences between per-caput dose rates between the values of both the country of discharge and European Union and those of the world are due to the contribution of iodine-129. The modelling used for global dispersion of iodine-129 distinguishes between doses received by different population groups (Titley et al, 1995). Other differences between the UK and European Union per-caput dose rates during this time period are due to long-term doses delivered from the first pass of discharges of the long lived radionuclide technetium-99. The per-caput dose rates estimated in Table 6 are all at very low levels.

Table 6 Indicative per-caput dose rates due to one year's marine discharge from the Sellafield site (discharge is the average annual discharge between 1999 and 2003)

Time period (y)	Per-caput dose rate in population (Sv/y)		
	UK	European Union*	World
1-50	6.8×10^{-10}	3.0×10^{-10}	5.6×10^{-11}
50-100	4.9×10^{-11}	3.8×10^{-11}	3.3×10^{-11}
100-500	2.1×10^{-11}	2.0×10^{-11}	1.9×10^{-11}
500-1000	1.3×10^{-11}	1.3×10^{-11}	1.2×10^{-11}
1000-5000	9.1×10^{-12}	8.5×10^{-12}	9.0×10^{-12}
5000-10000	4.9×10^{-12}	5.1×10^{-12}	5.2×10^{-12}
10000-50000	7.9×10^{-13}	7.5×10^{-13}	8.1×10^{-13}

Notes:

* Pre-2004 enlargement.

Presented to 2 significant figures.

Beyond approximately 500-1000 years per caput dose rates are expected to be the same for all populations for the times considered. The differences in the above table are a result of minor differences in the models used for the different populations and possible rounding errors.

2.3.4 General points

Comparison of the collective dose truncated at a range of times can provide an indication of the time period when the majority of the collective dose is delivered. Much of the collective dose due to the first pass is delivered within the first 50 years following discharge, although there is a continuing residual

dose delivered over the remaining time periods considered due to long-lived radionuclides. The contribution due to globally circulated radionuclides increases over time to represent the greatest contributor to total collective dose to the world population by 50 years and the European Union population by between 500 and 10,000 years (varying with site and differing for marine and atmospheric discharges). The collective dose rate from global circulation dominates the total collective dose rate by 500 years following discharge at the latest for all populations considered. The global component represents a uniform dose to the population group considered. In most cases, it can be shown that the annual rate of collective dose is greatest whilst discharges are continuing and that this rate decreases when discharges cease as continued environmental transfer and decay processes occur.

The collective doses presented here can be compared with those that are received from other sources of radioactivity. Of particular interest is the collective dose received from naturally occurring carbon-14 due to the importance of this radionuclide in the current study. In the UK the ionising radiation exposure of the UK population was reviewed in 2005 (Watson et al, 2005). This study reported that the average individual dose in the UK from naturally occurring carbon-14 was about 8.8 μSv per year. Multiplying this by the UK population used elsewhere in the current study, $5.5 \cdot 10^7$, gives an annual collective dose of about 480 man Sv per year to the UK population. This is significantly greater than the total UK collective dose from both atmospheric and marine discharges of all radionuclides from Sellafield integrated over all time (10 man Sv from Tables 3 and 6).

The per-caput doses estimated following 1, 50 and 100 years of continuous discharge show the average individual doses comprising the collective dose. The per-caput doses in the 50th and 100th year of continuous discharge show the greatest values assuming that the practice continues during this time. Additional information can be obtained from the indicative per-caput dose rates, which show that the rate of dose delivery is greatest in the first 50 years reducing by approximately an order of magnitude in the next 50 years for the UK and European Union populations. The per-caput dose rates broadly show convergence of dose rates between population groups after 500 years. In all considered cases, the per-caput individual doses are less than 10^{-5} Sv, representing a level of individual risk considered trivial by international bodies (IAEA, 1988; ICRP, 2004). It should be noted that the per-caput doses presented here would form only part of an assessment of the complete radiological impact of a practice. In addition, there is a continued requirement to consider the most exposed group within a population, referred to as the critical group or the reference group. An additional input to the assessment may be the consideration of individuals living close to the site, who have typical behaviour and consumption habits, referred to as typical individuals (Bexon, 2000).

3 CONCLUSIONS

Current models and codes used for the estimation of collective doses can determine collective doses to a limited number of population groups over various temporal periods, and thus go some way to providing the required 'group doses'² for a dose matrix. In some cases, as in this study, minor changes may be required to the model and/or code to obtain information on the desired temporal frame. Such problems are not expected to be a significant hindrance to the development of dose matrices. The majority of such models consider national and supra national populations (eg, EU and World). They could, in theory, be modified to address collective doses to smaller groups, for example, a region within a country. This would, however, require information on the transfer of food into and out of such a region. It is unlikely that such information would be readily available for areas below the country level. If 'group doses' are required for smaller population groups then alternative approaches may need to be developed.

In the example calculations undertaken for this study the most important exposure pathway was ingestion of contaminated food. Under these circumstances, for the reasons discussed in Section 2.1, it is not practicable to determine a distribution on individual doses.

The ICRP's suggested approach of looking at individual dose distributions within each group dose is therefore not possible for significant population sizes, except perhaps for rare cases where collective dose is dominated by other pathways. However this does not rule out the use of dose matrices as will be discussed later. For radionuclides that are globally circulated (the most important in this study being ¹²⁹I and ¹⁴C) individual doses are likely to be reasonably predictable for long time periods as contamination will be in all major foods so changes to dietary habits are unlikely to have a significant impact. Such doses also tend to be low. So when global circulation doses dominate, both the absolute levels of dose are low and the distribution is expected to be narrow. Under these conditions it is unlikely that decision-makers would find the distribution of individual doses of use. It is therefore recommended that once global circulation dominates there is no requirement for information on individual dose distributions.

A possible approach to maintaining information on individual dose levels for a dose matrix has been explored in this study. This involved determining per-caput doses to various population groups at various times. The group doses and associated per-caput doses could form a useful input to optimisation and option comparison decision-making.

Doses from global circulation are clearly an important input to any options comparison or optimisation study. However, the results of this study indicate that in general the benefits of disaggregating such doses are minimal. At long time periods it is likely that in many cases the collective doses from various

² ICRP draft guidance on optimisation referred to collective doses within particular population subgroups as 'group doses' (ICRP, 2005).

options will converge. In general the study results indicate that the complexity of a dose matrix would be expected to decrease with time.

It is not clear how the dose matrix should include the dose to the critical (or representative) group. These doses are an important part of any radiological impact assessment and need to be considered as well as collective and per-caput doses. It is likely that the distribution of individual doses will be of most importance to a decision maker mainly when doses are at their highest. It is suggested that before any further work is undertaken in this area that some dialogue be developed first with relevant stakeholders and then potential decision-makers to establish whether such information would be of use. It would also be useful to establish whether more detailed information on dose distributions to regional or country populations are required for the times (up to a few hundred years at most) before global collective dose dominates. It would also be useful to explore whether, if the average/or per-caput dose is below a certain level, then such additional information is not required.

The following main conclusions can be drawn from the study:

- Current models and codes used for the estimation of collective doses can determine collective doses to a limited number of population groups over various temporal periods, and thus go some way to providing the required breakdown of collective dose into different geographical regions and times for a dose matrix.
- The ICRP's suggested approach of looking at individual dose distributions within each group dose is not practicable for significant population sizes if ingestion of food is an important exposure pathway.
- It is recommended that once global circulation dominates there is no requirement for information on individual dose distributions. In general the study results indicate that the complexity of a dose matrix would be expected to decrease with time.
- It is possible to estimate per-caput doses associated with different 'group doses'. These could form a useful input to optimisation and option comparison decision-making.
- It is suggested that before any further work is undertaken in this area that some dialogue be developed first with relevant stakeholders and then potential decision-makers to establish the extent to which such information is required.

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