

Methods of Assessing Total Doses Integrated Across Pathways

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1. Introduction

The Radioactivity in Food and the Environment (RIFE) report series (Environment Agency *et al.*, 2003-2005) presents data from monitoring on behalf of the United Kingdom Government and retrospective dose calculations relating to disposals of radioactive waste from nuclear sites. In the past, total (or integrated) doses have been calculated from the addition of doses due to liquid discharges with those from gaseous discharges and those from direct radiation (where applicable). This approach ensured that dose calculations were generally overestimated, but was not always realistic. This is because the calculated doses apply to specific high-consumption/occupancy groups for each of these sources which, in reality, rarely overlap.

Various methods have been used to address the issue of total dose (Ministry of Agriculture, Fisheries and Food and Scottish Environment Protection Agency, 1998; Robinson *et al.*, 1994; Hancox *et al.*, 2002; Camplin *et al.*, 2002). However the available habits survey data did not always provide sufficient information to support a realistic dose assessment. This has been overcome by the new integrated habits survey methodology, which is described in this volume by Grzechnik *et al.* (2006).

It is the aim of this paper to consider the practical application of the assessment of total retrospective dose to critical groups of the UK public near nuclear establishments using monitoring and integrated habits survey data combined with International Commission on Radiological Protection (ICRP) age-related dose coefficients (ICRP, 1996).

2. Baseline Doses for Comparison

The RIFE series of reports (Environment Agency *et al.*, 2003-2005) gives details of the methodology and data used to determine doses to members of the public from the disposal of radioactive wastes from the main sources in the UK. These are referred to as 'baseline' doses, and are used as the main comparison with the total dose methodologies described in this paper. The effects of gaseous and liquid sources are considered separately because the environmental data and the individuals affected generally fall into two distinct groups. Direct radiation is not included in the baseline assessment, but the dose may be added separately if desired.

Gaseous discharge assessments involve the calculation of terrestrial foodchain doses. Pathways considered include ingestion of terrestrial foodstuffs (e.g. milk, vegetables, meat), and exposure due to inhalation and external exposure to both the plume and activity deposited from the plume. Doses are determined for 1 year-olds, 10 year-olds and adults, with foetal doses to be considered in the future.

Terrestrial foodchain doses are largely determined by combining the results of measurement of concentrations in samples with generic consumption rates typical of high rate consumers as determined from national surveys (Byrom *et al.*, 1995). The summation across food groups is determined by the 'Top-Two' method, where 97.5th and 50th percentile consumption rates are used to calculate doses from all food groups. After this calculation, the two food groups that give the highest dose are taken to be consumed at 97.5th percentile rates ('critical' rates), while the remainder are consumed at 50th percentile rates. The top-two approach is based on the premise that only a very small percentage of the population have been found to be critical rate consumers in more than two food groups and that consuming more than two foods at the 97.5th percentile would result in unrealistically high total calorific intakes.

Doses from plume-related pathways and the associated deposited activity are calculated for sites where these pathways are known to be important. The PC CREAM atmospheric model (Mayall *et al.*, 1997) is used to determine concentrations and dose rates. Inhalation and occupancy data were given typical default values that have been determined to be representative of the most exposed individuals.

For liquid sources, the main pathways considered are ingestion of fish and shellfish and external exposure over potentially contaminated beaches and other substrates. Where appropriate other less significant pathways are also considered, for example, inadvertent ingestion of water and sediments and handling of sediments or fishermen's nets. Historically, habits surveys have shown that consumption and occupancy rates vary considerably between sites around the UK (see Appendix 4, Environment Agency *et al.*, 2005). In view of this and the fact that aquatic discharge pathways tend to dominate overall dose at most sites, these doses are assessed on a more realistic basis using site-specific consumption and occupancy rates. Critical consumption and occupancy rates are calculated using the *cut-off* method (Hunt *et al.*, 1982), whereby for each pathway all rates within a factor of three of the maximum are averaged to give the 'critical rates'. Each group of people whose data has contributed to a critical rate for an exposure pathway is called a 'potential critical group'. The group with the highest calculated dose is known as the 'critical group'. This methodology is based on the ICRP homogeneity principle.

3. Methods Considered for Total Dose Assessment

There are a number of options for determining total dose, each with its own strengths and weaknesses. The most obvious methodology is to calculate the doses for each individual within the scope of the habits survey (the 'Individual' method). Dose for comparison with regulatory limits can then be determined from the upper parts of the distribution of individual doses. The significant disadvantage of this method is that it may only be independently reproduced if all data from the habits survey is available. As such, four other options have been proposed to overcome this problem, with the Individual method (referred to here as 'A') and the baseline used for comparison.

Each of the 5 methods was labelled (A to E) and given a short, relevant name for identification. The methods and their calculation are described in Table 1.

Table 1. Description of 5 options for determining total dose.

<i>Option, short name and description</i>	<i>Process</i>
<p><i>A. INDIVIDUAL</i></p> <p>Full calculation of dose to each individual in habits survey; dose for comparison with limit derived by cut-off method</p>	<ul style="list-style-type: none"> • Combine the data from the most recent site-specific habits survey with concentration and dose rate data to determine doses to each individual • Select individuals with doses above 1/3 of the maximum dose • Average the doses to these individuals <p>N.B. Alternatively, percentiles may be taken from the distribution of calculated doses.</p>
<p><i>B. INDIVIDUAL PLUS</i></p> <p>As A, but in year 1, derive average rates of consumption and occupancy by the critical group and apply these to future years</p>	<ul style="list-style-type: none"> • In year 1, combine the data from the most recent site-specific habits survey with concentration and dose rate data to determine doses to each individual • Select individuals with doses above 1/3 of the maximum dose • Average the consumption and occupancy habits in each pathway for these individuals, including zero habits • Use this derived set of habits data to determine doses by summation over all pathways until a new survey is available <p>N.B. Methods A&B have been combined in results tables as they will give identical results in year 1 calculations.</p>
<p><i>C. CONSTRUCT</i></p> <p>In year 1, construct a secondary habits dataset made up of all those individuals with habits rates defined to be critical ones, then average the rates and apply these to future years</p>	<ul style="list-style-type: none"> • For each pathway, determine those individuals who have consumption and occupancy rates above 1/3 the maximum rate • Construct a secondary database of all such individuals and their rates for all pathways • Average the rates excluding zeros • Use this derived set of habits data to determine doses by summation over all pathways until a new survey is available
<p><i>D. TOP-TWO</i></p> <p>In year 1, derive critical and average rates for each pathway and apply these to future years. Determine doses using the Top-two method previously adopted for terrestrial pathways</p>	<ul style="list-style-type: none"> • For each pathway determine critical consumption and occupancy rates by averaging those rates higher than 1/3 the maximum rate. Apply these until a new survey is available • Divide critical rates by three to obtain average rates. This simplifying assumption has been chosen to correspond to observations made with national habits survey data. Other group specific factors could be used. • Calculate doses for all sets of rate combinations that include two critical rates and the remainder as averages • Use the set of habits which gives rise to the highest dose for comparison with the dose limit
<p><i>E. PROFILING</i></p> <p>In year 1, derive profiles of habits rates that correspond to high consumers for each pathway and apply these to future years. Calculate doses for each profile and select the highest dose.</p>	<ul style="list-style-type: none"> • Starting with the first pathway, use the cut-off method to determine critical individuals. Average the consumption and occupancy rates of each of these individuals and assign the habits rates determined as 'Profile A' • Repeat for the second pathway (Profile B), and subsequent pathways. Use these data until a new survey is available • Use the habits profiles to calculate doses • Use the set of habits which gives rise to the highest dose for comparison with the dose limit

4. Assumptions for Total Dose Calculations

To compare these 5 methods, calculations have been undertaken using purpose-built automated spreadsheets that include ICRP 72 dose coefficients, local habits and environmental monitoring data. Limit of Detection values have been included in the monitoring data, and the same methodology used as for the baseline assessments (see Section 2). As for the baseline calculations, the sampling programme is tailored to measure the most important foodstuffs, even though there are non-zero consumption levels in cases where there were no measurements of food concentrations.

Pathways have been combined (where appropriate) into the headings shown in Table 3, with the facility provided to include additional or unusual pathways where required. Where dose rates of a number of species in combined pathways were significantly dissimilar, proportions of each foodstuff were applied. These proportions were based on critical consumption rates.

Child consumption rates have been estimated by applying a generic child/adult ratio to the adult consumption and occupancy rate for each group, mainly due to lack of site-specific data. The ratios used are shown in Table 3, and were derived from Smith and Jones (2003) and Byrom *et al.* (1995). A non-zero consumption rate for fish and shellfish for 1 year old children has been adopted because there has been some evidence from site-specific surveys that such consumption should be allowed for in order to ensure that doses are not underestimated.

Direct radiation doses from industry assessments are provided by the Health and Safety Executive (HSE, 2005). The doses provided are to the most exposed group, and have been fully applied to any individuals surveyed within a 1km radius of the site perimeter fence (England and Wales), or site centre (Scotland).

A calculation of gaseous plume pathways was included in the integrated dose where significant. Dose rates were assigned to areas corresponding to 0-250m, 250-500m and 500-1000m outside the site perimeter. The PC CREAM atmospheric plume model was used to calculate the dose rates ($\mu\text{Sv/hr}$) to adults and children for an entire year (8760hr/y). They were calculated at the middle of each of the areas, viz. 125m, 375m and 750m outside the perimeter fence. The occupancy data obtained in the habits survey of the region were then used to calculate doses based upon hours of occupancy per year in each of the three relevant regions. The occupancy rates for individuals in the habits dataset were taken as the sum of indoor and outdoor occupancy. The combined occupancy was adjusted using the generic factors given below to allow for the effects of shielding. The factors used for the baseline RIFE calculations for residential occupancy are shown in Table 2.

Table 2. Factors used in PC CREAM for baseline RIFE calculations.

Age group	Fraction of total time spent indoors	Fraction of outside dose rate received indoors	Fraction of outside dose rate received indoors
		Cloud gamma	Deposited gamma
1 year old	0.9	0.2	0.1
10 year old	0.8	0.2	0.1
Adult	0.7	0.2	0.1

Table 3. Pathways and child consumption ratios considered for total dose assessments.

Pathway	Ratio: child/adult	
	10 year old	1 year old
Sea Fish	0.20	0.05
Freshwater Fish	0.25	0.05
Crustacea	0.25	0.05
Mollusca	0.25	0.05
Cattle Meat	0.67	0.22
Domestic Fruit	0.67	0.47
Eggs	0.80	0.60
Game	0.50	0.14
Green Vegetables	0.44	0.22
Honey	0.79	0.79
Milk	1.0	1.3
Mushrooms	0.45	0.15
Offal	0.50	0.28
Other Domestic Vegetables	0.50	0.20
Pig Meat	0.63	0.14
Potatoes	0.71	0.29
Poultry	0.50	0.18
Root Vegetables	0.50	0.38
Sheep Meat	0.40	0.12
Wild Fruit and Nuts	0.49	0.11
Gamma External*	0.50	0.03
Plume Pathways**	1.0	1.0

* Gamma External pathways are those associated with liquid discharges and exposure over substrates such as intertidal areas and riverbanks.

** Plume pathways are those related to gaseous discharges (e.g. inhalation from the plume, inhalation of resuspended sediments from ground deposits and external radiation from the plume and ground deposits). A site-specific adjustment is made for child doses using ratios of modelled data in order to calculate the dose per unit intake for each age-group.

5. Example Calculations

Three sites were chosen for a comparison of the 5 methods: Aldermaston & Burghfield, Hartlepool, and Sellafield. Results have been compared with baseline calculations from the RIFE report for 2004 data (Environment Agency *et al.*, 2005). A summary of the results, including child doses where available, has been presented in Table 4. Direct radiation has been excluded to enable comparison with baseline doses, and natural radionuclides have been included in the Sellafield calculation due to the legacy of natural radionuclide discharges from a chemical works in nearby Whitehaven. Results for Methods A&B are presented together because doses will be identical during year 1 due to identical methods for choosing the critical group.

Taking into account the different approaches used, each of the new methods agrees reasonably well with the baseline dose. As such, it is difficult to draw distinct comparisons on the basis of dose alone. Generally, it can be expected that options A & B gave the most realistic dose because they reflect individuals' habits directly. Doses using Method E were closer to those obtained using the individual method than either of methods C & D. Method E doses were slightly more conservative than those obtained using methods A & B, and were also closer to the RIFE baseline doses in two out of the three sites presented.

Table 4. Comparison of doses for (combined – excluding direct radiation) baseline and Method A-E calculations ($\mu\text{Sv y}^{-1}$) for three example UK sites. The most dominant pathway refers to adult consumption/occupancy unless otherwise indicated.

Site		Baseline (liq., gas)	A&B	C	D	E
Aldermaston/ Burghfield	Adult dose	1.2, 1.9	0.96	2.8	2.7	1.3
	10y dose	N/A, 1.4	0.83	1.8	1.8	1.0
	1y dose	N/A, 2.2	1.6	1.8	2.0	1.7
	Dominant pathway	1 year old milk cons.	1 year old milk cons.	External (river)	External (river)	1 year old milk cons.
Hartlepool	Adult dose	2.5, 0.87	0.95	1.6	2.1	1.1
	10y dose	N/A, 1.2	0.57	0.75	0.88	0.54
	1y dose	N/A, 3.6	0.11	0.50	0.34	0.18
	Dominant pathway	1 year old milk cons.	Sea Fish cons.	Sea Fish cons.	External (sediment)	External (sediment)
Sellafield <i>(including natural radionuclides)</i>	Adult dose	630, 20	500	380	820	600
	10y dose	N/A, 23	240	200	400	280
	1y dose	N/A, 36	140	130	250	160
	Dominant pathway	Fish & Shellfish consumption	Mollusc cons.	Mollusc cons.	Mollusc cons.	Mollusc cons.

6. Criteria and Ranking

The criteria for successful adoption of a method for this calculation were:

Reproducibility – can the approach be easily used for an independent reassessment?

Rigour and realism – how good is the match with reality?

Transparency – a measure of the ease with which others can understand how the calculations are performed and what they mean.

Homogeneity – is the group receiving the dose relatively homogeneous with respect to age, diet and those aspects that affect the dose received? This feature has been recommended as being one to use when defining a critical group.

A qualitative comparison of the criteria described above is shown in Table 5.

Table 5. Qualitative comparison of the five methods for total dose assessment.

Method	Positive	Negative
A. Individual	Most rigorous and realistic for assessing dose.	Difficult to present and for others to reproduce. Potentially inhomogeneous.
B. Individual Plus	Easy to reproduce and present.	Less rigorous and potentially inhomogeneous.
C. Construct	Easy to reproduce.	Difficult to explain. Potentially very large critical group which does not actually exist.
D. Top-Two	High homogeneity.	Not fully scientifically robust. Critical group does not actually exist. Data manipulation difficult to explain.
E. Profiling	Homogeneity criteria most likely to be met. Easy to present and replicate.	Chance of overestimating dose due to unrealistically small number of individuals in critical group.

A suitability ranking was performed by a working group comprising of RIFE representatives using a paired comparison technique resulting in a quantitative measure of relative suitability of each option in relation to its features (Camplin *et al.*, 2005). For example, if option A was decided to exhibit better rigour and realism when compared with option E, then A was awarded one point and E none. The result of the ranking exercise is shown in Table 6.

Table 6. Results of ranking Options using paired comparisons

<i>Feature</i> <i>Option</i>	<i>Reproducibility</i>	<i>Rigour and realism</i>	<i>Transparency</i>	<i>Homogeneity</i>	<i>Total score</i>
<i>A. Individual</i>	0	4	2	1.5	7.5
<i>B. Individual plus</i>	3.5	2	3	1.5	10
<i>C. Construct</i>	3.5	1	1	0	5.5
<i>D. Top-two</i>	1.5	0	0	3	4.5
<i>E. Profiling</i>	1.5	3	4	4	12.5

The option found to be awarded the highest number of points (Method E, Profiling) was taken to be the optimal choice in terms of the features considered, with Method B (Individual plus) the second ranked option.

7. Profiling Method in RIFE

The profiling method has been applied at 10 sites around the United Kingdom in recent RIFE reports (Appendix 7, Environment Agency *et al.*, 2005). Consumption rates for critical profiles have been presented for gaseous/direct, liquid and combined discharge scenarios. Total dose and baseline calculations have been conducted simultaneously in RIFE reports, and a data comparison for combined releases is shown in Table 7. Comparisons thus far are promising, and it is expected that further comparison will be undertaken in the future. At this stage the profiling method has been shown to be a viable and reproducible alternative to baseline dose assessments.

Table 7. Comparison of adult baseline and profiling method (including direct radiation) dose outputs ($\mu\text{Sv y}^{-1}$).

<i>Site</i>	<i>Baseline</i>			<i>Profiling Method</i>
	<i>Direct</i>	<i>Liquid</i>	<i>Terrestrial</i>	
Aldermaston & Burghfield	Bkgd	1.2	2.2	<5.0
Amersham	240	<5.0	17	240
Cardiff	Bkgd	17	18	12
Devonport	N/A	<5.0	<5.0	<5.0
Dounreay	<10	6.6	7.8	11
Hartlepool	<20	<5.0	<5.0	21
Hunterston	<90	10	22	100
Sellafield	Bkgd	630	36	600
Winfrith	Bkgd	<5.0	<5.0	<5.0
Wylfa	<10	<5.0	<5.0	11

8. Conclusions

A reproducible methodology for calculating total doses for comparison with limits resulting from discharges into the environment has been developed and tested. Known as the profiling method or Method E, doses are calculated for a number of consumer profiles across all relevant pathways and food groups determined in the combined habits survey.

It has been shown that the profiling method outperforms other methods (A to D described above) according to the criteria;

- Reproducibility,
- Rigour and realism,
- Transparency,
- Homogeneity.

The methodology has been applied to retrospective dose assessments at ten nuclear sites around the United Kingdom with reasonable success. It is envisaged that further sites will be included as combined habits survey data are collected in the future.

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