The Development of a Methodology to Assess Population Doses from Multiple Sources and Exposure Pathways of Radioactivity

R&D Project P3-070/TR

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Statement of use
To provide a methodology for the Environment Agency to routinely assess and report total radiation doses received by members of the public. It will be of general interest for those organisations undertaking retrospective radiological assessments.

Keywords
Radiation, Dose, Public, Retrospective, Aggregated Total Exposure

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Background

The Environment Agency (EA) has new duties in accordance with the Basic Safety Standards Directive under which it is required to ensure that doses to individuals received from exposure to anthropogenic sources of radioactivity are within defined limits. In order to assess compliance with these requirements, the EA needs to assess the doses to members of the most highly exposed population groups ('critical' groups) from all relevant potential sources of anthropogenic radioactivity and all relevant potential exposure pathways to such radioactivity.

The EA has identified a need to develop a methodology for the retrospective assessment of effective doses from multiple sources of radioactive materials and exposure pathways associated with those sources. Under contract to the EA, AEA Technology has undertaken the development of a suitable methodology as part of EA R&D Project P3-070. The methodology developed under this research project has been designed to support the EA in meeting its obligations under the Euratom Basic Safety Standards Directive and is consistent with UK and international approaches to radiation dosimetry and radiological protection. The development and trial application of the methodology is described in this report.

Main Objectives/Aims

In order to develop a suitable methodology for assessing compliance with the regulatory requirements, the scope of the required assessment procedure was defined through review of the relevant regulatory documents. The scope of the assessment methodology is as follows:

- **Exposure Routes**
  The dose limits apply to doses received from all exposure routes except:
  - exposures to natural radiation;
  - radon in dwellings; and
  - medical exposures.
- **Types of Dose**
  The assessment methodology is essentially restricted to the retrospective estimation of effective dose to representative members of critical groups.

Methodology

The assessment methodology has been developed with a theoretical approach to the definition of critical groups. In particular, the developed methodology differs from previous assessment methods in that the critical groups are defined by their estimated doses (from a range of pathways) rather than from their habits. As such, the critical groups are effectively composites of those that would be defined using a more traditional approach of homogeneity in terms of behaviour affecting the dose that they receive.

The methodology enables assessment of critical group doses from both licensed nuclear facilities (around which significant levels of environmental monitoring and habit survey data are available) and non-licensed sites (around which monitoring data are at best limited and for which critical groups may not typically have been previously identified). To facilitate efficient assessment of sites, such that the level of effort involved in their assessment is

commensurate with their radiological significance, the assessment methodology has been developed as a three-stage process:

- preliminary screening assessment;
- generic regional assessment;
- detailed site/region specific assessment.

The assessment methodology has been used in two trial assessments:

- an assessment of critical group doses local to the BNFL Sellafield facility in Cumbria; and
- an assessment of critical group doses in the EA Thames region due to discharges from both licensed and non-licensed sites in the region.

Results

The trial assessment of the doses around Sellafield produced individual annual effective dose estimates for representative members of the "composite" critical group broadly comparable to the high marine food consumer critical group doses estimated by, for example, the Food Standards Agency. Hence, the application of the new methodology provides confidence that, not only have the key critical group habits previously been identified, but also that the taking into account of multiple sources for a variety of exposure pathways does not lead to the dose limit for the representative member of the critical group being exceeded.

Conclusions

The assessment methodology for licensed sites relies on the availability of sufficient suitable environmental monitoring and habit survey data. In particular, the approach is best served by the availability of integrated habit survey data in which all surveyed individuals provide details of habits that relate to all possible exposure routes. This type of integrated survey has not yet been undertaken and, for the trial assessments reported here, an approach has been developed to show how integrated habit survey datasets may be generated from a synthesis of partial surveys by the use of assumed/derived correlations between habits. Nonetheless, the use of integrated surveys is recommended and it is noted that the main organisations funding the gathering of such data, *i.e.* the EA and FSA, are now moving towards this goal.

For assessment of the individual doses that may result from the discharge of radioactivity from non-licensed sites, a conservative, modelling-based assessment approach was developed. This methodology has been implemented within a spreadsheet format and applied to the Thames region. For the Thames region, it has been demonstrated that, under strictly conservative assumptions, the doses to members of the public comply with the limit on annual effective dose of 1mSv. The implementation of the methodology within a spreadsheet tool facilitates the application of the approach to other regions. Were this to show that doses from certain non-licensed sites or combinations of such sites, challenged the dose limit, then environmental monitoring and the collection of habit survey data would be merited in order to allow a more rigorous assessment to be undertaken (in a manner similar to that for licensed sites). It is noted, also, that the assessment method for non-licensed sites would benefit from future development onto a GIS-based system.

1 INTRODUCTION

The Basic Safety Standards (BSS) Directive [1] has been implemented in England and Wales through the Ionising Radiation Regulations (IRR) and amendments to other existing legislation, such as the Radioactive Substances Act (RSA). A key requirement of the BSS is that member States ensure that doses to individuals received from exposure to anthropogenic sources of radioactivity are within defined limits. Following the implementation of the BSS in England and Wales, the Radioactive Waste Policy Group of the Department of Environment, Transport and the Regions (DETR)[1] recommended that the Environment Agency (EA) should take the lead on assessing and reporting on compliance with these dose limits. In order to undertake these duties, the EA needs to assess the doses to members of the most highly exposed population groups ('critical' groups) from all relevant potential sources of anthropogenic radioactivity and all relevant potential exposure pathways to such radioactivity.

The EA has identified a need to develop a methodology for the assessment of effective doses from multiple sources of radioactive materials and exposure pathways associated with those sources. Under contract to the EA, AEA Technology has undertaken the development of a suitable methodology as part of EA R&D Project P3-070. The methodology developed under this research project has been designed to support the EA in meeting its obligations under the Euratom Basic Safety Standards Directive and is consistent with UK and international approaches to radiation dosimetry and radiological protection.

A phased approach has been adopted as follows:

Task 1	Review Existing Assessment Approaches and Define the Scope of the Assessment Approach to be Adopted
Task 2	Develop the Proposed Assessment Methodology and Deliver an Interim Report
Task 3	Collate Discharge and Monitoring Data
Task 4	Undertake an Assessment using the Proposed Methodology
Task 5	Undertake a Critical Review and Revision of Proposed Methodology and Deliver a Final Report.

This report represents the final project deliverable and describes the outcome of the above tasks. In particular, this report provides:

- A review of the regulatory framework (Section 2);
- An agreed definition of the scope of the required assessment methodology (Section 3);
- A review of existing approaches to dose assessment (Section 4);
- A description of the proposed assessment methodology. The methodology comprises a three-level assessment process. An overview of this process is presented in Section 5 and detailed descriptions of the three assessment levels are provided as follows:
  - A preliminary screening protocol (Section 6);
  - A generic regional assessment methodology (Section 7); and
  - A detailed site/regional specific assessment methodology (Section 8).

[1] Now part of the Department for Environment, Food and Rural Affairs (DEFRA).

- A description of trial applications of the methodologies in the Sellafield region (detailed assessment methodology trial) and the Thames region (preliminary screening and generic regional assessment methodology trials) is provided in Section 9.

2 REGULATORY BACKGROUND

The Environment Agencies[1] have statutory duties and powers under the Radioactive Substances Act 1993 (RSA93) for the authorisation of radioactive discharges from the nuclear industry and from registered 'users' of radioactivity. As required by their role, they strive to ensure that the basic radiation protection standards as set out in Command 2919 [2] are met, and look to the International Commission on Radiological Protection (ICRP) and the National Radiological Protection Board (NRPB) for recommendations on methods and data.

In May 2000, the Department of Environment, Transport and the Regions (DETR, now DEFRA) placed duties on the EA in accordance with the Basic Safety Standards Directive [1] under the IRR and The Radioactive Substances (Basic Safety Standards) Direction 2000 [3]. This direction formalises duties that were previously only implicit in the EA's role. In particular, under the Direction, the EA is required to:

- *Ensure that all exposures to ionising radiation of any member of the public and of the population as a whole resulting from the discharge of radioactive waste are kept as low as reasonably achievable, economic and social factors being taken into account (Article 14)*
- *Ensure that the sum of the doses resulting from the exposure of members of the public to ionising radiation arising from discharges of radioactive waste should not exceed the dose limits set out in Article 13 (e.g. maximum effective dose of 1mSv per year)*

(The role of granting discharge authorisations under the Radioactive Substances Act 1993 [4] was originally performed jointly by the Ministry of Agriculture, Fisheries and Food (MAFF) and the HMIP. Although this responsibility now rests exclusively with the Environment Agencies, the Food Standards Agency (FSA), as successor to MAFF, remains a statutory consultee in the authorisation process. Therefore, in addition to the Environment Agencies, MAFF made, and the FSA now makes, its own assessment of radiation doses to critical groups.)

The UK system of radiation protection and the regulation of radioactive releases to the environment is currently based on the estimation of doses to representative members of critical groups, defined as *'those individuals in the population which receive the highest dose'*. Several habit surveys have been carried out to support the definition of such critical groups by the various parties involved [5, 6, 7].

In the UK, as in most other countries, legislation and regulations relating to protection from ionising radiation are based on the guidance issued by the International Commission on Radiological Protection (ICRP). The most recent basic recommendations of the ICRP are those published in 1991 as ICRP Publication 60 [8].

Dose limits apply to the sum of exposures due to sources associated with all relevant practices. This distinction means that the critical group appropriate to determining compliance with dose limits may not be identical to any of the critical groups defined for the purpose of determining compliance with dose constraints, as such dose constraints are constraints on optimisation applicable to a single source.

[1] The Environment Agencies include the Environment Agency (EA) for England Wales, the Scottish Environment Protection Agency (SEPA) and the Department of Environment for Northern Ireland.

The philosophy underlying the application of the critical group approach in limiting exposure of members of the public to ionising radiation has been clearly set out by the ICRP in Paragraph 85 of their 1977 recommendations [9]. Although these recommendations have been superseded by the 1990 recommendations [8], the underlying principles remain the same. Paragraph 85 is reproduced, in part, below.

> The actual doses received by individuals will vary depending on factors such as differences in their age, size, metabolism and customs, as well as variations in their environment. With exposure of members of the public it is usually feasible to take account of these sources of variability by the selection of appropriate critical groups within the population provided the critical group is small enough to be relatively homogeneous with respect to age, diet and those aspects of behaviour that affect the doses received. Such a group should be representative of those individuals in the population expected to receive the highest dose equivalent, and the Commission believes that it will be reasonable to apply the appropriate dose-equivalent limit for individual members of the public to the weighted mean dose equivalent of this group. Because of the innate variability within an apparently homogeneous group some members of the critical group will in fact receive dose equivalents somewhat higher than the mean. However, because of the maximising assumptions used, the dose equivalent actually received will usually be lower than the estimated dose equivalent.

This view is consistent with that expressed in the 1990 recommendations of the ICRP, at Paragraph 186 and in the context of normal exposures.

> In practice, almost all public exposure is controlled by the procedures of constrained optimization and the use of prescriptive limits. It is often convenient to class together individuals who form a homogeneous group with respect to their exposure to a single source. When such a group is typical of those most highly exposed by that source, it is known as a critical group. The dose constraint should be applied to the mean dose in the critical group from the source for which the protection is being optimized ...'

A key point in the above guidance is the concept of adopting a cautious approach to the dose assessment for a critical group. There is a requirement to use maximising assumptions. The implication seems to be that the dose to the representative member of a critical group will be overestimated to a sufficient degree that, if the **assessed** dose to the representative member is less than the dose limit or constraint, the **actual** doses received by all members of the critical group will be less than the dose limit or constraint. However, the ICRP does not provide guidance in ICRP Publication 26 on how these maximising assumptions should be selected.

The characterisation of critical groups is addressed in more detail in ICRP Publication 43 [10]. The key statements are provided in Paragraphs 67 to 69 of that publication and are summarised below.

- The dose limits are intended to apply to the mean doses in a reasonably homogeneous group.
- In an extreme case, it may be convenient to define the critical group in terms of a single hypothetical individual, for example when dealing with conditions well in the future which cannot be characterised in detail.
- Usually, however, the critical group would not consist of one individual nor would it be very large, for then homogeneity would be lost.
- The size of a critical group will usually be up to a few tens of persons. In a few cases, where large populations are uniformly exposed, the critical group may be much larger.

- In habit surveys, it is not necessary to search for the most exposed individual within a critical group in order to base controls on that one person. The results of a habit survey should be regarded as an indicator of an underlying distribution and the value adopted for the mean should not be unduly influenced by the discovery of one or two individuals with extreme habits.
- In calculating doses to critical groups, metabolic parameters should be chosen to be typical of the age groups in the normal population, rather than extreme values.
- The necessary degree of homogeneity in the critical group depends on the magnitude of the mean dose in the group as a fraction of the relevant source upper bound (or constraint). If that fraction is less than about one tenth, a critical group should be regarded as relatively homogeneous if the distribution of individual doses lies substantially within a total range of a factor of ten, *i.e.* a factor of about three on either side of the mean. At higher fractions, the total range should be less, preferably no more than a factor of three.

Although these principles are helpful, some ambiguities remain. For example, if it is not necessary to seek out the most exposed individual within a critical group, how can it be demonstrated that the distribution of individual doses lies substantially within a factor of ten (or three). The term 'substantially' would seem to imply that some small percentage of individuals could lie outside the acceptable range, but if this were the case, why should a smaller group not be defined that has a higher dose to the representative member and encompasses those individuals within the range. In particular, there would be a strong argument for defining such a smaller group if the highest doses were received in consequence of qualitatively distinctive behaviour by the individuals involved, *e.g.* through consumption of a specific highly contaminated food.

It should also be noted that critical groups are fundamentally defined in terms of reasonable homogeneity of radiation exposure. However, radiation exposure is not directly observable in members of the public. Rather it is calculated, based on the degree of contamination in the environmental materials to which they are exposed and factors such as their age, diet and aspects of behaviour that affect the doses received. In general, critical groups are defined to be reasonably homogeneous with respect to age, diet and behavioural characteristics. However, it seems that a case can be made for defining a composite critical group, including individuals of different ages and substantially different patterns of diet and behaviour, provided that the doses to members of that group conform to the requirement of reasonable homogeneity.

It should also be noted that whereas factors such as age, diet and behaviour are taken into account in defining critical groups, individual variations in radionuclide biokinetics and radiosensitivity are disregarded. Dose limits and dose constraints for members of the public are expressed in terms of effective dose, or committed effective dose for internal exposure. It is normal practice to use standardised compilations of information such as ICRP Publication 72 [11] to relate intakes of radionuclides by ingestion and inhalation to committed effective doses. These compilations are for reference individuals of various ages and hence the estimated doses will not correspond exactly to the actual doses that would be received by real individuals in the critical group with the specified intakes. Furthermore, a single dose limit or constraint is defined for all members of the public in a specific context, without consideration of variations in radiosensitivity between subgroups or individuals within that population. (The issue of individual variations in radiosensitivity has been addressed recently by the

ICRP [12], but there are no recommendations relating to radiological protection that take this factor into account.)

In the UK, the issue of how critical groups should be defined has recently been discussed in a consultation exercise on dose assessments organised by the Food Standards Agency [13]. The genesis of this consultation exercise was a long-standing difference of view between the Radioactive Waste Management Advisory Committee (RWMAC), the operators, and some regulators, and the FSA over how the FSA carries out its dose assessments. Overall recommendations from the consultation exercise relevant to this study are set out below.

- The FSA should make its habits survey data available to all parties.
- The FSA should use rolling averages of at least 5 years' worth of aquatic consumption data to improve the stability of this data set.
- The FSA should re-examine its use of probability distributions of dose. There should be more consistency in gathering survey data and the FSA, operators and EA should co-ordinate their requirements for fieldwork. There should be more consistency in the treatment of data for constructing the aquatic and terrestrial critical groups. The FSA should consider if the latter group needs to be more homogeneous, in line with ICRP recommendations.
- Probabilistic calculations should continue to be explored by all parties, along with the use of scenarios as a useful way of presenting these results to the public.
- The EA and FSA should work more closely with one another on dose assessments. Although there may be some overlap, they should ensure exchange of each other's data and ideas. One group needs to take the lead for total risk assessment, this includes all pathways. As a minimum, the same age groups should be used.
- Pre-existing anthropogenic sources of radioactivity cannot be ignored, and effort should be made to present people's total risk from new, current and past discharges from all controlled sources.
- Data on direct shine need to be included in assessments. The idea of using dose contours around sites should be explored. This would allow individual properties to remain anonymous, whilst facilitating the provision of better information to the public. The industry, Nuclear Installations Inspectorate (NII) and all other agencies need to work towards better provision of data to the public.
- All parties who do dose assessments should collaborate and ensure that their approaches are transparent. The assumptions used in the assessments need to be made clear, as do the steps used to get the final result, so that comparisons can easily be made between the different agencies' approaches. Changes to methods should be made when appropriate knowledge is gained, but should be undertaken in a step-wise fashion, and not continuously. Changes should be explained, published and disseminated.
- The question of exposure of the fetus and babies on breast milk needs to be fully explored and then the decision taken as to whether this needs routine consideration in assessments. There is a need for NRPB to explore and expand on previous work.
- Whole-body measurements of radioactive caesium have shown real exposures to be considerably less than predictions. Further thought is needed on the use of such data in interpreting the output of models. There is also evidence that environmental measurements are sometimes very much at odds with modelling. All groups should

consider whether best use is being made of existing environmental monitoring data in terms of model development.

- The EA, FSA and NRPB should consider setting up a national dose assessment working group that could serve to ensure closer co-ordination between all parties involved. This should be primarily a technical group, and should include operators, as well as other stakeholders, *e.g.* Non-Governmental Organisations (NGO's) and specialists.

These recommendations were taken into account in developing the methodology reported here. However, some aspects, *e.g.* evaluation of exposure of the fetus and babies on breast milk, could not be addressed, as further work is required by other organisations. It is considered that the work reported here will constitute a useful input to any future national dose assessment working group.

3 SCOPE OF ASSESSMENT METHODOLOGY

The aim of the study is to develop an assessment methodology to support the EA in meeting its obligations under the Euratom Basic Safety Standards Directive [1] and the DETR 2000 Direction [3]. (The study also informs the other Environment Agencies of a methodology that they could reasonably adopt.) Furthermore, the assessment methodology needs to be consistent with UK and international approaches to radiation dosimetry and radiological protection.

In order assess compliance with the Dose Limit set out in Article 13 of the Euratom Basic Safety Standards Directive, the EA requires a methodology for the assessment of *retrospective* doses to the public. (As retrospective doses are already committed they cannot be regulated, except through intervention; such doses are assessed mainly in order to confirm, or otherwise, the suitability of existing authorisations and to provide guidance on the setting of new or revised authorisations.) The dose exposure routes to be considered in the assessment against the Dose Limit, are set out in Article 2 of the Euratom Basic Safety Standards Directive as being all exposure routes except:

- exposures to natural radiation (except in special circumstances, such as the production wastes containing Naturally Occurring Radioactive Material or 'NORM');
- radon in dwellings (it may be noted that whilst this is strictly a natural source of radiation, it was felt necessary to explicitly exclude it under the Directive, as it is strongly influenced by human activities relating to construction and ventilation of buildings); and
- medical exposures.

The above definition essentially encompasses all exposures due to releases authorised under the RSA93, but consideration also needs to be given to:

- discharges that are exempted from authorisation but are still covered by RSA93 (*i.e.* they are exempt only from particular provisions of the Act); and
- exposures to anthropogenic radioactivity released from overseas sources (*e.g.* the impact of discharges from Cap de la Hague on the Channel Islands and the South coast of England).

It is unclear whether the BSS requires exposure from historical weapons fallout to be taken into account. However, it is noted that the level of exposure from this route is relatively small and it is has been agreed that distinguishing between the exposure from fallout and more recent discharges is not merited.

In order to provide realistic assessments of effective doses from past releases, the assessment methodology should be, as far as is practicable, based on actual discharges (as opposed, for example, to authorised discharge limits) and monitored levels of anthropogenic radionuclides in the environment within the defined assessment period.

The UK system of radiation protection and the regulation of radioactive releases to the environment is currently based on the estimation of doses to representative members of critical groups, defined as "*those individuals in the population which receive the highest*

dose". Critical groups are not specifically mentioned in the Euratom Basic Safety Standards Directive, but rather Article 1 of the Directive defines the concept of a "Reference Group" as:

a group comprising individuals whose exposure to a source is reasonably uniform and representative of that of the individuals in the population who are the more highly exposed to that source.

This definition, based on the group of *more* highly exposed individuals, appears to be less strict than the critical group definition that is based on the group of *most* highly exposed individuals. Nonetheless, for the practical purposes of this study the definitions of reference and critical groups are considered to be equivalent. It is noted that addressing the most highly exposed individuals is necessarily cautious relative to the more highly exposed individuals.

Article 13 of the Directive sets a Dose Limit of 1mSv/y for "*members of the public*". No explicit guidance is provided in the Directive as to whether the Dose Limit should be interpreted as applying to the members of critical/reference groups or, for example, the Maximum Exposed Individual (MEI) within the population. Furthermore, the DETR 2000 Direction [3] requires that the Dose Limit should be applied to:

"the sum of the doses resulting from the exposure of ***any member of the public*** *to ionising radiation"*

This statement may be interpreted as implying that the requirement is for the assessment of the dose received by the Maximum Exposed Individual (MEI). However, the practical and philosophical difficulties inherent in the identification of the MEI are well known (see, *e.g.* [13]). Consideration of this problem led to the development of the critical group concept and the current UK system of radiation protection and the regulation of radioactive releases to the environment has consistently been based on the estimation of doses to representative members of critical groups. It has therefore been agreed with the EA that, despite the difficulties in interpretation of the Euratom Basic Safety Standards Directive and the DETR 2000 Direction, the assessment methodology should be based on assessment of effective individual doses to representative members of critical groups rather than the MEI. (This approach is consistent with guidance proposed in the DETR consultation paper on guidance on the regulation of radioactive discharges into the environment from nuclear licensed sites [13]).

Under Article 14, the Euratom Basic Safety Standards Directive places a requirement for the exposure of the population as a whole to be kept to As Low As Reasonably Achievable (ALARA). (It may be noted that this is not how optimisation is defined by the ICRP; the ICRP requires that the magnitude of the individual doses, the number of people exposed, and the likelihood of incurring exposures should all be kept as low as reasonably achievable, economic and social factors being taking into account – see Section 2.) However, it has been agreed with the EA that the Directive should not be interpreted as requiring the assessment of collective population doses associated with releases that have occurred. For this reason, collective doses are not explicitly accounted for in the proposed methodology. Nonetheless, collective doses to selected subsets of the population can prove useful in providing information as to the level of exposure around sources of key significance and hence the proposed assessment methodology has provision for a limited treatment of collective dose.

4 REVIEW OF EXISTING METHODOLOGIES

4.1 Overview

The UK system of radiation protection and the regulation of radioactive releases to the environment is currently based on the estimation of doses to representative members of critical groups. Several habit surveys have been carried out to support the definition of such critical groups by the many parties involved [5, 6, 7]. Formal assessment of radiological impact of radioactive waste discharges has historically been undertaken by:

- the Environment Agency (*e.g.* [7]);
- the Ministry of Agriculture, Fisheries and Food (MAFF) (*e.g.* [6]);
- the Health and Safety Executive (HSE); and
- the National Radiological Protection Board (NRPB) (*e.g.* [15, 17]).

(It is worth noting the distinction between the NRPB, which acts in the capacity of both a Non Departmental Public Body and a contract consultancy organisation, and the EA, MAFF/FSA and the HSE, all of which act solely as government organisations.)

The role of granting discharge authorisations under the Radioactive Substances Act 1993 was originally performed jointly by the Ministry of Agriculture, Fisheries and Food (MAFF) and the HMIP. Although this responsibility now rests exclusively with the Environment Agencies, MAFF remained a statutory consultee in the authorisation process until this responsibility was transferred to the newly formed Food Standards Agency (FSA). Therefore, in addition to the Environment Agencies, the FSA makes its own assessment of radiation doses.

Some criticisms of the methodology adopted by the MAFF in relation to the Sellafield discharge authorisation in 1996 were made by the Radioactive Waste Management Advisory Committee (RWMAC) [4]. Although these criticisms relate directly to prospective dose assessments, certain principles, for example aspects of the interpretation of human habit surveys, apply to both retrospective and prospective assessments. For this reason, some discussion on the views of the RWMAC is merited (see also [13]).

In the view of the RWMAC, the methodology adopted by the MAFF for the 1996 discharge authorisation for Sellafield was '*designed to produce an upper bound of possible dose to the most affected population*' [4]. The RWMAC suggested that, in their opinion, this methodology was at variance with both MAFF's previous assessments of authorisations, and its current practice in its published Annual Reports. However, it should be noted that the MAFF/FSA methodology has been evolving. Although the development of the methodology necessarily leads to differences between previous and future assessments, the aim of improving and updating assessment procedures in the light of new information and recent research is obviously desirable.

At present, it is not unusual for three different sets of dose calculations to be carried out, *i.e.* by the operator, one of the Environment Agencies and the FSA, and for these to come up with three slightly different answers as they may be based on slightly different assumptions. This has been viewed by RWMAC [4] as unnecessary and confusing to the general public, not to mention the excessive use of time and resources. However, it should be noted that the

different assessment organisations have somewhat different responsibilities in regard to such assessments and this influences their approach. For example, the FSA carries out its assessments in order to ensure the safety of the public with respect to food, whereas the EA has to consider other issues such as those relating to non-food pathways. Nonetheless, it may be seen to be desirable for the different assessment methodologies to be as consistent as possible in order to avoid unnecessary confusion. In this respect, discussions between the different organisations with regard to consensus on assessment methods, for example through the CEDA process and the proposed national dose assessment working group, offer a useful way forward.

The RWMAC has also expressed concern about perceived gross pessimism in the assumptions made in these dose calculations and they suggest that this practice seems to be a contravention of the basic philosophy of the Basic Safety Standards Directive 96/29/Euratom [1]. However, two points need to be made with regard to this issue:

1. It is not always the case that the degree of caution differs widely between the different assessors; for example comparison of the assessment results for the recent Magnox authorisation processes [14] showed generally reasonable agreement (and, indeed, the MAFF/FSA methodology does not always produce the highest dose estimates).
2. The need for a higher degree of caution in the assessment of prospective doses than retrospective doses can be justified by reference to the inherent uncertainties in future practices and habits as compared with the historical information utilised for retrospective assessments. Nonetheless, certain aspects of the interpretation of available information are important to both prospective and retrospective assessments, particularly in respect to the definition of critical group habits, *e.g.* through interpretation and use of food consumption survey data.

Commentary on the development and application of existing assessment methodologies is provided in Section 4.2.

4.2 Commentary on Existing Assessment Methods

4.2.1 Preamble

Quantifying the radiological impacts from routine discharges of radioactive material from nuclear installations, and industrial and other processes is a long established practice and uses well-developed methods. However, in the past there have often been differences in the calculations performed by operators, regulators and others to estimate these impacts (see also Section 4.1). It has been common for differing methodologies and assessment databases to be used, so that the corresponding estimates of radiological impact have often differed. It is noted that it is not considered necessary for the various organisations to adopt identical methodologies, as a degree of professional independence will serve to strengthen the conclusions of the radiological assessments on the acceptability or otherwise of continuing or proposed practices (as discussed in [13]). Nonetheless, it is always important to present the main methodological features of each assessment, along with the major parameters and assumptions, and it is fair to say that this has not always been done. Notwithstanding what is stated above on professional independence, a degree of agreement on methodological principles would undoubtedly benefit operator, regulator and independent reviewer alike.

Doses to members of the public from discharges should take into account transport of radionuclides in the environment, including migration from one medium to another, together with multiple exposure pathways. These complex and interacting issues have been addressed comprehensively recently by NRPB and MAFF/FSA, to whose reports appropriate reference is made.

As far as is practicable or meaningful, the actual or current doses to members of the public should be estimated through monitoring of environmental concentrations and dose rates in preference to modelling, as modelling results are not always in good agreement with monitoring data [13]. The same principle applies to aspects of individuals' consumption rates and other habits, so that information from surveys of identifiable exposed individuals should be utilised in preference to inferences from national surveys.

Radionuclides discharged to the environment may give rise to radiation doses to members of the public by a number of exposure pathways. These may be classified and grouped as follows:

1. Inhalation of air containing radionuclides arising directly from atmospheric discharges or due to activity in seaspray or material resuspended from the ground.
2. Ingestion of radionuclides in terrestrial and aquatic foods, drinking water and the inadvertent ingestion of radionuclides in soil, sand, sediments and house dust.
3. External irradiation from the installation itself, or due to discharges to atmosphere or water bodies. External irradiation can occur from radionuclide distribution throughout the volume of the environmental media, or from superficial contamination, *e.g.* of terrestrial soils and sediments.

Maximum annual effective doses to members of the public via these pathways from discharge(s) are generally evaluated using the concept of the critical group. The critical group has been defined differently by different organisations, and is described in detail by Robinson [15]. In general, the critical group is intended to be representative of those individuals in the population expected to receive the highest dose (see also Section 2). Until recently, the practice in the UK was to assess doses from the operations of a single site for a single related group of exposure pathways, for example, due to liquid discharges. Where necessary, the overlapping effects of different groups of pathways were considered using deliberately cautious assumptions; in most cases pathway-specific doses were simply added. The NRPB in their study of doses around nuclear sites in the UK [16] considered a range of actual and hypothetical individuals (within groups) who may be exposed at elevated levels. In that study, they concluded that where possible, site-specific habits (including consumption and occupancy) should be used in preference to generalised data, such as can be obtained from national statistics (various relevant surveys are discussed in the FSA Radioactivity in Food and the Environment (RIFE) monitoring report [6]).

Owing to the potential for contamination of several environmental media from any particular discharge (and from other discharges), several potential critical groups may be identified for each site (for example separate critical groups for atmospheric and liquid releases). A substantial complication in the process of critical group identification is that information is very often not available on the *total* habits of individuals, so that the co-membership of more than one 'simple' group (*i.e.* that defined primarily from one set of 'related' pathways, such as local seafood consumers and those with high beach occupancy) is often not known. Also, there may exist groups in which individuals receive elevated doses from the *totality* of their

habits and consumption behaviour, even though no individual constituent of these is characteristic of a highly exposed group. This is an area in which the FSA, in particular, recognises that more information would be of value.

As a practical approach to these issues the NRPB proposed that four groups of individuals should be identified for each installation. Three of the groups are intended to be representative of those members of the public who are most exposed as a result of:

- Aquatic discharges;
- The consumption of contaminated terrestrial foods; and
- The inhalation of, and external dose from, atmospheric discharges together with direct irradiation from the site.

The fourth group was chosen to represent those individuals who may receive higher than average exposure from a combination of pathways, although not in an identified group for any one pathway.

For some sites more than four groups can be postulated, for example in the case of the combination group, where different options may be put forward. Resolution of this imponderable awaits the gathering of further information on total habits, as mentioned earlier.

Each of the exposure pathways listed earlier can then be considered for each group. As pathway additivity is considered in arriving at the total doses to each of the groups, it follows that the total doses to the groups should not be added. Where necessary, a distinction should be made between groups of different ages. In these cases, the contributions from different exposure pathways should be summed for each age group separately and the highest total value for any age group should be used.

An important issue in the identification of individual members' habits is the fraction of the food consumed from local sources, and how to characterise the remainder. The amount of food derived from local sources can be estimated from information provided by the FSA.

Potential assumptions to be adopted in assessing the doses for the four generic groups listed above are made in turn below. A generic approach to the resolution of aggregation over different sources and pathways is developed in Section 8.

Group 1: Individuals most exposed to aquatic discharges

In this case, the best source of information on the identity and characteristics of a group of individuals so exposed is undoubtedly the FSA (although in future integrated survey work will be undertaken by the EA, FSA and NII). The FSA regularly collates catch and consumption statistics, as well as performing detailed habits surveys in the vicinity of nuclear sites. High consumption rates for aquatic foodstuffs are more variable in individual cases than those for terrestrial foodstuffs (see below), and therefore the reliance on local habits surveys, as distinct from deductions from national habits surveys, is necessarily greater.

Where it is judged to be important to add the contribution of doses derived from atmospheric releases, the location of the group is required so that the necessary addition can be

undertaken. Often, the choice between representative home and work locations would have to be made so that the more significant of the two (from an exposure perspective) can be selected. For modelling purposes, locally produced foods should be assumed to be taken from a representative location (the NRPB recommend 5 km from the site), and generalised intakes from publications such as References 5 and 17. Unless specific habit information to the contrary is available, it should be assumed that only a fraction of the total intake of food to group members is derived locally. In their most recent comprehensive study of critical group doses in the UK, the NRPB assumed that 50% of green vegetables and 25% of other foods were obtained from local sources [16]. Non-locally-derived foodstuffs should be assumed to be contaminated with anthropogenic radionuclides at representative UK levels.

Group 2: Individuals most exposed from consumption of terrestrial foods

These individuals are likely to be affected mainly by atmospheric discharges, and are most likely to be members of a local farming community, as farmers will often derive a significant proportion of their food from any localised area (though domestic gardeners and purchasers from farm shops may also be important in this regard). The primary sources of information needed in these calculations on consumption rates and on occupancies (on agricultural land, for example), will be the MAFF/FSA TRAMP and RIFE Reports (*e.g.* [6] and [18]), and, for licensed sites, the monitoring carried out by the operator. Where information on site-specific consumption rates is lacking, the results of more general research [17] should be used. Values selected from general survey results should usually be at a representative high percentile (typically the 97.5th) of national consumption rates for the relevant foods.

In most cases, the members of the critical group will be defined to be situated at the nearest location to the atmospheric discharge where significant agricultural activity takes place. A number of farm locations and practices should be considered, however, and the location that would give the highest dose contribution should be chosen using the RIFE database or using modelling, together with information on the effective dose per unit activity intake for each exposure pathway. If possible, information on the consumption rates and behavioural patterns of individuals should be used. In the absence of such information on total habits, and based upon work funded by MAFF/FSA, the NRPB has suggested that group members should be assumed to consume two foods at the high rates measured or assumed, together with lower rates [17] for the others[1]. This maintains a considerable degree of conservatism whilst avoiding the excessive pessimism, bordering on physical impossibility in some cases, inherent in the previous general practice of assuming that *all* foods are consumed at a high rate.

As for the first Group above, other pathways such as those associated with aquatic foodstuffs and direct radiation should be assessed to judge or quantify their relative contribution to the total individual dose. As for the majority of individual terrestrial foodstuffs, and subject to the specific information available, non-limiting habits and consumptions should be used for these other contributions. In the absence of such information, the NRPB recommended that 10% of the marine or freshwater foods consumed in addition to the terrestrial foods other than those consumed at high rates should be taken to be derived from local sources at 'average' rates [5, 17]. Non-locally-derived foodstuffs should be assumed to be contaminated with anthropogenic radionuclides at representative UK levels.

[1] As Robinson and Simmonds make clear [15], limited information exists on individuals who have above average but not 'critical' habits in this regard. Recent progress in this area is reported in Reference 5.

In summary, therefore, measured concentrations of radionuclides in foodstuffs and known habits should be used if at all possible. In the absence of this, the guidelines reproduced above are adopted in the methodology developed here.

Group 3: Individuals most exposed from (non-agricultural) atmospheric pathways and direct radiation from the site

These pathways are only likely to be significant for a small number of sites that discharge significant quantities of radionuclides to atmosphere or have spatially extensive on-site sources of penetrating gamma radiation, *e.g.* reactors with heat exchangers external to the biological shielding. Owing to the fact that the doses would be delivered at relatively close proximity to the discharge, it is very unlikely that neighbouring discharges could influence the characteristics of these otherwise very site-specific groups of individuals.

Individuals in this group would in all probability comprise those who dwell nearest to a site and/or spend time working close to a site. To preserve sufficient additivity over pathways, it would be necessary to add the contribution from local foodstuff consumption. Survey information should be used to inform the decision as to whether the consumption rates could be significantly more than 'average values'. To preserve a degree of caution, in the absence of specific information, agricultural produce should be assumed to be derived from about 5 km from the discharge (or elsewhere if there is a neighbouring site). Unless specific information exists or can be gathered, the fraction of the individual's consumption derived locally should be as for aquatic pathways above (50% for green vegetables, 25% for others). Non-locally-derived foodstuffs should be assumed to be contaminated with anthropogenic radionuclides at representative UK levels and be consumed at levels appropriate to the specific situation [5, 17].

Group 4: Individuals most exposed from a combination of pathways

The individuals within this general category are those who would receive higher than average doses from a number of pathways, but would not be considered to be in the most exposed group for any particular exposure pathway or group of related pathways. These groups present a significant problem, as in general the specific lifestyle information required to characterise their consumption habits is not available. As a result, a number of 'candidate' consumption rate combinations have to be proposed. Being largely hypothetical, numerous combinations of non-extreme habits and consumption behaviours could be postulated for each site, and indeed, where the influences of sites overlap radiologically, potentially for a number of locations within each region. Hence iteration is often required to define a meaningful number of potential groups. It should be possible to formulate several combination groups from the information used to characterise the components of Groups 1-3, but a degree of uncertainty will always remain as to whether the full range of possible combinations has been explored adequately.

In their study of critical group doses around nuclear sites in the UK, the NRPB found [16] that, in general, one or more of the representative combination groups was located in the urban or residential areas nearest to a site. What was stated previously about the overlapping nature of potential radiological impacts from two or more discharging sites applies here also, so the focus of the search for combination groups should not be confined to the vicinity of individual sites, although the most significant pathways for each site (see Groups 1-3) provide a good basis for constructing combination groups for individual sites.

The habits used to formulate such combination groups should, if at all possible, be derived from site or region-specific data. Examples of combination groups are wildfowlers and anglers, who can have high occupancies in key locations (those that lead to elevated doses due to relatively high concentrations of radionuclides in environmental media), may consume their quarry and also share in above-average consumption of other locally-derived foodstuffs.

In the context of 'multiple sources' a more general approach is taken, that recognises individuals may utilise several different domains (or resource areas) which could be contaminated to different degrees by a single source. Each domain may also be contaminated by a number of separate sources of distinct types, for example crops in a particular domain may be contaminated from atmospheric releases due to deposition, and by releases to rivers due to irrigation with abstracted river water.

4.2.2 Degree of Caution in the Calculation of Annual Doses

One of the most problematic issues in the estimation of public doses from discharges of radionuclides to the environment, and one that frequently results in differences in the dose assessments conducted by operators, regulators and other parties is that the degree of caution assumed differs widely. (However, it is noted that this not always the case and, for example, comparison of the assessment results for the recent Magnox authorisation processes showed generally reasonable agreement between the different assessors.)

It is clearly important that annual doses to members of the public are not underestimated when comparing with statutory limits. However, for retrospective dose assessments, gross pessimism is not justified, either in the habits and consumption rates adopted for hypothetical individuals, or in the plausibility of exposure pathways or their combination. The need for realism applies to all stages of the dose assessment, comprising the estimates of discharges and levels of direct irradiation, the modelling of pathways by which individuals are exposed, and the assumptions made concerning the location, habits and characteristics of those exposed [21]. The requirement for realism is important where doses are added and compared with one another. Although calculations based on observed behavioural patterns are important, it is necessary that assessments based on the critical group approach should also cover a selection of alternative combinations of *feasible* pathways of exposure of individuals with reasonable overall patterns of habits and behaviour (see also [13]).

The issue of caution in radiological assessment is also relevant in another area, namely where hypothetical exposures are estimated on the basis of pathways that may not be 'active' currently (possibly having been so in the past, as was the case of the laverbread consumers for Sellafield liquid discharges), or those whose existence has only recently been discovered (such as the recent discovery of the contamination of birds nesting in facilities at Sellafield). No general guidance can be offered in most of these cases, other than to bear in mind that standard radiological assessments should always be supported by more detailed studies on the possibility of previously unknown significant exposure of members of the public. An important principle here is that discharge dose assessments in the UK are mostly conducted to provide estimates that are relevant over the next few years at most. In this context, highly unlikely exposures, or those that may occur at some considerable time in the future due to changes in habits, are not of interest.

In estimating public doses, it is important that all potential pathways are at least identified. The difficulties of achieving this are evident from earlier sections of this report. Assessors, therefore, should never rely exclusively on existing habits surveys and should always seek to identify previously undisclosed habits and consumption patterns that could lead to elevated doses. Potential habits that do not currently exist, but that could easily be initiated in the specific environmental context, need also to be identified. This task could be fulfilled through conducting scenario analyses and structured brainstorming by groups of experts (who should include those with local knowledge) from a range of fields.

4.2.3 Assessment Tools

As well as agreeing the scope of the dose assessment and the information on which this would depend, assessment tools have to be selected to perform the large number of calculations involved. These should represent the movement of radionuclides in the environment (including transport between media), and quantify radiation doses to members of the public via a number of exposure pathways. As elsewhere, a balance has to be sought between robustness, comprehensiveness and usability.

In the absence of detailed information requiring an alternative approach, the European Union-sponsored computer suite PC-CREAM [24] would seem to represent a good basis for conducting most of the calculations required for discharges to atmosphere, to rivers and to the coastal marine environment. It utilises well-established models and has been subjected to a stringent quality assurance programme. However, some limitations on the range of radionuclides represented have been identified in this study. More detailed atmospheric assessments may require the use of ADMS [19] and direct exposure codes, and assessments in which cross-media transport is significant may require additional calculations. In particular, specialist assessment models may be required to model radionuclide transport through certain pathways, *e.g.* discharges to sewers, application of sewage sludge to agricultural land and the use of surface waters for crop irrigation and cattle watering.

4.2.4 The Approach Adopted in This Study

A detailed approach as to how the aggregated radiological impacts from a range of different sources and exposure pathways may be assessed is set out in Section 8. This methodology takes a generic approach to the development of both ‘traditional’ types of critical groups (*i.e.* groups 1 to 3 in Section 4.2.1) and ‘combination’ critical groups.

5 OVERVIEW OF METHODOLOGY DEVELOPMENT

5.1 Introduction

Radioactive material discharged to the environment will be dispersed by a variety of natural processes, and will lead to the exposure of members of the public at a range of locations and over an extended period [20]. Radionuclides migrate from one medium to another, so, for example, radionuclides initially discharged to atmosphere may enter terrestrial foodstuffs and deliver doses by ingestion, or radionuclides discharge to a river may become associated with sediments, be resuspended and then inhaled. Individuals will therefore always receive radiation doses from a number of exposure pathways, through the contamination of a number of environmental media. A further complicating factor in the task of estimating public doses is that individual members of the public will be exposed (albeit at widely differing levels) to releases from more than one discharging site.

One important objective of any overall assessment methodology is to identify individuals (who could be actual or hypothetical) whose location, habits and behaviour lead to their receiving the largest doses, and to evaluate these doses. Here and throughout the term "dose" is used as shorthand for effective dose.

The specific objective of the methodology development reported here was to go beyond this general principle and focus on the issue of aggregating across individual sources (discharges) as well as exposure pathways, as these issues are widely judged to present some of the greatest challenges to ensuring consistency between different methodologies.

The major concerns of this study were therefore to formulate methodological principles on how to address the following topics:

- Multiple sources – specifically those additional sources that would have to be considered for each site-specific assessment and those that can effectively be ignored;
- Multi-media transport – specifically how discharged radionuclides could expose members of the public to a significant degree via a range of pathways;
- Range of habits – specifically how (and to what degree) actual or hypothetical individuals may receive radiation doses from a number of potential exposure pathways;
- Degree of caution in the calculations – how far and to what degree pessimistic assumptions should be adopted in the estimation of doses.

The methodological principles that have been developed acknowledge the limitations that will always be imposed by lack of data, but indicate how best use may be made of available information, as well as identifying the areas in which further data would be most beneficial.

Guidance on methodological principles, as given in this report, should be seen as complementary to expert opinion. In very many cases the application of the advice will depend on the knowledge and experience of the individual assessor to ensure appropriate application of the advice in a specific context. The intention is not to impose inappropriate uniformity, but to minimise unnecessary divergence in the methods used to estimate public doses in complex situations.

5.2 Methodological Principles

5.2.1 Radiological Criteria

When considering the radiological criteria to be employed for discharge assessments, the extant advice of NRPB should be followed [21]. For individual proposed controlled sources (such as discharges), the annual effective dose to members of the public should be *constrained* to be no more than 0.3 mSv, and optimisation should be used to lower the actual annual dose as far as possible below this value. Where possible, existing sources should also be constrained by this value, although the NRPB recognises that some existing practices may be unable to comply for a variety of reasons. Doses to members of the public from anthropogenic sources (excluding medical exposures) should be subject to a statutory *limit* of 1 mSv.

When considering the *predicted* radiation doses to members of the public from *projected, single sources*, the former criterion is appropriate, whereas when considering the *actual* radiation doses that currently arise from *all existing discharges*, or from the combination of projected discharges with existing ones, the latter criterion should be used.

It is emphasised that the assessment methodology developed in this study is for retrospective assessments. Constraints on individual sources are used in the context of optimisation and ongoing control of discharges from current and proposed practices, so they are not directly relevant to this work.

5.2.2 Radionuclide Concentrations in Environmental Media

In estimating actual or hypothetical doses to members of the public, concentrations in foodstuffs and other environmental media are used. Such concentrations may be obtained by measurement (for existing practices) or by modelling prediction. All of the literature reviewed (notably the major NRPB [16] and MAFF [6] studies) support the view that, for existing sources, if at all possible, representative environmental monitoring should be used, and natural background levels of radionuclides in the environment should be subtracted. Doses to members of the public can then be constructed on the basis of a combination of monitored radiation levels (such as over river or beach sediments) and monitored concentrations (such as in dust or foodstuffs). Such values necessarily include the contribution from past discharges. Where environmental levels are below the threshold of quantification, are otherwise indistinguishable from fluctuations in natural levels, or monitoring data are unavailable, mathematical models should be used. (Mathematical models may also be used where monitoring data are available for purposes of interpolation and extrapolation, for example where incomplete datasets are collected in each year or forward projections of impacts of past discharges are required.)

It should be noted that this is a general principle that can be applied independently of others within the methodology.

5.3 Overview of the Assessment Methodology

The assessment methodology has been developed with a theoretical approach to the definition of critical groups. In particular, the developed methodology differs from previous assessment methods in that the critical groups are defined by their estimated doses (from a range of pathways) rather than from their habits. As such, the critical groups are effectively composites of the critical groups that would be defined using a more traditional approach.

The methodology enables assessment of critical group doses from both licensed nuclear facilities (around which significant levels of environmental monitoring and habit survey data are likely to be available) and non-licensed sites (around which monitoring data are at best limited and for which critical groups may not typically have been previously identified). In order to assess compliance with the BSS dose limits, it is required that the release of radioactive material from all licensed and non-licensed sites is considered. However, the number of such sites is large and to facilitate their efficient assessment it is important that the level of effort involved in their assessment is commensurate with their radiological significance. In order to achieve this, the assessment methodology has been developed as a three-stage process:

- **Preliminary Screening Assessment**

  A preliminary screening protocol has been developed in order to identify those sites that may merit more detailed assessment. As such, the data requirements for the preliminary screening protocol are limited and, as far as is reasonable, are based on conservative, generic data. It is likely that only the non-licensed sites will be subject to the screening protocol, as the licensed sites will typically be carried forward to the next assessment phase directly. The details of the screening protocol are described in Section 6.

- **Generic Regional Assessment**

  Those sites that are identified for more detailed assessment following the preliminary screening process are assessed on a generic regional level. The generic regional assessment will enable a more detailed assessment based on more specific data regarding the nature of the radiological releases and the physical characteristics of the receiving environment. However, the generic regional assessment does not require detailed information regarding either the composition or habits of the critical groups (generic assumptions are made), nor monitored levels of radioactive contamination in the environment (modelling is undertaking using simple, conservative approximations). The generic regional assessment methodology is described further in Section 7.

- **Detailed Site/Regional Specific Assessment.**

  Those sites meriting detailed assessment are identified either because they are licensed sites or following the generic regional assessment. The detailed assessment has greater data requirements. In particular, it utilises environmental monitoring data for contamination levels in the environment (in terms of either radionuclide concentration levels in media or external dose rates at certain locations) and habit survey data for relevant individuals. For licensed sites, the identification of the relevant individuals and environmental media required for monitoring purposes will be reasonably well understood and will be based on the "traditional" critical groups identified for these sites in existing studies undertaken by, for example, the EA and the FSA. For non-licensed sites, the results of the generic regional assessments will help guide the identification of such

individuals and media, though further studies may also be required. A full description of the detailed assessment method is presented in Section 8.

An overview of the three-stage assessment process is provided diagrammatically in Figure 1.

6 PRELIMINARY SCREENING METHODOLOGY

In order reduce the scale of the overall assessment in terms of the number of sources analysed in detail, a screening process is adopted whereby only those sources that may potentially lead to significant doses are subject to full assessment. In this screening process, simple scoping calculations are made to estimate the doses received by potential critical groups for each identified source. The estimated critical group dose for each source is then compared with a pre-developed dose criterion and, any source for which the estimated critical group dose is less than the criterion value is excluded from further consideration. To provide confidence that none of screened out sources may lead to significant doses, either relative to dose limits or relative to estimated doses from more major sources, it is necessary that:

- the scoping estimates of dose to a representative member of a critical group are based on cautious assumptions of both critical group behaviour and the transfer of released radioactive material in the receiving environment; and
- the dose criterion against which the scoping estimates are compared needs to be developed through consideration of:
    - the dose limit for members of the public over all controlled practices and sources (*i.e.* 1 mSv/yr);
    - the level of dose at which uncontrolled releases of radioactive materials would be acceptable (around 0.01 mSv/yr); and
    - the estimated critical group doses due to exposure from other, more major, sources (*e.g.* licensed nuclear facilities).

Additionally, the aggregated effects of screened sources also need to be considered. Thus, the screening protocol cannot merely consider the impacts of the various sources in isolation. Rather some system of aggregation across the sources is required, where appropriate. The proposed method of assessing individual doses for each source in isolation is described below in Section 6.1 and the methods for aggregating different sources is detailed in Section 6.2.

6.1 Assessment of Doses from Single Sources

For each source under consideration, a simple assessment is made of the dose received by the representative member of the critical group. This assessment uses cautious assumptions regarding the habits and location of the critical group, the characteristics of the receiving environment and the transfer of the released radioactive material through this environment. Methods are set out for the assessment of both atmospheric and liquid discharges[1] and these are described below in turn. For each type of release, the proposed method for estimating the critical group dose from each source in isolation is broadly analogous to the approach of Burholt [27] and the methods by which the Generalised Derived Constraints (GDCs) have been developed [22] (though the assessment methodologies outlined here differ from the GDC methods in that the estimated doses are placed in the context of a screening criterion other than the Dose Constraint).

[1] In the present methodology direct shine exposure routes have been omitted as generally negligible for such sites.

6.1.1 Atmospheric Releases

Critical group doses are based on generic characteristics of both the representative member of the critical group and the behaviour of the released radioactivity in the environment. Doses from atmospheric discharges are considered to result from:

- internal irradiation from inhalation of airborne radionuclides;
- external irradiation from radionuclides in the release plume;
- external irradiation from radionuclides deposited on the ground;
- internal irradiation from inhalation of deposited radionuclides resuspended into the air;
- internal irradiation from ingestion of radionuclides in terrestrial foods.

(Doses may also occur from contamination of potable water supplies. However, the contribution to drinking water contamination from atmospheric deposition is considered to be negligible in comparison to either the pathways listed above or in comparison to the liquid discharge pathways considered in Section 6.1.2.)

The doses from the above exposure pathways were estimated assuming a unit release rate from 15m release height using the PC CREAM assessment tool. The members of the critical group were assumed to reside (at 100% occupancy) 300m from the release point and to obtain all of their food from an area 500m from the release point. The air and ground concentrations at 100m and 500m were estimated assuming frequency weighted Pasquill meteorological categories and a uniform windrose. The food transfer factors (used to estimate the concentrations in different foodstuffs) and the ingestion rates are based on default data within PC CREAM. The basis of assessment for the aerial discharges is summarised in Table 1. The dose rates per unit aerial release rate used in the preliminary screening protocol are presented in Table 2 for a range of radionuclides.

The above dose assessment is made for unit release rates of a range of radionuclides. The overall dose to a representative member of the critical group for any individual source is then estimated by scaling the unit release rate doses by the actual release rate and then summing over all pathways and radionuclides of interest.

6.1.2 Liquid Discharges

Critical group doses are based on generic characteristics of both the representative member of the critical group and the behaviour of the released radioactivity in the environment. Doses from liquid discharges are considered to result from[1]:

- internal irradiation from ingestion of radionuclides in drinking water;
- internal irradiation from ingestion of radionuclides in freshwater fish;
- external irradiation from radionuclides deposited on river sediments;

[1] Dose pathways arising from land irrigation with contaminated water and liquid discharges to estuaries and the marine environment have not presently been included in the assessment methodology (either the preliminary screening protocol or the generic regional assessment methodology). However, these may be incorporated into the methodology presented here following, for example, the assessment methods of Burholt [27].

- irradiation of sewage workers due to:
  - external irradiation from radionuclides in sewage sludge stored in tanks;
  - internal irradiation from inhalation of radionuclides resuspended from sewage sludge;
  - internal irradiation from inadvertent ingestion of radionuclides in sewage sludge;
- irradiation due to application of sewage sludge to land:
  - external irradiation from radionuclides in the soil;
  - internal irradiation from inhalation of radionuclides resuspended from soil;
  - internal irradiation from ingestion of radionuclides in plant products;
  - internal irradiation from ingestion of radionuclides in animal products.

The doses from direct discharges to rivers are estimated by making broadly cautious assumptions on river characteristics compatible with the river being acceptable to receive discharges and using the PC CREAM assessment tool. In particular, the volumetric flow rate of the receiving river is taken to be $1m^3/s$. All exposures to the critical group are based on rates of occupancy, fish abstraction and water (potable and irrigation) abstraction at a point 1000m downstream of the release point. The utilisation rates for river reaches are presented in Table 5.

Doses to workers at the sewage treatment plant are estimated using the method on McDonnell [26]. Doses arising from the application of contaminated sludge to agricultural land are estimated following the method of Burholt [27]. The basis of estimation of doses from the discharges to sewage treatment works is summarised in Table 3.

The above dose assessment is made for unit release rates of a variety of radionuclides. The overall critical group dose for any individual source is then estimated by scaling the unit release rate doses by the actual release rate and then summing over all pathways and radionuclides.

6.2 Aggregation of Doses

The aim of the preliminary screening process is to ensure that the aggregated effect of the releases of radioactive material from the screened-out sources on the dose received by representative members of any critical group does not exceed a pre-specified criterion. In other words, in order to ensure that the exclusion of sources does not lead to significant underestimation of individual doses, the maximum aggregated effective individual dose to the representative critical group member from the excluded sources should not exceed a set value, say D_{TL}. A value of 60μSv/yr was adopted for D_{TL}, as this is approximately the lower bound of the estimated doses to critical group members from releases at licensed sites found in previous studies (*e.g.* [16]). Additionally, in the current methodology, it is suggested that the doses estimated from the aerial, liquid (directly to rivers) and sewage discharge routes are conservatively aggregated. This is unlikely to be the case in practice and the threshold of optimisation of 20 μSv/yr can be applied to each of these disposal routes separately, giving a combined total of 60μSv/yr. Although, this combined value was adopted for the current study, a different value of D_{TL} might be selected for future implementation of this R&D. Alternatively, a screening dose rate of say 20μSv/yr could be applied separately to each discharge route.

The adopted approach to aggregating the dose impacts of releases from non-licensed sites is three-phase:

1. aggregation of dose impacts from atmospheric releases;
2. aggregation of dose impacts from liquid discharges;
3. aggregation of dose impacts from atmospheric and liquid releases.

6.2.1 Atmospheric Releases

The individual dose to representative members of the critical group associated with a particular source is cautiously assessed in the manner described in Section 6.1. For a particular release, the dose received by the representative members of the critical group, D_A (Sv/yr), may be estimated using this method. In order to justify the screening of all sources with releases that lead to individual doses to the representative member of the critical group of less than or equal to D_A, the aggregated effect of all such sources on the representative member of the critical group associated with the target source must be less than the dose screening criterion (*i.e.* less than D_{TL} Sv/yr).

Those sources for which the individual dose to a representative member of the critical group associated with the target source is $\leq D_A$, are termed the "exclusion sources" as these are the sources to be screen out. Consider one particular source, denoted the "object source", and also denote the associated critical group as the "object group". The requirement is to assess the aggregated individual dose impact of all the exclusion sources on a representative member of the object group.

Under the assessment methodology described above, the individual doses to the members of the object group that result from the object source are due to doses received from the environment within a 500m radius from the source. Therefore, the critical groups for exclusion sources within a 1km radius of the object source may overlap in terms of location and resource utilisation, with the object group. Thus, the dose received by members of the object group from any one exclusion source within the 1km radius will be no more than D_A. The aggregated impact of all such exclusion sources on the object group will be less than or equal to the product of N_A and D_A, where N_A is the number of exclusion sources within a 1km radius. Note that these exclusion sources include the object source.

In order to assess the impact of the exclusion sources located beyond the 1km radius, it is cautiously assumed that the dose received at distances beyond 500m declines proportionally to the decrease in ground-level air concentration. The annual average air concentration, C (Bq/m^3) at a distance r from a single exclusion source may be estimated using the 'R91' Gaussian dispersion model [23]. The R91 estimates of C may be reasonably fitted to a power function of the form $C = ar^b$. For a ground-level unit release rate into a uniform windrose and with a 50% frequency of category D conditions, the constants a and b may be taken as a=0.018 and b=-1.55.) The ratio of the dose rate at distance r (m) to the dose rate at 500m is given by $(r/500)^b$.

The aggregated effect of the exclusion sources lying beyond the 1km radius on the individual doses received by members of the object exclusion group is then estimated by making assumptions regarding the density of exclusion sources beyond 1km. Assuming that such sources are uniformly spatially distributed and that the density of the exclusion sources is ρ_A (sites/m^2) then the total aggregated dose to a representative member of the object group from all exclusion sources, D_{AT} (Sv/yr), is estimated by:

$$D_{AT} \leq D_A \, (N_A + M_A)$$

where M_A is given by:

$$M_A = \frac{2\pi\rho_A}{500^b} \int_{1000}^{R} r^{(b+1)} dr$$

and R is the furthest radial distance (m) to be considered. (It is noted that as B>-2, M_A does not converge at large R and hence a cut-off distance is required.)

This approach is shown diagrammatically in Figure 2.

6.2.2 Liquid Discharges

The individual dose to the representative member of the critical group for an individual site is cautiously assessed in the manner described in Section 6.1. For a particular release, the annual effective dose received by the representative members of critical groups for releases to surface waters D_W (Sv) and to sewage works D_S (Sv), may be estimated using these methods.

For releases to rivers, it is cautiously assumed that the doses received at downstream distances beyond 500m (the distance at which doses are assessed) decline proportionally to the reduction in water concentration. Assuming that the density of discharges to a reference river reach is ρ_W (sites/m), then a simple approximate method for aggregating the effects of a number of river discharge sites is:

$$D_{WT} \leq D_W \cdot M_W$$

where: D_{WT} is the total aggregated annual individual dose to the representative member of the critical group (Sv);
D_W is the individual dose received by members of the critical group for a single discharge source (Sv) at a downstream distance of 500m from that release; and
M_W is given by:

$$M_W \leq \frac{\rho_W}{C_W} \int_{500}^{L} C(x) dx$$

where C_W is the water concentration at a downstream distance of 500m from a single discharge source (Bq/m^3);
$C(x)$ is the water concentration at a downstream distance of xm from a single discharge source (Bq/m^3);
L is the furthest distance (m) to be considered (*i.e.* the length of the river upstream from the location of the critical group).

For discharges to sewage works, the dose from the exposure routes associated with ultimate discharge to rivers is estimated as part of the river discharge calculations above. However, individual doses from the other sewage release exposure routes are aggregated over different sources discharging to a single sewage treatment works as follows:

$$D_{ST} \leq D_S N_S$$

where D_{ST} is the total aggregated annual individual dose to the representative member of the critical group (Sv);
D_S is the annual individual dose received by a representative member of the critical group for a single discharge source to the sewage works (Sv);
N_S is the number of sources discharging radioactive material to the sewage works.

6.3 Development of Preliminary Screening Criteria

The total aggregated effect of all screened-out sources on the individual doses received by representative members of any critical group must not exceed the limiting value of D_{TL}. Aggregating the individual annual doses from discharges to atmosphere, rivers and sewage works by simple summation, leads to the following constraint for the cut-off criteria for doses from these types of releases:

$$D_A(N_A + M_A) + D_W M_W + D_S N_S \leq D_{TL}$$

In the present assessment a value of 60μSv/yr is adopted for the screening criterion D_{TL}. However, as noted earlier, in reality, doses from the above three pathways may not be additive to any single critical group. Hence an alternative future approach would be to screen each pathway separately against a screening dose rate of 20μSv/yr.

7 GENERIC REGIONAL ASSESSMENT METHODOLOGY

7.1 Introduction

Those sites that are identified for more detailed assessment following the preliminary screening process are assessed on a generic regional level. The generic regional assessment is a more realistic assessment based on more detailed data regarding the nature of the radiological releases and the physical characteristics of the receiving environment. However, for most of the sites to be assessed at the generic regional level, for example non-licensed sites, little information will exist regarding the composition or habits of the critical groups or the associated relevant geographical areas (*i.e.* the areas or "domains" where the critical groups may access contaminated environmental media).

Therefore, within the generic regional assessment methodology, the critical group habits and the location and level of utilisation of relevant environmental domains and media are based upon generic assumptions. These assumptions are described in Section 7.2. Furthermore, the estimation of the doses that arise from the utilisation of these domains is based on model estimates of the levels of contamination in the environmental media within these domains (rather than monitoring data). The assessment of doses is described in Section 7.3.

The generic regional assessment considers the same basic exposure pathways as the preliminary screening protocol, namely exposures from discharges to atmosphere, rivers and sewage treatment works. The selection of exposure routes currently included in the methodology reflects the nature of the trial application undertaken and reported in Section 9. However, it is noted that other pathways, such as those relating to discharges to estuaries and the marine environment and also the use of irrigation water may be usefully incorporated into the methodology in future.

7.2 Assumed Critical Group Behaviour

For non-licensed sites, critical group composition and behaviour and the associated relevant geographical areas (*i.e.* the areas or "domains" where the critical groups may access contaminated environmental media) will typically not have been previously identified. Access to the environmental media within these domains by individuals is generally not known and hence conservative assumptions have to be made. The utilisation of the domains adopted for the generic regional assessment methodology considers each spatial element on a 1km grid. It is assumed that individuals residing at each grid element:

- consume food grown at that location at the rates defined in Table 5;
- have occupancies as defined in Table 5;
- utilise the nearest river reach provided that the reach is within some pre-defined distance of the residence location. In the trial application of the methodology, it is assumed that rivers within a distance of 20km are utilised and further that their utilisation is as defined in Table 5.

It is further assumed that food grown at the location is contaminated by aerial discharges from any distance and the application of contaminated sludge from any sewage treatment works within an fixed radius (for the current study it is assumed that sludge may be applied out to a radius of 10km from the works).

The basis of the assessment described above applies to general members of the public. However, for non-licensed sites, releases are often made to sewage treatment works and doses to workers at those works are of potential interest. Therefore, dose estimates are also made for such workers (who are also members of the public, as they are not classified as being occupationally exposed). These are undertaken by assuming that the workers receive both doses from their place of work (due to exposure to contaminated sludge) and at their place of residence. To achieve this, it is assumed that workers reside within a pre-defined distance from the sewage treatment works (for this study, this distance was taken to be 30km). The total dose received is then the sum of the dose received at the sewage treatment works and the dose calculated for the residence location (see above). The spatial ranges over which doses from rivers and sewage treatment works extent are shown in Figure 3.

The contamination levels in the environmental media in these domains are generally not monitored and hence modelling is required. The methods for estimating these concentrations (and dose rates) are described below.

7.3 Estimation of Doses

For each type of discharge considered (*e.g.* to atmosphere, sewer, or river), the long-term degrees of dilution can be readily evaluated using established models, or methodologies. The methods of estimating radionuclide concentrations following releases to atmosphere, rivers and sewage treatment works have been developed in order to be broadly consistent with existing methodologies produced for the EA and the FSA, such as [25] and [27], and to utilise industry standards tools (such as PC CREAM [24]) where available. The methodologies are now described in turn:

7.3.1 Aerial Releases

Doses due to aerial releases of radionuclides from non-licensed sites are assessed using the NRPB/EC Consequence of Releases to the Environment Assessment Methodology software tool PC CREAM [24], the modelling for which is largely defined by Simmonds *et al.* [20]. PC CREAM is used to calculate doses per unit release rate for a variety of radionuclides. For the terrestrial food consumption pathways (see Table 5 for the considered food types and assumed consumption rates), the calculated doses are based on the consumption of foods grown at a distance of 500m from the release stack.

For all other pathways (*i.e.* inhalation, resuspension, groundshine and cloudshine) doses are calculated at a distance of 300m from the release stack. All doses within a 1km radius of the site are then assumed to be equal to the doses at these calculated distances. For distances beyond 1km, the doses are assumed to decline proportionally to $(r/1000)^{-1.55}$ where r (m) is the radial distance from the release stack. The general basis of assessments for aerial discharges from non-licensed sites is summarised in Table 1.

Doses at each grid point from aerial releases of all radionuclides and from all release sites are then estimated by summing over the doses calculated at that grid element from each release.

7.3.2 Liquid Releases to Rivers

Doses from liquid releases to rivers are estimated using the PC CREAM river discharge model. Dose per unit release rate values are calculated for a variety of radionuclides from the following pathways: consumption of edible fish; consumption of drinking water; and bank residence. The doses are calculated for a distance 1km downstream from the release point and are based on the utilisation rates presented in Table 5 and a mean annual river flow rate of $1m^3/s$. In order to calculate the doses in an actual receiving river reach, the doses per unit release for a $1m^3/s$ flow rate are multiplied by the actual release rate and divided by the actual river flow rate. The doses calculated for the 1km distance downstream of the release point are applied to the whole river reach. Doses in subsequent river reaches are calculated (as consistent with Simmonds [20] and Venter [25]) from:

$$D_i = \frac{D \cdot F}{F_i} \cdot \exp\left(\frac{-\lambda \cdot x}{v}\right)$$

where
D is the dose rate in the first reach (Sv/y per Bq/y);
D_i is the dose rate in the i^{th} reach (Sv/y per Bq/y);
F is the flow rate in the first river reach (m^3/s);
F_i is the flow rate in the i^{th} reach (m^3/s);
x is the downstream distance from the first reach to the i^{th} reach (m);
v is the river velocity (m/s); and
λ is the decay constant for the radionuclide under consideration (s^{-1}).

Doses from multiple releases to a river system are estimated by summing over the doses calculated for each release in each river reach.

7.3.3 Liquid Releases to Sewers

Two types of dose are predicted for releases to sewers: doses to workers at the sewage treatment works; and doses resultant from application of sewage sludge to agricultural land.

Dose rates per unit release rate of various radionuclides have been calculated for workers at the sewage treatment works following the methodology outlined in [26] (this is consistent with the approach adopted by Burholt [27]). Under this methodology, doses are assumed to result from:

- inhalation of re-suspended solids;
- inadvertent ingestion of solids;
- external doses arising from gamma emitting radionuclides in sewage (assuming a semi-infinite slab source as being representative of an open sewage tank).

The dose rates are calculated for unit release rate of each radionuclide and for an assumed sewage flow to the works of 1 m^3 per day. Worker dose rates for an actual sewage treatment works are then estimated by multiplying this dose rate by the actual radionuclide release rate and dividing by the actual sewage flow.

Dose rates from application of sewage sludge to land are calculated per unit release rate of various radionuclides to a normalised sewage treatment works with a sewage flow of $1m^3$ per day following the methodology of Burholt [27]. Dose rates for a variety of radionuclides have been taken from [27]. The sludge application doses for an actual sewage treatment works are then estimated by multiplying these dose rates by the actual radionuclide release rate and dividing by the actual sewage flow at the works. The basis for the calculation of the doses associated with the sewage treatment works and sewage sludge application is summarised in Table 3.

The dose rates per unit liquid discharge utilised in the preliminary screening protocol are presented in Table 4 for a range of radionuclides.

7.3.4 Aggregation of Doses

The maximum individual annual dose across all the considered grid elements is calculated by summing over all the relevant pathways. Two types of maximum dose are calculated:

- the dose to members of the general public – this is calculated by summing over all pathways except those associated with sewage treatment workers;
- the dose to sewage treatment workers (who are also members of the public) – this is calculated by summing over all pathways including the worker doses, but is only performed for grid elements within the required distance of the STW (*i.e.* 30km).

These maximum values are then compared with the dose limit in order to assess compliance.

8 DETAILED ASSESSMENT METHODOLOGY

8.1 Theoretical Basis for the Development of Critical Groups

8.1.1 Overview

When releases of radioactive effluents occur to the environment, individuals are exposed to various radionuclides by multiple pathways. The particular habits and behaviour of an individual determine his degree of exposure. These factors affect the degree to which he is exposed by each of the pathways to radioactively contaminated environmental media.

In principle, individual exposures could be determined by monitoring the radionuclide concentrations in all the media to which the individual is exposed and determining his degree of exposure to those media. In practice, such detailed monitoring is not possible and simplifications have to be made. In this section, a general formalism for evaluating radiation exposure is set out for application in the context of a detailed local assessment being required. This formalism encompasses the option of detailed monitoring of individual exposures and provides a framework within which alternative simplifications of the monitoring and assessment process can be described.

If detailed monitoring of individuals was undertaken, committed effective doses from each year of exposure to environmental contamination could be estimated using the following formalism:

$$H_{ijk} = M_{ij} C_{ijk} S_{jk}$$

where H_{ijk} is the committed effective dose to individual i due to exposure to radionuclide k in environmental medium j during the year in question;
M_{ij} is a measure of the interaction of individual i with environmental medium j over the year in question;
C_{ijk} is the average concentration of radionuclide k in the sample of environmental medium j that individual i encounters over the year in question;
S_{jk} is a mapping function that relates unit interaction with environmental medium j exhibiting unit concentration of radionuclide k to committed effective dose. This does not depend on the individual, but can depend on the population group under consideration (see below).

To make this more concrete, for ingestion of a particular type of food, M would be the annual consumption (kg), C would be the average concentration in the material consumed (Bq kg^{-1}) and S would be the intake to committed effective dose factor (Sv Bq^{-1}). Similarly, for external exposure, M would be the annual occupancy of a particular area (h), C would be the average concentration in the material externally irradiating the individual (Bq kg^{-1}) and S would be the dose rate (Sv h^{-1}) due to exposure to the material externally irradiating the individual if it were contaminated at unit concentration (1 Bq kg^{-1}).

It should be noted that a spatial linkage exists between M and C. For certain exposure routes, such as external radiation, this link is direct as the occupancy is related to a particular medium in a particular area and the exposure is based on the concentration in the medium at that location. However, for internal radiation from ingestion of contaminated foods the link is more indirect; the dose resultant from the consumption of a particular foodstuff is dependent

on the concentration in the food at the location from which it is produced. Because of this spatial linkage both M and C may be further sub-divided into spatial domains and thus the committed effective dose is described by:

$$H_{ijk} = \Sigma_l M_{ijl} C_{ijkl} S_{jk}$$

where M_{ijl} is the interaction of individual i with medium j in domain l and C_{ijkl} is the concentration of radionuclide k in medium j in domain l. This is discussed in more detail in relation to habit survey and monitoring data in Section 8.1.2 below. However, for simplicity of presentation, the summation over domains is neglected in the immediate discussion below.

In practice, for routine monitoring, measurements of radionuclide contents in environmental materials are not tied to the habits and behaviour of specific individuals. In contrast, in research projects, specific individuals may be asked to provide a duplicate of the foods that they consume for radionuclide analysis. Such research-type approaches are not considered further here.

Similarly, where radionuclide concentrations are estimated by mathematical modelling, those concentrations are not explicitly related to specific individuals.

As radionuclide contents of environmental materials are not related to specific individuals, but are applied across the population of interest, it is appropriate to replace C_{ijk} with C_{jk}. This leads to:

$$H_{ijk} = M_{ij} C_{jk} S_{jk} = M_{ij} F_{jk}$$

where F_{jk} is the product of C_{jk} and S_{jk}. For intakes of foodstuffs, water or soil (the last either by ingestion or inhalation) it typically has units of Sv kg^{-1}. For external exposure, it typically has units of Sv h^{-1}.

In relation to the above, it is important to note that values of S_{jk} do not distinguish between individuals, but can distinguish between populations. In particular, committed effective dose per unit intake factors differ between adults, children and infants. This means that several populations associated with different values of S_{jk} may need to be carried forward in the analysis. Henceforth, the discussion is for a single population, as the extension to several populations is straightforward.

As values of F_{jk} are defined by a combination of routine monitoring information with standard conversion factors, they do not need to be considered further in this study. Therefore, attention can be concentrated on alternative approaches to specifying M_{ij}. In evaluating these approaches, it is important to remember that it is not individual values of H_{ijk} that are important, but rather total annual committed effective doses to individuals summed over pathways and radionuclides. Following the nomenclature adopted above, interest is in the distribution of values of H_i defined by:

$$H_i = \Sigma_j M_{ij} \Sigma_k F_{jk}$$

As values of F_{jk} are not dependent on the individual, it is convenient to write the second summation as G_j. This leads to:

$$H_i = \Sigma_j M_{ij} G_j$$

i.e. the problem reduces to selection of appropriate individual exposure measures and scaling factors characteristic of the local environment and the population under consideration.

For conciseness, it is convenient to express the above relationship in matrix form. Thus:

$$\boldsymbol{H} = \underline{M}\boldsymbol{G}$$

where bold characters represent vectors and underlined characters represent 2-D matrices.

All the habit and behaviour information required to characterise the radiation exposure of a specific population is contained in the matrix $\underline{M}$. The issue is how to assign values to all the elements of this matrix.

Ideally, values of M_{ij} would be determined for all the individuals of interest and the matrix would be populated directly. However, recourse often has to be made to more general survey data. In particular, there may be only limited information on correlations between values of M_{ij} for individuals.

Whatever method is used to populate $\underline{M}$, $\boldsymbol{H}$ will contain a distribution of values of H_i. For compliance purposes, interest is in the upper end of this distribution. The requirement is to pick out a reasonably homogeneous subgroup from $\boldsymbol{H}$ ($\boldsymbol{H'}$) such that $\boldsymbol{H'}$ comprises the most highly exposed members of $\boldsymbol{H}$. If H_1 is the most highly exposed member of $\boldsymbol{H}$, $\boldsymbol{H'}$ can be defined as all members of $\boldsymbol{H}$ that satisfy $H_i > fH_1$, where f is a relative homogeneity factor between 0 and 1. Typically, a value of around 0.33 would be adopted.

Having defined such a reasonably homogeneous subgroup (the critical group), the requirement is to define an individual representative of that group. Traditionally, this has been done in terms of specific habits and behaviour and an effective dose has then been computed. However, this is not necessary. If the distribution of effective doses to the reasonably homogeneous subgroup has already been computed, a representative value such as the geometric mean may be determined directly, without giving consideration to the pattern of behaviour that gave rise to it.

From the above discussion, it will be seen that the requirement is not to populate the whole of $\underline{M}$, but only those elements that contribute to the determination of $\boldsymbol{H'}$. In identifying those elements, two considerations have to be borne in mind:

- which pathways contribute substantially to exposure;
- which individuals have large measures of interaction with the pathways that contribute substantially to exposure.

To determine which pathways contribute substantially to exposure, it is not necessary to have detailed information on the measures of interaction of individuals with those pathways. It is sufficient to use typical measures of interaction across the whole of $\boldsymbol{H}$, with a degree of caution introduced such that pathways that could contribute substantially to the exposure of a few individuals are not overlooked. Specifically, it seems appropriate to use arithmetic mean values, as these are readily computed from survey data and are reasonably robust for different

sample sizes and sampling regimes. Thus, a typical exposure profile vector $\boldsymbol{M}$ is defined, such that:

$$M_j = \Sigma_i M_{ij}/N$$

For habits that are undertaken (to at least some degree) by a large percentage of the population, N may reasonably be defined as the number of individuals in the population of interest. However, in order to appropriately consider those habits that are only exhibited by a smaller (though still significant) proportion of the population, N may be best defined as the number of individuals within the population group that partake in the activity. In general, the existence of habits that are only exhibited by certain portions of the population may be treated using probability density functions with a 'delta' function component at the origin. These functions define both:

- the fraction of the population that does not exhibit the particular habit (*e.g.* the fraction of the population group that are non-consumers of a certain food); and
- the probability distribution of the level of exhibition of the habit by the remainder of the population group (*e.g.* the distribution of the consumption rates of a particular food over only those individuals that eat the food).

It is emphasised that the whole of the population does not have to be studied to determine $\boldsymbol{M}$. A relatively small sub-sample will typically be sufficient. Indeed, estimates of $\boldsymbol{M}$ may be obtained from different populations provided that these populations are broadly similar to that of interest. For example, food consumption rates can be based on national or regional surveys, if the population group of interest is considered to be typical of the nation or region. In practice, it may be appropriate to take many elements of $\boldsymbol{M}$ from national or regional data and modify a limited number of values to take account of particular characteristics of the population of interest.

Having defined such an exposure profile, it is possible to compute typical contributions by pathway as $M_jG_j/\Sigma M_jG_j$. Only contributions larger than some predetermined level, possibly of the order 0.01, need to be carried forward for further consideration. By this approach, the number of pathways that needs to be addressed can be reduced.

For those pathways that are carried forward, it is necessary to characterise those individuals that have large measures of interaction with one or more of those pathways. Two extreme approaches are readily identified. A reasonable approach is to obtain survey data for all individuals in the population N or an analogue population for these pathways and computes $\boldsymbol{H}$. The relevant subgroup of doses, $\boldsymbol{H'}$, can then be determined by inspection.

A cautious approach ignores correlations between pathways. Survey data are used to define some high percentile (typically the 97.5^{th}) of the measure of interaction for each pathway and a hypothetical individual is defined that exhibits this high percentile interaction over all pathways. Thus, the hypothetical individual will exhibit high consumption of all contaminated foodstuffs and will exhibit high occupancy of areas where external irradiation occurs. This approach ignores anticorrelations, arising because high consumption of some food types is associated with low consumption of others. This method can be further refined by filtering out those combinations that give rise to unsustainable calorific intakes.

An intermediate position can be adopted if some information is available concerning correlations between the various measures of interaction. Specifically, the distribution of measures of interaction can be discretised. Thus, for pathway j, one might distinguish high levels of interaction from moderate and low levels of interaction (e.g. for food consumption above the 90th percentile and below the 90th percentile, respectively). From survey data on the population of interest or an analogue population one would then define the fractions of the population that exhibited a high level of interaction for more than one pathway. If there are J pathways carried forward in the analysis and a two-level discretisation is adopted, there are 2^J potential population subgroups, g. For example, denoting high interaction by h and moderate to low interaction by m, for J=3 there are 8 groups that can be characterised in obvious notation as {hhh}, {hhm}, {hmh}, {mhh}, {hmm}, {mhm}, {mmh}, {mmm}. Setting representative values of M_{jg} for each of these groups, it is possible to compute representative values of H_g for each group. This leads to a table of values of f_g and H_g, where f_g is the fraction of the population of interest associated with group g.

Survey data may not provide information on correlations between more than two food types, *e.g.* all that may be known are P_{ij}, defined as the probability that a high level of interaction for pathway i is associated with a high level of interaction for pathway j. If this is the case, either higher-level correlations may be neglected, or higher-order correlations may be computed assuming that only binary correlations between pathways are relevant. In this latter approach, the probability of exhibiting a high level of interaction for pathways 1,2 and 3 would be the product of the probability of a high level of interaction for pathways 1 and 2 and the probability of a high level of interaction for pathways 1 and 3.

In practical terms, where discrete survey data is available for different exposure routes, the overall habit patterns may be assessed using assumed or derived correlations between the different habit types. This may be performed by sampling from the one or more discrete sets of habit data with assumed correlations to create a single, integrated set of habit data for an artificial population group. Such manipulation may be undertaken using, for example, the Palisade @Risk™ software tool.

8.1.2 Application to Dose Calculations

At the most basic level (at which data may be available), radiological exposure for an individual, i, can be broken down into a series of exposure 'events', *i.e.* for interaction with environmental medium, j:

$$H_{ije} = M_{ije}G_{je}$$

Each event takes place in time and space, and links the measure of dose rate of an environmental medium, G_{je} , with the individual's interaction with that medium.

Examples of M_{ije} could be:

- "Survey person #10 eats 100 grams of plaice on April 12th, 1999. The fish was caught on April 8th from the local Irish Sea area"; or

- "Survey person #101 spent 2hours on Morecambe Bay Sands on August 10th , 1999".

An example of G_{je} may be:

- "A catch of plaice was made on February 8th 1999 from the local Irish Sea area. Monitoring of the catch revealed an average contamination equivalent to 0.3 μSv kg^{-1}.

In the context of monitoring and habit surveys, a realistic estimate of dose could only be made if concentrations in the environmental media, and habits (leading to radiological exposure) of the individual of interest were recorded, or somehow duplicated, for each radiological exposure event occurring for the individual over an entire year. In practice, it is sufficient to use monitored concentrations and habit survey data provided reasonable correlations between exposure events for individuals and monitoring and habit survey 'events' exist.

For instance, in the above examples, although the fish eaten was not monitored, it may be reasonable to assume that a fish caught from the same area in February had a similar level of contamination to that in April. Furthermore, as doses are evaluated on an annual basis, if it is known that fish consumption by the individual is fairly uniform throughout the year, and that fish samples are monitored for contamination at, say, bimonthly intervals, it would be sufficient to evaluate the total exposure from the fish pathway from the product of the annual ingestion amount and the average level of contamination in the samples (expressed in Sv kg^{1}).

In addition, common monitoring practice may introduce levels of caution by searching out times and places where levels of contamination in media are highest and assuming these levels for the evaluation of individual dose, so as to ensure that the predicted dose is not underestimated.

For practical purposes, it is noted that each exposure event (e) is a member of a spatial and temporal domain (d_l) that defines the area and time period to which the exposure event belongs:

$$e \in \{d\}$$
$$d=d_1 \cup d_2 \cup d_3 \ldots\ldots \cup d_L$$

Summing over the 'exposure events' that occur during the period of the assessment year, the total exposure is calculated from:

$$\begin{aligned} H_{ij} &= \sum_e H_{ije} \\ &= \sum_{e\in d_1} H_{ije} \ldots + \sum_{e\in d_l} H_{ije} \ldots + \sum_{e\in d_L} H_{ije} \\ &= \sum_{e\in d_1} M_{ije} G_{je} \ldots + \sum_{e\in d_l} M_{ije} G_{je} \ldots + \sum_{e\in d_L} M_{ije} G_{je} \\ &\cong \sum_{e\in d_1} M_{ije} \sum_{e\in d_1} \frac{G_{je}}{N_1} \ldots + \sum_{e\in d_l} M_{ije} \sum_{e\in d_l} \frac{G_{je}}{N_l} \ldots + \sum_{e\in d_L} M_{ije} \sum_{e\in d_L} \frac{G_{je}}{N_L} \\ &= \sum_{l=1}^{l=L} M_{ijl} \overline{G}_{jl} \end{aligned}$$

where the last summation is over domains, l such that $e \in d_l$, and

N_l is the number of events in domain, d_l

M_{ijl} (kg y^{-1}, or hr y^{-1}) is the individual exposure rate for individual group i, in relation to medium, j, and domain, l, and

$\overline{G}_{jl}$ (Sv kg^{-1} or Sv hr^{-1}) is the average dose rate per unit exposure rate (i.e. dose per unit exposure) in relation to medium, *j* and domain, *l*.

The above equations show that when summing over a large number of exposure events, sets of habits (*M*) and dose per unit exposure rate to specified media (*G*) are found to share common domains. For example an individual may consume fish caught from two different areas, where two separate sets of monitoring are conducted. Moreover, within each of the domains the habits, *M*, and the doses per unit exposure, G, can be decoupled, so that the dose to an individual summed over exposure events is calculated from averages of habit survey events, M, and monitoring events, G, applying to common domains. The domains should therefore be specified so that there would not be too great a loss of accuracy in computing dose by decoupling habits which are related to habit-survey data, and doses per unit exposure related to monitoring. Generally, these domains are chosen to cover those areas in which highest levels of contamination occur. In addition concentrations in these areas should be reasonably uniform, so that the doses received by members of the same *potential* critical groups are reasonably similar. In other words, the critical groups can be considered homogeneous with respect to dose, as well as with respect to habits.

When computing doses, it may be convenient to express the individual habit quantities with respect to specified domains, e.g. consumption of fish from a specified sea area, in terms of a fraction of the total habit quantity for that individual. Groups of individuals, for example 'enthusiastic fish consumers' may have similar high-rate consumption rates, but individuals within this general group, may obtain their fish from different areas. Representing domains by the subscript, *l*, the habits in respect to each domain, l, are expressed as fraction $f^{(M)}_{ijl}$ of the total:

$$H_{ij} = \Sigma_l M_{ijl} G_{jl}$$

$$= \Sigma_l f^{(M)}_{ijl} M_{ij} G_{jl}$$

where

$$\mathrm{M_{ijl}} = f^{(M)}_{ijl} M_{ij}$$

and the sum of the fractions is equal to one,

$$\Sigma_l f^{(M)}_{ijl} = 1$$

In addition to the possibility that different individuals with similar exposure rates with respect to a specified medium, may derive parts of that exposure from different domains, the possibility arises that individuals with overall similar exposure to a medium category, such as 'fish' may also derive parts of their exposure from different media within the medium category, for example, cod and eels would be classed into the fish category.

Situations may arise when the concentrations in specific media are known, but habit data are applicable only to each medium category. In these situations, the partitioning of exposure within a category has to be guessed.

The total exposure rate for a medium category, m, is expressed as

$$M_{im} = \Sigma_j f^{(J)}_{ij} M_{ij} ,$$

where the summation is limited to be over media, j in the specified medium category, m, and

$$\Sigma_j f^{(J)}_{ij} = 1. \qquad [\text{such that } j \in m]$$

In the above methodology, the following data items are required to evaluate population doses:

M_{im} *Habits* (kg y^{-1}, or h y^{-1}). The media interaction rates for population group, i, and for medium category m.

$f^{(J)}_{ij}$ *Media fractions* (-). The fraction of the total medium interaction rate for population group i medium category m, that is attributable to medium, j.

$d_1 \ldots d_L$ *Domains* (various). Specification of the relevant domains, *e.g.* areas, where radiological exposure may take place, or originate, from.

$f^{(M)}_{ijl}$ *Domain fractions* (-). The fraction of *Habits* can be attributed to a particular domain, l.

G_j *or* G_m Dose per unit exposure (Sv kg^{-1}, or Sv h^{-1}) for medium j (or media category m) and for a specified age group (e.g. adults, or infants, or children).

where:

i is the identifier for the population subgroup for which dose is being calculated; and

m is the medium category.

The dose to a population group, i, is then given by:

$$H_i = \Sigma_m G_m M_{im}$$

8.2 Performance of Calculations and Use of Data

This section describes the set of UK population group calculations to be carried out and the sources and application of available data required for the calculations. The objective of the calculations is to explore the spectrum of potential doses amongst those receiving the highest dose either in the vicinity of, or at distance from, licensed sites. In particular, the methods of definition and characterisation of the following are presented:

- Population groups and habit data (Section 8.2.1);
- Media categories (Section 8.2.2);
- Domains (Section 8.2.3).

The methods of estimating individual doses and then doses to the representative member of a critical group are described in Section 8.2.4 and Section 8.2.5 respectively.

8.2.1 Population Groups and Habit Data

In the majority of environmental assessments, the scope of the quantitative evaluation has to be reduced to manageable proportions. Ideally, the doses received by all members of the public would be evaluated, and the critical group defined in terms of the total dose received over all pathways in line with the critical group definition provided by the ICRP. This would entail comprehensive surveillance of all individual habits and the anthropogenic radioactivity contamination of all the environmental media accessed. As noted in Section 8.1, this scale of monitoring is clearly impractical. However, it was demonstrated in Section 8.1 how certain subgroups can be selected with particular habits that characterise them as the ones that receive the highest radiation exposures. These groups are referred to as critical groups.

A common feature of many dose assessments undertaken for UK nuclear sites to date has been that the population groups identified as receiving most significant exposures are generally focused on a single pathway or small number of closely related pathways (see Section 4). For these groups of individuals, a single source-pathway combination was commonly found to dominate the radiological exposure incurred. However, as discharges of radionuclides giving rise to these exposures have been reduced in recent years, it is possible that exposure from a number of sources and a variety of pathways could be of similar importance.

Certain individuals may exist who, although not regarded as part of a ‘critical’ group with regard to a specific pathway, may receive significant exposures from a range of pathways associated with environmental radiation from one or more site. Indeed, it is possible that individuals may, in fact, belong to more than one pathway specific critical group. In order to assess this possibility, a fresh look at the collection and analysis of survey data is required.

Historically, habit surveys have focused on limited population groups that have been identified as potential critical groups for a single pathway (or small number of associated pathways) in relation to a specific source, for example dietary surveys of high seafood consumers around coastal nuclear facilities. However, these surveys have tended to elicit information only on those habits pertaining to the pathways associated with the assumed critical group definition. Around any one nuclear facility, therefore, a number of separate habit surveys have been routinely undertaken on population groups assumed to represent the

critical groups associated with a number of different exposure pathways. These surveys have tended to be undertaken in isolation from each other.

As noted earlier, it is not practical to extend survey work to significantly larger populations. However, it is feasible to extent the scope of the data elicited from the surveyed individuals. In particular, the development of integrated survey questionnaires for use with all population groups would enable the total doses to the surveyed individuals from all pathways to be assessed. For example, if the critical group of high-seafood consumers were also questioned regarding they consumption of terrestrial foods produced in the vicinity of the nuclear facility, an assessment of the total ingestion doses to individuals could be undertaken. In essence this would enable dose assessments to be made of not just the critical groups pertaining to particular pathways, but also a "combination" critical group encompassing all the key pathways.

This type of integrated habit data is not presently available. However, the main monitoring organisations, *i.e.* the EA and the FSA, are currently moving towards this approach. In the meantime, and as described in Section 8.1.1, separate survey data for the different critical groups may be combined through consideration of assumed and/or derived correlation coefficients between the various habit types.

8.2.2 Media Categories

The main environmental media categories that have been considered in the study are presented in Table 6.

8.2.3 Domains

The levels of radioactive contamination in environmental media will vary according to where the media are located and with time. Therefore, in order to estimate the doses incurred by individuals due to their interactions with contaminated environmental media, it is required that the areas (or "domains") from where the media are accessed are identified in habit surveys and, further, that the contamination levels in the domains are monitored. Habit surveys have historically attempted to account for this to some extent. However, difficulties arise in the precise determination of where environmental media are accessed by individuals, particularly in relation to elicitation of information regarding the geographic distribution of sources of foods. Nonetheless, an integrated approach to habit surveys and monitoring programmes is of key importance.

In the existing survey and monitoring data, domains have been defined as areas (and potentially periods of time) over which significant levels of contamination originating from man-made sources of radiation are likely to exist. These are most often areas previously identified in connection with nuclear sites where the highest levels of contamination and substantial interactions with members of the public combine to signal the possibility of significant exposures. Monitoring in the vicinity of nuclear sites is also undertaken where little contamination exists, to ensure discharge limits are adhered to, and because of the potential for unauthorised discharges, for example due to accidents.

For the assessment of doses around licensed nuclear sites, the position is taken that the domains should, in general, be based on those presently identified in monitoring programmes undertaken by the EA and the FSA.

Where possible, monitoring data for the environmental media in the different domains should be utilised. However, where such data are not available (or are insufficient), predictive modelling may be utilised in order to build up a fuller picture of the distribution of contamination in the environment. Alternatively, where only elements of the monitoring data are missing, interpolation and/or extrapolation of available data may be used fill the data gaps. Methods for data filling are further discussed in Section 8.2.4.

8.2.4 Estimation of Individual Doses

Dose per unit exposure, G, corresponds to dose per unit ingestion, or dose per unit occupancy with respect to the age group of the individual and the specified media and domain giving rise to exposure. At the most basic level, G_{je} refers the dose per unit exposure rate in relation to a specified event:

$$G_{je} = \Sigma_k \Sigma_w D_{wk} \ \varepsilon_{we} C_{jke}$$

where the summation is over radionuclides, k, and the different ways, w, in which exposure from the same medium can take place.

D_{wk} (Sv Bq^{-1} or Sv hr^{-1} per Bq m^{-3}) is the *dose conversion factor* appropriate to the mode by which exposure can take place (see below) for nuclide k. For convenience the notation neglects reference to age group. For this study, the dose conversion factors are based on ICRP-60 recommendations (*e.g.* [8, 11]) for adults.

ε_{we} is an environmental scaling factor. For example, for exposure to beach sediments, which is primarily by external exposure and inhalation, an environmental scaling factor is needed for inhalation, to convert the concentration in sediments to that in breathable air. Often this factor is not required, and can be set to one.

C_{jke} (Bq kg^{-1}) is the concentration in environmental medium, j, for radionuclide, k, occurring at exposure event, e.

As discussed, the dose per unit exposure values can be aggregated so that they refer to domains and/or media categories rather than individual events.

It should be pointed out that the dose per unit exposure factors can form a useful intermediate calculation in the presentation of monitoring results. In particular, the availability of dose per unit exposure values for environmental media enables estimates of individual exposure to be made by taking into account the occupancy or intake rates for that individual.

Radionuclide concentrations in media located in contaminated domains may be available as result of (in order of preference):

- Monitoring;
- Interpolation, where there are ‘gaps’ in data;
- Extrapolation beyond the spatial or temporal boundaries of the monitored domain;
- Modelling, where little or no data are available.

It is expected that monitoring information on radionuclide concentrations in areas contaminated by discharges of radionuclides will be available at different degrees of spatial

and temporal averaging, and different levels of aggregation over media categories. To reduce the volume of data handled, concentrations below a specified cut-off should be eliminated from consideration in calculations.

Where monitoring data are not available for a particular environmental medium, the concentration may be estimated from measurements made on another domain medium. A hierarchical method of data "filling" is proposed based on the domains as defined in Table 7. If the concentration of a particular radionuclide in a specific environmental medium in a particular domain is missing then this value is filled by one of the following methods (given in order of preference):

1. If the missing data are for a medium in the far-field, then the missing data are taken to be the same as the concentration of the same radionuclide in that environmental medium in the near-field domain if such data are available; or else:
2. If the concentration of the radionuclide is available in other media of the same generic class as the specific medium for which data are missing (in the same domain), then the missing datum is taken as the maximum of the average concentrations in these other media; or else:
3. The missing data are taken to be the maximum of the average concentrations in any other environmental media (except seaweeds) in that domain.

It is recognised that this method of data filling may be quite cautious. The main sources of monitoring data for environmental concentrations and dose rates in the UK are as follows:

- The EA (*e.g.* the annual Radioactivity in the Environment Reports [7]):
  - Soil/sediment background dose rates;
  - Beach dose rates;
  - Radioactivity in surface and ground waters.
- The FSA:
  - Food concentration data (*e.g.* RIFE reports [6] and the FSA web site [28]);
  - Beach dose rates (*e.g.* RIFE reports);
  - Background concentrations in food (*e.g.* RIFE reports).
- HSE (NII):
  - Direct shine dose rates (currently not published but available on request to the NII).

8.2.5 Critical Group Doses

Where individual doses have been assessed through the utilisation of habit surveys and environmental monitoring, as will typically be the case for licensed nuclear sites, then individual doses will have been estimated for a range of individuals. Where integrated habit surveys are available, the doses to each individual will be calculated across all exposure routes and hence total individual doses will be estimated for all individuals in a single integrated population group.

Where integrated habit surveys are not available, then the separate survey data for the different critical groups may be combined through consideration of assumed and/or derived correlation coefficients between the various habit types. This may be performed by sampling from the one or more discrete sets of habit data using the assumed correlations to create a single, integrated set of habit data for an artificial population group. Such manipulation may be undertaken using, for example, the Palisade @Risk™ software tool. When undertaking such sampling it is important to ensure that important observations (for example particularly high utilisation values) are not lost. To achieve this, a sufficiently large number of samples (relative to the number of individuals within each of the separate habit surveys) needs to taken. This can be facilitated by the use of a stratified sampling scheme, such as Latin Hypercube Sampling (LHS); this approach has been adopted in the trial application of the methodology described in Section 9.

Once the total individual doses have been calculated for each member of the single integrated population group, the sub-population that forms the critical group is defined as those individuals whose total dose is above a pre-defined fraction of the total dose to the maximally exposed individual. This fraction is taken to be 0.1 if the mean dose of the critical group is less than about one-tenth of the individual dose limit (*i.e.* 1mSv/y); otherwise the fraction is set to 0.33. The mean individual dose received by members of this critical group can then be compared with the dose limit in order to assess compliance.

8.2.6 Summary

An overview of the calculation flow required for the detailed site/location assessment methodology is presented in Figure 4.

9 RESULTS OF TRIAL APPLICATION OF THE ASSESSMENT METHODOLOGY

9.1 Introduction

The aim of the trial application of the dose assessment methodologies described earlier is to assess their usefulness in terms of their feasibility of use and their performance in comparison to existing methods.

The main focus of the trial application of the detailed dose assessment methodology outlined in Section 8, was the assessment of individual doses to members of the public around the Sellafield site in the year 1999. The Sellafield site was selected for this assessment as the habit survey and environmental monitoring data are generally more extensive around this site than for any other licensed facility. The method of application and the results of the Sellafield assessment are presented in Section 9.2. However, in addition to the assessment of Sellafield, the assessment methodology has also been applied, in simplified form because of the less extensive data, to other licensed nuclear sites, as described in Section 9.3.

The preliminary assessment protocol and generic regional assessment methodology have also been applied to sites in the EA Thames Region in order to assess the utility of the first two stages of the proposed assessment method. In order to provide a benchmark for this application, this assessment also included consideration of the licensed sites in the Thames Region. The assessment of the Thames region is described in Section 9.4.

9.2 Sellafield Dose Assessment

Application of the dose assessment methodology to the Sellafield site can be described as a three-stage process:

- Collection and manipulation of environmental concentration and dose rate data for environmental media in the defined domains (the domains are as defined in Table 7 and are based, in part, on the locations at which monitoring habit surveys have been undertaken by the EA and the FSA);
- Collection and manipulation of the habit data defining utilisation of the environmental media in each of the defined domains;
- Calculation of the individual doses to members of both the whole surveyed population group and the critical group.

The performance and output from each of these stages is described in turn in Sections 9.2.1 through to 9.2.3.

9.2.1 Environmental Concentration and Dose Rate Data

Monitoring data providing concentrations and dose rates in/from environmental media around Sellafield were obtained from the following sources for the year 1999:

- The EA (Radioactivity in the Environment report for 1999 [7]):
  - Beach dose rates.
- The FSA:
  - Food concentration data (RIFE-5 [6] and the FSA web site [28]);

  - Beach dose rates (RIFE-5);
  - Background concentrations in food (RIFE-5).
- HSE (NII):
  - Direct shine dose rates (supplied directly by the NII).

The main tasks involved in the processing of the above data were manipulation into suitable format and, more particularly, data gap filling, especially with regard to concentration levels in foodstuffs.

Food concentration data are available from the FSA for a variety of radionuclides, environmental media and spatial locations. The first task required was to associate each location at which monitoring had been undertaken to one of the food domains as defined in Table 7. The mapping of sampling locations to domains is summarised in Table 8. Next, a complete set of the food types to be considered needed to be defined and, further, each specific food type needed to be associated with a generic category in order to facilitate the data-filling regime described in Section 8.2.4. Additionally, when developing the food lists, reference was also made to the types of food for which consumption data was available from habits surveys. The complete list of specific and generic food types is provided in Table 9.

Once this definition of food types had been completed, the food concentration data were aggregated and the data gap filling protocol was implemented. Due to the large amount of data involved, an Excel spreadsheet tool was developed to undertake the data-filling process. The output from this tool is the average concentration of each radionuclide in each of the different food types in each of the defined domains. It is noted that for concentrations of some radionuclides and in certain foodstuffs, the FSA present concentrations averaged over a number of samples. Where this is the case, the computed concentrations are suitably weighted to account for this. Finally, background concentrations in foods (where available in RIFE-5) were subtracted from the final average concentrations. The list of background concentrations is presented in Table 10.

For external exposure to beach sediments, dose-rate measurements were taken from EA [7] and FSA [6] data sources. The locations at which the measured dose rates are reported were assigned to one of two domains, either salt marsh or mud/sand. This definition of the domains was made on the basis of the location information available in the data sources which, in turn, is influenced by the stability of the these type of beach areas (the sand and mud areas may change between monitoring periods, whereas salt marsh locations are typically more stable). Nonetheless, the definition of the marine/foreshore domains for different facilities needs to be made on a case-by-case basis.

Direct shine dose rate data were not available in uninterpreted form for Sellafield. However, the annual individual effective dose to an assumed critical group member was provided by the NII.

9.2.2 Habit Data

The following habit survey data were available for the Sellafield region:

- High marine food consumers dietary survey
  This survey was made available by the FSA and provided dietary data for a group of high seafood consumers. The survey provided information regarding the location from where each seafood was sourced and hence allowed mapping of the foods to the domains defined in Table 7. However, these survey data provided no information regarding other habits of the surveyed group, such as consumption of locally produced terrestrial foods (for beach occupancy rates for this group see below).
- Beach occupancy survey
  Beach occupancy data were collected as part of the high marine food consumers' survey. However, to avoid infringement of the Data Protection Act, the FSA was unable to provide the beach occupancy data as an integrated part of the marine food survey. Nonetheless, the beach occupancy data were provided separately, but in such a way that individuals' beach occupancy could not be matched to their consumption data.
- Terrestrial food dietary survey
  Survey data were available from the FSA for a group of high consumers of locally produced terrestrial food. These data included consumption rates of marine foods.
- Inland indoor/outdoor occupancy data
  Inland indoor/outdoor occupancy data in the vicinity of the Sellafield site were not available. The most complete survey dataset of this type available from the FSA for 1999 was from Hinkley. Therefore, purely for the purposes of demonstration, data from this survey were used as a surrogate for the inland indoor/outdoor occupancy in the near-field domain around Sellafield.

The nature of the habit data described above gave rise to two key problems. Firstly, the above data surveys were not integrated and hence they had to be combined to produce a single integrated survey data set. Correlations between the various habit types were assessed using 1991 BNFL habit data made available for previous Department of Health studies [29]. From analysis of these data, statistically significant correlations were only identified for three cross-survey habit combinations. Given the uncertainties in the derivation of these correlations, the correlation coefficients assumed following this analysis were rounded to the nearest 0.25. The correlations (ρ) assumed are as follows:

- total meat / total seafood, $\rho = -0.75$;
- total terrestrial food / total inland occupancy, $\rho = 0.5$;
- sand occupancy / mollusc consumption, $\rho = 0.5$.

A single, integrated set of habit data was created for an artificial set of 400 individuals by sampling from each of the separate habit surveys. The sampling process was undertaken using the @Risk analysis software tool, taking account of the above correlations.

The second problem was that insufficient information was available to distinguish between:

- inland occupation in the near and far-fields; and
- consumption of terrestrial food produced in the near- and far-fields.

Therefore, it was decided to assess four groups of individuals (see Table 7 for the definition of domains for each pathway):

- **Group G11** These individuals obtain their locally produced terrestrial food from the near-field domain only and their inland occupancy is exclusively in the near-field domain. These individuals do, however, access the marine foods and beach areas in all the relevant defined domains in accordance with the habit survey data.
- **Group G12** As for G11, but the inland occupancy is assumed to be in the far-field domain.
- **Group G21** As for G11, but locally produced terrestrial foods are assumed to be produced in the far-field domain.
- **Group G22** As for G11, but both inland occupancy and terrestrial food production are assumed to be in the far-field domain.

Four versions of the integrated habit survey data generated from the sampling process were therefore created, one for each of the group types G11 to G22.

9.2.3 Dose Calculations

Once the concentration/dose rate data for the environmental media and the habit survey data had been processed, the total doses to each individual in the year 1999 were calculated by combining these datasets with published ICRP dose conversion factors (ICRP-60 [8]). Different gut uptake factors are used in RIFE for the assessment of doses arising from plutonium and americium in Cumbrian winkles and polonium in seafood. The gut uptake factor for Cumbrian winkles leads to a lower dose conversion factor and hence lower doses. The alternative gut uptake factor for polonium in seafood, gives rise to higher doses, but is derived from specific research study involving crab meat and it is noted in RIFE-5 that it is cautious to apply this to all seafood. The dose calculations were undertaken using a specially developed Excel spreadsheet tool. These dose calculations were undertaken four times, once for each of the population groups G11 to G22.

The results of the Sellafield trial assessment are presented in Table 11. It can be seen that the mean critical group doses are of the order of 0.7mSv, *i.e.* within the dose limit of 1mSv. However, it may be noted that the dose received by some members of the critical group may therefore exceed the dose limit. Effective doses received by the most exposed members of the critical group are dominated by the marine food consumption pathway. In particular, the most exposed individuals' annual doses are dominated by high consumption of marine foods, especially cod, crab and molluscs. (It should be remembered that the individuals in this assessment are artificial individuals whose habits have been generated by sampling from survey data of actual individuals.) The predicted mean critical group doses are broadly consistent with annual dose estimates for high marine food consumers obtained by the FSA [6].

Further examination of the underlying data showed that the dose rates from consumption of marine food are dominated by ^{210}Po and ^{210}Pb contamination. Two points need to be made in relation to ^{210}Po and ^{210}Pb levels in marine foods. Firstly, only limited monitoring data were available for these radionuclides and, hence, their concentrations in many of the marine foods have been estimating using the data-filling protocol described in Section 8.2.4. Therefore, the assumed concentrations are somewhat uncertain. Secondly, estimation of background levels of ^{210}Po and ^{210}Pb is problematic, and it is likely that anthropogenic levels of these radionuclides have been overestimated in the assessment. Furthermore it is noted that ^{210}Po

and ^{210}Pb do not originate from the BNFL Sellafield facility. They have been discharged in the past from Rhodia Consumer Specialities Ltd at Whitehaven.

In order to assess the impact of ^{210}Po and ^{210}Pb, and to assess (as far as possible) the impact of Sellafield discharges in isolation from other facilities, the doses to the population group G11 were also assessed without consideration of ^{210}Po and ^{210}Pb. The results of this assessment are presented in Table 11 as population group G11b. It can be seen that, in this case, the mean annual critical group dose is reduced to about 0.2mSv. The distribution of doses for the population groups G11 and G11b are presented in Figure 5. It can be seen from this figure that the highest assessed individual doses are reduced by a factor of 2 to 3 when ^{210}Po and ^{210}Pb are neglected. The distribution of doses for the population groups G11 and G11b are also presented in Figure 6, where there has been no filling of monitoring data. The methods which were used for data filling have been discussed in Section 8.2.4. This shows that the caution method of data filling adopted increases the doses by 30%.

9.3 Other Licensed Sites

Data for other licensed sites, particularly habit survey data, was found to be much less extensive than was the case for Sellafield. Because of this, these other facilities have been assessed in a simplified manner where necessary, whereby doses from each pathway were assessed separately and then the total doses were estimated by summation (rather than through the generation of an integrated habit set). Additionally, it is noted that, for certain pathways, the absence of habit survey data meant that doses for those pathways could not be estimated. The results of the dose assessments for these other licensed sites are presented in Table 12. It is noted that, for the pathways assessed, the mean critical group individual doses are within the limit. It may also be seen that the highest mean critical group dose is assessed for Bradwell and that the greatest contribution to this dose is from direct shine dose estimates provided by the NII.

9.4 Assessment of Radiological Discharges in the Thames Region

9.4.1 Introduction

In order to trial the preliminary screening and generic regional assessment methodologies, the 1999 discharge data from all non-licensed sites in the EA Thames region were collated using information supplied from the regional head office at Reading. A list of the non-licensed sites for which (non-zero) discharge returns were held by the EA is provided in Table 13 (for gaseous releases) and Table 14 (for liquid discharges). In addition to non-licensed sites, the assessment of the Thames region also included consideration of the discharges from the licensed nuclear sites in the region. The licensed nuclear sites in the Thames region are UKAEA Harwell, Nycomed Amersham and MoD sites at Aldermaston and Burghfield. Discharge data for 1999 from these sites were obtained from the EA Radioactivity in the Environment Report [7], and the discharges are summarised in Table 16.

The discharges from all sites were then assessed against the preliminary screening protocol described Section 6 in order to identify those sites with discharges that merited more detailed assessment. The preliminary screening of the sites is described in Section 9.4.2 and the detailed assessment of the sites remaining after screening is described in Section 9.4.3.

9.4.2 Preliminary Screening

The preliminary screening protocol is described in Section 6. This protocol was implemented in an Excel spreadsheet in order to facilitate the screening of the licensed and non-licensing sites in the Thames region. The spreadsheet tool calculates the annual doses from each site, compares these doses with the screening limit (60μSv) and provides a list of all sites that exceed the limit.

The screening tool contains dose per unit discharge factors for a variety of radionuclides for both gaseous and liquid discharges. However, a number of radionuclides are identified in the 1999 discharge returns that are not included in the spreadsheet tool, either because those radionuclides are not available in the underlying model tools (*e.g.* PC CREAM) or else the discharge returns relate to generic radionuclide categories (*e.g.* "alpha emitters" or "activation products"). In order to over come this problem, surrogate radionuclides were identified for those radionuclides (or radionuclide categories) not included in the screening tool. The surrogates for the screening assessment were chosen to be broadly conservative (*i.e.* to over-estimate radiological impacts). A list of surrogates is provided in Table 15.

The list of sites from which the discharges were estimated to exceed the screening limit are presented in Table 17. It should be noted that the dose estimates in the preliminary screening process are made under highly conservative assumptions and are hence likely to be gross over-estimates of the actual doses received by typical individuals around these facilities. The predicted doses estimated for one site, the Appleton Rutherford Laboratory at Harwell, stand out as being particularly high in the preliminary assessment. Inspection of the discharge for this site identifies the release to be 31.1 TBq/y of "activation products". Under the surrogate scheme presented in Table 15, activation products are considered as ^{60}Co, a long-lived radioisotope that has a high yield of energetic gamma emissions (2.5 MeV per transformation). However, following discussions with the EA Thames Region Head Office, it was determined that much of this release comprised short-lived activated air products. However, it was also noted that a significant proportion of the release was made up of ^{41}Ar and for the more detailed assessment, the activation product release was assumed to be entirely comprised of ^{41}Ar.

In total, 45 of the assessed sites were identified as meriting further assessment. The vast majority (42) of these are sites with releases that are dominated by liquid discharges to sewers. It is also noted that whereas discharges from UKAEA Harwell and Nycomed Amersham are sufficient to merit further assessment, the discharges from the MoD facilities at Aldermaston and Burghfield were screened out. In the assessment of Harwell, it was conservatively assumed that all releases discharged to the Lydebank Brook were discharge via the private UKAEA sewage treatment plant. However, following contract with UKAEA it was found that, in fact, only a small amount of the Lydebank Brook discharges were routed through the sewage treatment plant in 1999 and, further, that this plant has now been shutdown. Therefore, it was decided that the discharges to Lydebank Brook would be best assessed in the detailed assessment assuming none is routed through the sewage treatment plant.

9.4.3 Generic Regional Assessment

In order to assess the discharges from the Thames region in more detail, the discharges to sewers first needed to be aggregated for each Sewage Treatment Works (STW). The STW that received discharges from the screened sites are summarised in Table 18. The doses to STW workers and from sludge application are directly proportional to the sewage flow rate to the STW in the detailed assessment methodology (see Section 8). Hence the sewage flow rate and details as to whether sludge is used for land improvement are also presented in Table 18. Data for some of the STW were taken from Venter [25]; for the remaining STW, difficulties were encountered in collecting this information from Thames Water and hence conservative default values were taken.

To assess the liquid discharges to rivers, either directly or via STW, the River Thames and it relevant tributaries needed to modelled. To achieve this, the Thames river system was broken down into a number of river reaches (69 reaches in total were used). The detailed assessment methodology for releases to rivers requires the length and flow of each reach and also information on the connections between various river reaches. Data on the lengths of the reaches were taken from the EA web site [30], and the river flow data were taken from the HR Wallingford web site [31] (flow data was not available for each reach and conservative defaults were taken as necessary). The information on the river reach system is summarised in Table 19.

The detailed assessment methodology for the non-licensed sites was implemented in an Excel spreadsheet. This spreadsheet takes as input the discharges from each of the screened sites in terms of the amount of each radionuclide discharged, the six-figure grid reference for the release point and, for the STW, the sewage flow rate and a flag to indicate whether sludge form the works is used for land improvement. The spreadsheet also takes as input the river reach system (as summarised in Table 19). The total doses to individuals residing at each spatial grid element in the Thames region (on a 1km grid) are then calculated for STW workers and non-STW workers separately.

The maximum annual doses at any grid point for both STW workers and non-STW workers are summarised in Table 21. The maximum annual dose is estimated to be 78μSv, the main contributor to this dose being the aerial discharges from Nycomed Amersham. This dose is over an order of magnitude lower than the dose limit of 1mSv. The maximum annual doses from each of the various discharges types (*e.g.* aerial, river, sludge application and STW worker dose) are presented in Table 20, together with the facility (or river reach) with which the maximum dose is associated. It can be seen from Table 20 that the estimated doses from aerial releases, discharges to rivers and sludge application are, at most, of the order of tens of μSv per year, and that STW worker doses are estimated to be at most of the order of 1 μSv/y.

It should be stressed that the detailed assessment methodologies utilised here estimate the critical group doses under conservative assumptions and that the actual maximum doses received by members of the public in the Thames region are likely to be somewhat lower than those presented here. (It should also be recognised that doses received by typical members of the public in the Thames region will be very much lower that the critical group doses estimated here.) Given the conservative nature of the assessment and the estimation of a maximum annual individual dose of less than 10% of the dose limit, it may be concluded that the discharges of radioactivity within the Thames region do not lead to anyone exceeding the individual annual dose limit of 1mSv.

10 SUMMARY AND CONCLUSIONS

The EA has new duties in accordance with the Basic Safety Standards Directive [1] and the DETR Radioactive Substances (Basic Safety Standards) Direction 2000 [3]. In particular, the EA is now required to ensure that the sum of the doses resulting from exposure to members of the public resulting from the discharge of radioactive waste should not exceed the dose limit set out in article 13 (*i.e.* a maximum annual individual effective dose of 1mSv). In order to develop a suitable methodology for assessing compliance with the regulatory requirements, the scope of the required assessment procedure has been defined through review of the regulatory documents.

The scope of the assessment methodology is summarised as follows:

- **Exposure Routes**
  The dose limits apply to doses received by all exposure routes except:
  - exposures to natural radiation (except in special circumstances, such as the production wastes containing Naturally Occurring Radioactive Material or 'NORM');
  - radon in dwellings (it may be noted that whilst this is strictly a natural source of radiation, it was felt necessary to explicitly exclude it under the Directive, as it is strongly influenced by human activity relating to the construction and ventilation of dwellings); and
  - medical exposures.
- **Types of Dose**
  The assessment methodology is essentially restricted to the retrospective estimation of effective dose to representative members of critical groups. Nonetheless, the assessment methodology does include the provision for qualitative treatment of collective dose to selected subsets of the population.

The assessment methodology has been developed with a screening protocol to enable the scale of the assessment to be kept to a manageable level without loss of rigour. For those sources that pass the screening process, a detailed assessment methodology has been developed that allows for the aggregation of doses from a number of different sources and exposure routes. A theoretical approach has been taken to the definition of critical groups that allows for definition of such groups in terms of homogeneity in received dose. The key parameters required for the identification and characterisation of such critical groups have been identified as those describing:

- Population habits and behaviour;
- Environmental media (categorisation and levels of contamination);
- Spatial environmental domains of interaction between individuals and environmental media;
- Dose conversion factors.

An assessment methodology has been developed to assess critical group doses from both licensed nuclear facilities (around which significant levels of environmental monitoring and habit survey data are available) and non-licensed sites (around which monitoring data are at best limited and for which critical groups may not typically have been previously identified). These methodologies have been implemented through the development of a number of Excel spreadsheets, which should facilitate future assessments. The developed methodology differs from previous assessment methods in that the critical groups are defined by their estimated doses (from a range of pathways) rather than from their habits. As such, the critical groups are effectively composites of those that would be defined using a more traditional approach.

The assessment methodology has been used in two trial assessments:

- an assessment of critical group doses around the BNFL Sellafield facility in Cumbria; and
- an assessment of critical group doses in the EA Thames region due to discharges from both licensed and non-licensed sites in the region.

The trial assessment of the doses around Sellafield produced individual annual effective dose estimates for members of the "composite" critical group broadly comparable to the high marine food consumer critical group doses estimated by, for example, the FSA. Hence, the application of the new methodology provides confidence that, not only have the key critical group habits previously been identified, but also that the taking into account of multiple sources for a variety of exposure pathways does not lead to the dose limit being exceeded by the representative member of the critical group. However, it is noted that the most exposed individual was assessed as receiving an effective dose slightly above the dose limit. The BSS is unclear as to whether the dose limit applies to the most exposed individual or to a representative member of the critical group. It was considered by the authors that, for practical assessment purposes, the limit should be assumed to apply to the representative member of the critical group. This view was agreed with the EA and the NII, although the FSA has yet to finalise its position in this regard. It is suggested that clarification of this point is sought by the EA from the DEFRA.

The assessment methodology for licensed sites relies on the availability of sufficient suitable environmental monitoring and habit survey data. In particular, the approach is best served by the availability of integrated habit survey data in which all surveyed individuals provided details of habits that relate to all possible exposure routes. This type of integrated survey has not yet been undertaken and, for the trial assessments reported here, an approach has been developed to show how integrated habit survey datasets may be generated from a synthesis of partial surveys by the use of assumed/derived correlations between habits. Nonetheless, the use of integrated surveys is recommended and it is noted that the main organisations funding the gathering of such data, *i.e.* the EA and FSA, are now moving towards this goal.

For assessment of the individual doses that may result from the discharge of radioactivity from non-licensed sites, a conservative modelling-based assessment approach was developed. This methodology has been implemented within a spreadsheet format and applied to the Thames region. For the Thames region, it has been demonstrated that, under very conservative assumptions, the doses to members of the public comply with the limit on annual effective dose of 1mSv. The implementation of the methodology within a spreadsheet tool facilitates the application of the approach to other regions; were this to show that doses from certain non-licensed sites challenged the dose limit, then environmental monitoring and the collection of habit survey data would be merited in order to allow a more rigorous assessment

to be undertaken (in a manner similar to that for licensed sites). Also, it is noted that the assessment method for non-licensed sites would benefit from future development onto a GIS-based system.

11 REFERENCES

1 Council Directive 96/29/Euratom of 13 May 1996, laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation, L159, Vol 39, 29 June 1996.

2 *Review of radioactive waste management policy: Final Conclusions*, Cm 2919 HMSO (1995).

3 The Radioactive Substances (Basic Safety Standards) (England and Wales) Direction 2000, DETR direction, May 2000.

4 RWMAC. Advice on Issues which need to be addressed in the Guidance to be given to the Environment Agencies on the Principles for determining Radioactive Waste Discharge Authorisations, 1998.

5 *Generalised habit data for radiological assessments*, NRPB-M636 1996.

6 MAFF/SEPA, *Radioactivity in Food and the Environment, 1999*, RIFE-5, 2000.

7 Environment Agency, *Radioactivity in the Environment, a summary and radiological assessment of the Environment Agencies Monitoring Programmes*, Report for 1998.

8 ICRP Publication 60, *1990 Recommendations of the International Commission on Radiological Protection*, Annals of the ICRP, **21(1-3)**, 1991.

9 ICRP Publication 26, *Recommendations of the ICRP*, Annals of the ICRP, **1(3)**, 1977.

10 ICRP Publication 43*, Principles of Monitoring for the Radiation Protection of the Population*, Annals of the ICRP, **15(1)**, 1985.

11 ICRP Publication 72, *Age-dependent Doses to Members of the Public from Intakes of Radionuclides: Part 5 - Compilation of Ingestion and Inhalation Dose Coefficients*, Annals of the ICRP, **26(1)**, 1996.

12 ICRP Publication 79, *Genetic Susceptibility to Cancer*, Annals of the ICRP, **28(1/2)**, 1998.

13 Food Standards Agency. Consultative Exercise on Dose Assessments 3rd & 4th October 2000. Discussion of the methods of assessing the impact of radioactive discharges on the public. May 2001.

14 Magnox Consultation pack, Supporting Information, Annex 7.1 – Intercomparison of Radiological Assessments by BNFL, the Environment Agency and MAFF of discharges from Eight Magnox Power Stations in England and Wales, February 2000.

15 C A Robinson and J R Simmonds, *Recent Developments in Critical Group Methods* In: Proceedings International Conference on Implications of the New ICRP Recommendations on Radiation Protection Practices and interventions, Salamanca, November 1991.

16 C A Robinson, A Mayall, C A Attwood, T Cabianca, D H Dodd, C A Fayers, K A Jones, and J R Simmonds, *Critical Group Doses Around Nuclear Sites in England and Wales*, NRPB-R271 (DOE/HMIP/RR94/026) (MAFF FSD RP 0306), 1994.

17 J Byron, C A Robinson, J R Simmonds, B Walters and R R Taylor, *Food Intakes for Use in Generalised Radiological Dose Assessments,* Journal of Radiological Protection, **15**(4), 335-341, 1995.

18 MAFF, *Terrestrial Radioactivity Monitoring Programme (TRAMP) report for radioactivity in food and agricultural products in England and Wales,* London, MAFF, TRAMP/Report number, (various years).

19 D J Carruthers *et al.*, *UK-Atmospheric Dispersion Modelling System,* Crete NATO-CCMS Conference, 1991.

20 European Union, *Methodology for Assessing the Radiological Consequences of Routine Releases of Radionuclides to the Environment,* EUR 15760 EN, 1995.

21 NRPB, *Public Exposure: Guidance on the 1990 Recommendations of ICRP,* Documents of the NRPB, **4(2)**, 1993.

22 *Generalised Derived Constraints for Radioisotopes of Strontium, Ruthenium, Iodine, Caesium, Plutonium, Americium and Curium*, Documemts of the NRPB, **11(2)**, 2000.

23 R H Clarke, *A Model for Short and Medium Range Dispersion of Radionuclides Released to the Atmosphere*, NRPB-R91, 1979.

24 PC-CREAM 98, EUR 17791 EN, NRPB-SR296, 1998.

25 A Venter, G Smith and M Loose, *Radioactivity in Food due to Disposals from Non-Licensed Sites*, QS-MAFF-6134, QuantiSci Report to MAFF under Project Number RP-0441, 2000.

26 C McDonnell, *Assessment of the Radiological Consequences of Accumulation and Disposal of Radioactive Wastes by Small Users of Radioactive Materials*, NRPB-M744, 1996.

27 G Burholt and A Martin, *Radiological Assessment of Radioactive Waste Disposal from Non-Nuclear Premises in Anglian Region, Volume 1 – Methodology*, Report to the EA under Contract Ref. P0035/DOSE/CT, AMA/J95/R1, 1999.

28 www.foodstands.gov.uk

29 H Barr, *Stochastics of Individual Radiation Doses*, AEA Technology report to the Department of Health, AEA/CS/18142004/Z8/Issue 1, 1995.

30 www.environment-agency.co.uk

31 www.nerc-wallingford.ac.uk

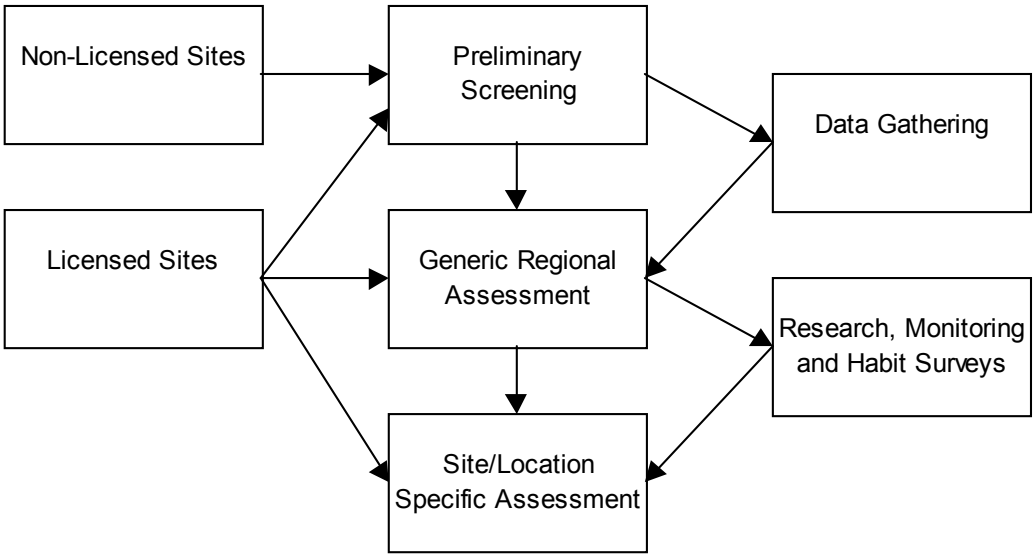

Figure 1 Outline Assessment Methodology

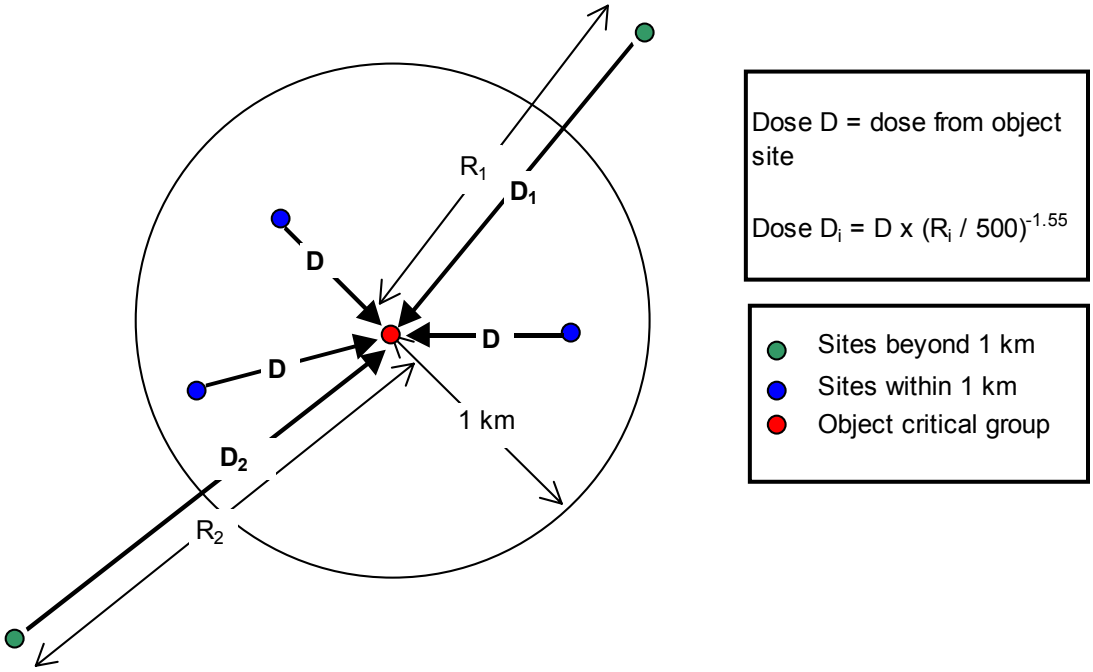

Figure 2 Doses to the Object Critical Group in the Preliminary Screening Protocol

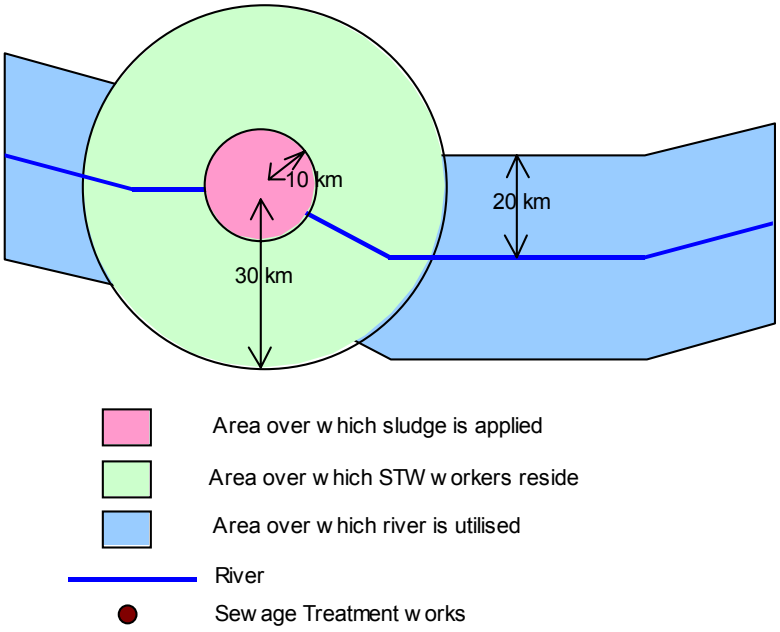

Figure 3 **Spatial Extent of Doses from Rivers and STW in the Generic Regional Assessment**

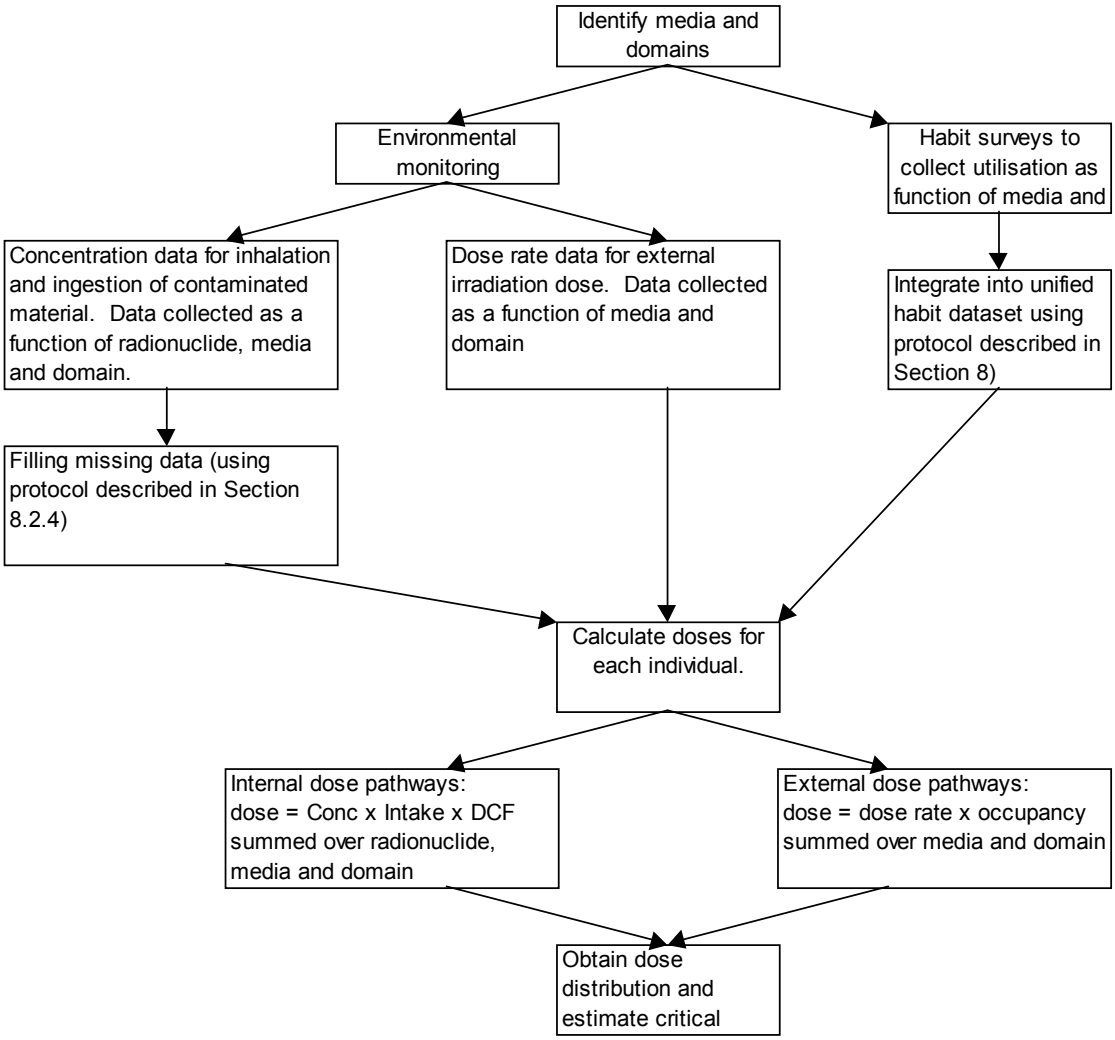

Figure 4 Calculation Flow for the Detail Site/Location Assessment

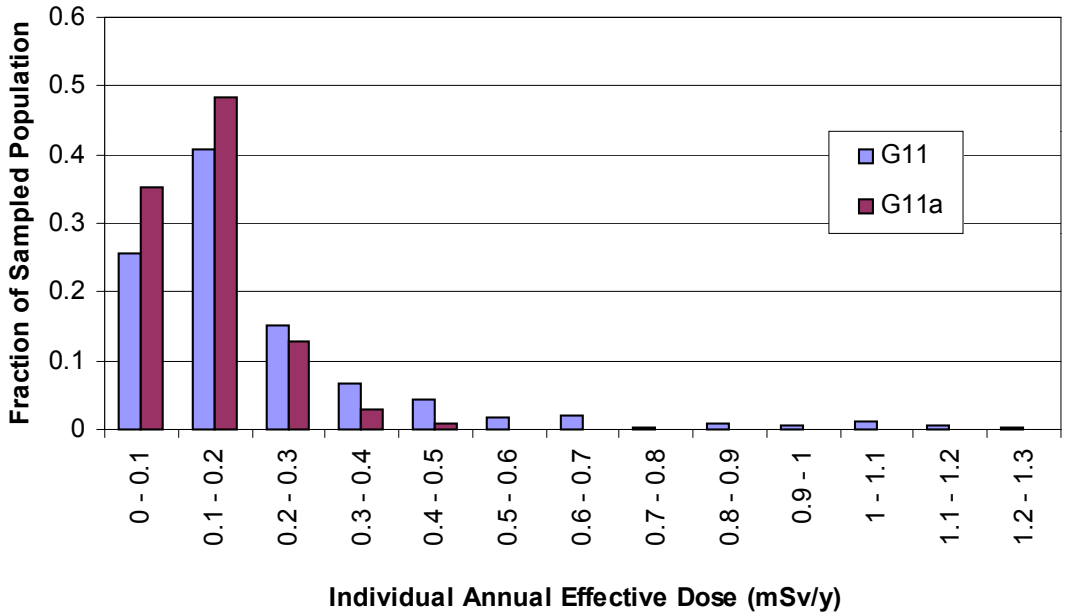

Figure 5 Distribution of Individual Doses for the Sellafield Assessment

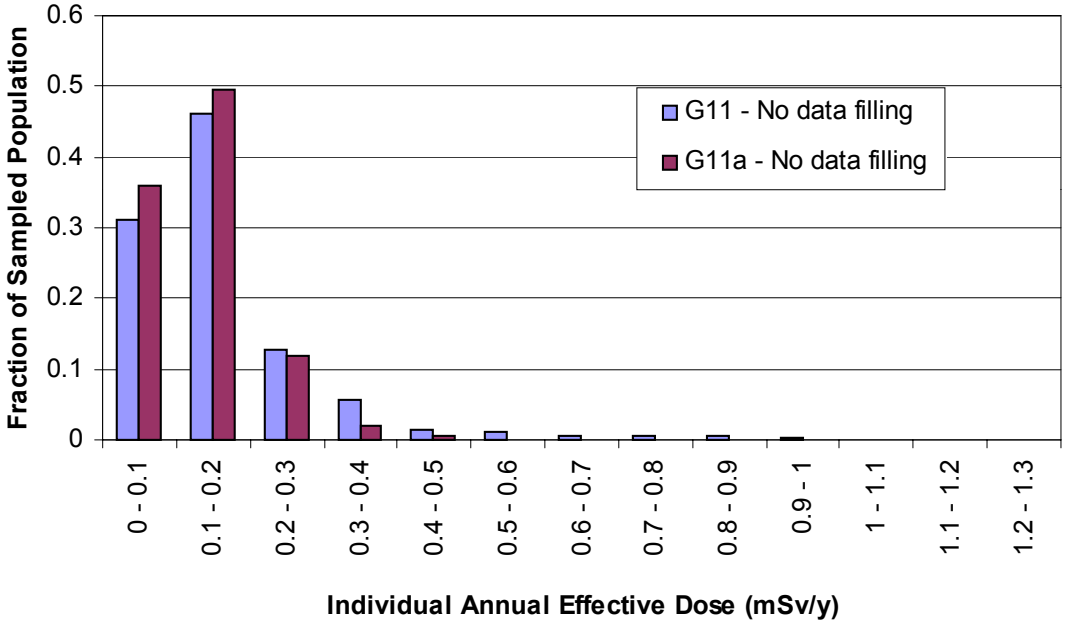

Figure 6 Distribution of Individual Doses for the Sellafield Assessment (No Filling of Monitoring Data)

Table 1 Basis of Assessment for Aerial Releases for the Preliminary and Generic Regional Assessments

Parameter	Unit	Value
Inhalation rate	m^3/y	7300[a]
Cloud γ location factor[b]	-	0.2
Deposited γ location factor[b]	-	0.1
Stack height	m	15

[a] Based on 20 m^3 d^{-1} which is appropriate to a mix of light activity, recreation and sleep.
[b] Building shielding factor from [20]

Table 2 Dose per Unit Aerial Release used in the Preliminary and Generic Regional Assessments (μSv/y per MBq/y)

Radionuclide	Ingestion Dose	Dose from Other Pathways	Total Dose
Ar-41	0	4.00E-08	4E-08
C-14	1.70E-05	9.20E-07	1.79E-05
Co-60	3.50E-05	5.50E-04	0.000585
Cr-51	1.20E-07	1.90E-07	3.1E-07
H-3	6.00E-08	2.60E-08	8.6E-08
I-125	2.30E-03	4.30E-06	0.002304
I-131	6.00E-04	1.20E-05	0.000612
I-133	5.00E-06	1.70E-05	0.000022
Kr-85	0	4.50E-10	4.5E-10
Nb-95	3.30E-07	6.20E-06	6.53E-06
P-32	1.60E-04	4.30E-06	0.000164
Pu-239	3.00E-04	3.50E-02	0.0353
S-35	8.50E-05	9.90E-07	8.6E-05
Sr-90	4.40E-04	2.60E-05	0.000466
Xe-133	0	1.60E-09	1.6E-09

Table 3 Basis of Assessment for Sewage Treatment Worker Doses

STW Worker Doses		
Parameter	**Unit**	**Value**
Occupancy (inhalation pathway)	h/y	2000
Occupancy (other pathways)	h/y	1000
Worker breathing rate	m^3/h	1.2[a]
Inadvertent ingestion rate	kg/h	$5x10^{-5}$ [b]
Resuspended sewage concentration	mg/m^3	0.1[c]
Sewage Sludge Land Application Doses		
Parameter	**Unit**	**Value**
Sludge application rate	kg/m^2	1
Occupancy on treated land	h/y	1000
Green vegetables consumption rate[d]	kg/y	80
Root vegetables consumption rate[d]	kg/y	130
Fruit consumption rate[d]	kg/y	75

[a] Based on moderate to high activity levels.
[b] Corresponds to 0.4 g/d and is equivalent to values used in [22].
[c] Based on typical observed dust load in air.
[d] High consumer consumption values taken from [5].

Table 4 Normalised Dose Rates per Unit Liquid Release used in the Preliminary and Generic Regional Assessments (μSv/y per MBq/y)

Radionuclide	**River Dose[a]**	**STW Factor[b]**	**Sewage Worker Dose[c]**	**Sludge Application Dose[c]**
Am-241	3.90E-04	1	9.23E-05	4.00E-03
C-14	1.70E-04	1	8.20E-08	3.80E-03
Ca-45	1.50E-05	1	9.80E-08	3.10E-06
Cl-36	7.00E-06	1	1.20E-07	1.50E-01
Co-57	2.60E-05	1	9.10E-05	3.17E+00
Co-58	5.30E-05	1	6.80E-04	4.00E-03
Cr-51	7.00E-07	1	2.30E-05	5.10E-05
Cs-137	1.70E-03	1	1.54E-04	1.30E-02
F-18	3.00E-07	1	6.90E-04	1.00E-10
Ga-67	3.40E-06	0.1	1.10E-04	1.10E-05
H-3	3.40E-07	1	5.90E-09	1.40E-03
I-123	1.40E-06	1	1.20E-04	1.10E-09
I-125	1.20E-04	1	3.10E-05	1.70E-05
I-131	1.70E-04	1	2.70E-04	1.30E-05
In-111	5.60E-06	1	2.90E-04	2.20E-05
P-32	4.40E-05	1	3.20E-07	2.90E-09
P-33	4.40E-06	1	3.30E-08	7.80E-08
Ra-226	9.80E-03	1	4.90E-05	1.50E-01
S-35	2.30E-05	1	1E-07	1.10E-05
Se-75	4.70E-04	0.1	0.00027	2.70E-03
Sr-89	5.50E-05	1	3.5E-07	1.20E-05
Sr-90	5.90E-04	1	4.2E-06	1.30E-01
Tc-99m	3.60E-07	1	0.000091	1.00E-10
Tl-201	4.40E-06	1	0.000065	5.70E-06

[a] Based normalised to a river flow rate of 1 m^3/s.
[b] Factor applied to the sludge application dose
[c] Doses normalised to a sewage flow rate of $1000m^3/d$. A flow rate of $2m^3/d$ (per discharging site to the works) is used in the preliminary screening protocol. STW specific flow rates are used in the generic regional assessment.

Table 5 Assumed Adult Utilisation Factors for Preliminary and Generic Regional Assessments

Utilisation at residence grid element		
Consumption of local food[a]		
Beef	kg/y	45
Milk	l/y	240
Milk Products	kg/y	60
Cow Liver	kg/y	10
Sheep Meat	kg/y	25
Sheep Liver	kg/y	10
Green Vegetables	kg/y	80
Root Vegetables	kg/y	130
Fruit	kg/y	75
Occupancy rates		
Occupancy at grid element	h/y	8760
Fraction spent indoors	-	0.5[b]
Utilisation of Nearest River Reach		
Drinking water consumption	l/y	600
Freshwater fish consumption	kg/y	2
River bank occupancy	h/y	500

[a] values based on critical group habits recommended in [5].
[b] Value based on outdoor workers [5].

Table 6 Principal Media Categories Considered in Assessment of UK Population Doses

Media Categories[1]	Release Environment	Exposure Modes	Population Type[2]
Air	Atmospheric	Inhalation External	Local farmers Local population
Installation (Direct shine)	N/A	External	Local farmers Local population
Agricultural Produce, *e.g.*: - Cereals[2] Potatoes & Root vegetables Green & other vegetables Tree and soft fruits Meat (Beef, sheep, Pig) Poultry Eggs Milk Milk Produce	Atmospheric[3]	Ingestion	Local farmers Wider population
Garden Produce: Potatoes & Root vegetables Green & other vegetables[2] Tree and soft fruits	Atmospheric	Ingestion	Local population
Wild Produce, *e.g.* Blackberries	Atmospheric	Ingestion	Local population
Freshwater systems as source of food/water abstraction Public water supply Non-public water supply Edible freshwater fauna Edible freshwater flora	River, reservoirs	Ingestion	Anglers Local population Wider population
Freshwater systems (other uses) Recreational use Residential use	River, lake, reservoir	Ingestion, inhalation external	Anglers, boatmen, boat dwellers, wind surfers *etc.*
Freshwater systems (sediments)	River, lake reservoir	External and Inhalation	Anglers
Sewage systems	Sewage works Sludge treated land	Ingestion, inhalation external	Sewage workers Food consumers Farmers
Marine/ Estuarine Fish Crustaceans Molluscs Macrophytic algae	Marine[4]	Ingestion	Fishermen, bait diggers, other high rate consumers
Marine Fishing nets Water	Marine[4]	External External (shine, submersion)	Fishermen Swimmers
Foreshore (estuarine & marine) Sediments	Marine[4]	External	Local & wider Baitdiggers Houseboat dwellers Wildfowlers

Notes:
1 Refers to media categories, not individual media, e.g. lettuce, cabbage which are members of the green & other domestic vegetable. media category.
2 Including garden herbs.
3 Limited potential from marine discharges via seaspray.
4 Limited potential for exposure from via rivers and estuaries discharging to sea.

Table 7 Definition of Domains for Detailed Site Assessments

Pathway	Near-field range	Far-field range
Marine food consumption	<15km	15km to 100km
Marine/foreshore occupancy[a]	<15km	-
Terrestrial food consumption	<1km	1km to 5km
Terrestrial occupancy (inhalation, groundshine, directshine and cloudshine pathways)	<1km	1km to 5km

[a] The marine/foreshore environment may be further sub-divided by type. For example, in the trial application of the method presented in Section 9, two domains were used, namely mud/sand and salt marsh based on the availability of monitoring data.

Table 8 Mapping of Environmental Monitoring Locations around Sellafield to Assessment Domains

Marine Food Monitoring			
Monitoring Location	**Domain[a]**	**Monitoring Location**	**Domain[a]**
Fleetwood	Far	Millom	Near
Fleswick Bay	Far	Nethertown	Near
Flookburgh	Far	North Harrington	Near
Laverbread	Far	Parton	Near
Morecambe Bay	Far	Ravenglass	Near
Saltom Bay	Far	River Derwent	Near
St Bees	Far	River Duddon	Near
Whitehaven	Far	Seascale	Near
Sellafield pipeline	Near	Sellafield Coastal Area	Near
Braystones South	Near	Sellafield Offshore Area	Near
Calder Farm Pond	Near	Silloth	Near
Drigg	Near	Tarn Bay	Near
Haverigg	Near	Whitriggs	Near
Terrestrial Food Monitoring			
Monitoring Location	**Domain**	**Monitoring Location**	**Domain**
Ravenglass	Far	Sellafield	Near
Drigg	Far		
Beach Dose Rate Monitoring			
Monitoring Location	**Domain**	**Monitoring Location**	**Domain**
Arnside	Salt marsh	Ravenglass Raven villa	Sand/Mud
Drigg Barn Scar	Sand/Mud	Ravenglass Salmon garth	Sand/Mud
Flookburgh	Sand/Mud	Rockcliffe Marsh	Salt marsh
Haverigg	Sand/Mud	Saltom Bay	Sand/Mud
High Foulshaw	Salt marsh	Sand Gate Marsh	Salt marsh
Millom	Sand/Mud	Sellafield	Sand/Mud
Nethertown	Sand/Mud	Sellafield pipeline	Sand/Mud
Newbiggin	Salt marsh	St Bees	Sand/Mud
Newton Arlosh	Salt marsh	Tarn Bay	Sand/Mud
Parton	Sand/Mud	Walney channel	Sand/Mud
Ravenglass Carleton Marsh	Salt marsh	Whitehaven	Sand/Mud
Ravenglass ford	Sand/Mud	Whitehaven outer harbour	Sand/Mud

[a] Domains defined in Table 7.

Table 9 Food Types Considered in the Sellafield Assessment

Marine Food Types			
Specific Food Type	**Generic Food Type**	**Specific Food Type**	**Generic Food Type**
Cockles	Molluscs	Plaice	Fish
Cod	Fish	Prawns	Crustacea
Crab	Crustacea	Scallops	Molluscs
Crustacea	Crustacea	Seaweed	Seaweed
Fish	Fish	Shrimps	Crustacea
Laverbread	Seaweed	Skate	Fish
Limpets	Molluscs	Squid	Molluscs
Lobsters	Crustacea	Tinned Laverbr'd	Seaweed
Molluscs	Molluscs	Whelks	Molluscs
Mussels	Molluscs	Winkles	Molluscs
Nephrops	Crustacea		
Terrestrial Food Types			
Specific Food Type	**Generic Food Type**	**Specific Food Type**	**Generic Food Type**
Apples	Fruit	Milk	Milk
Barley	Cereal	Mushrooms	Fungi
Beans	Green Veg	Offal other	Offal
Beef Meat	Meat	Green Veg Other	Green Veg
Beef Offal	Offal	Root Veg Other	Root Veg
Cabbage	Green Veg	Veg Other	Root Veg
Carrots	Root Veg	Pears	Fruit
Cereals Other	Cereal	Pheasants	Poultry
Chicken	Poultry	Pig Meat	Meat
Duck	Poultry	Pigeons	Poultry
Eggs	Poultry	Potatoes	Root Veg
Fruit Other	Fruit	Poultry Other	Poultry
Fungi Other	Fungi	Rabbits	Meat
Grass	Green Veg	Sheep Meat	Meat
Hares	Meat	Sheep Offal	Offal
Honey	Honey	Swede	Root Veg
Lettuce	Green Veg	Wild Fungi	Fungi
Meat Other	Meat		

Table 10 Assumed Background Concentrations in Foods around Sellafield

Terrestrial Food Background Concentrations (Bq/kg or Bq/l)			
Food Type	**^{14}C Concentration**	**Food Type**	**^{14}C Concentration**
Apples	10	Meat Other	44
Beans	23	Milk	18
Beef Meat	44	Mushrooms	5
Cabbage	8	Pears	10
Carrots	8	Pig Meat	54
Chicken	72	Potatoes	23
Eggs	38	Poultry Other	72
Fruit Other	10	Rabbits	54
Fungi Other	5	Root Veg Other	8
Green Veg Other	8	Sheep Meat	54
Hares	54	Swede	8
Honey	79	Veg Other	23
Lettuce	8	Wild Fungi	5
Marine Food Background Concentrations (Bq/kg or Bq/l)			
Food Type	**^{14}C Concentration**	**^{210}Pb Concentration**	**^{210}Po Concentration**
Cockles	24	0.69	18
Cod	26	0.025	0.28
Crab	27	0.3	15
Crustacea	27	0.08	5.2
Fish	26	0.025	0.28
Limpets	24	0.69	9.4
Lobsters	27	0.08	5.2
Molluscs	24	0.69	9.4
Mussels	24	1.1	33
Nephrops	27	0.08	5.2
Plaice	26	0.025	0.28
Prawns	27	0.08	5.2
Scallops	24	0.69	9.4
Shrimps	27	0.08	5.2
Skate	26	0.025	0.28
Squid	24	0.69	9.4
Whelks	24	0.69	9.4
Winkles	24	0.69	12

Table 11 Summary of Annual Effective Doses to Individuals for the Sellafield Assessment in 1999 (mSv/y)

Population Group	Total Dose Critical Group Mean[#]	Terrestrial Food Critical Group Mean[#]	Marine Food Critical Group Mean[#]	Beach Occupancy Critical Group Mean[#]	Inland Occupancy Critical Group Mean[#]
G11	0.669	0.0831	0.583	0.0715	0.0501
G12	0.654	0.0831	0.583	0.0715	0.0017
G21	0.667	0.0647	0.583	0.0715	0.0501
G22	0.646	0.0647	0.583	0.0715	0.0017
G11b*	0.228	0.0831	0.120	0.0715	0.0501

[#] Critical group mean, where the critical group is defined as those individuals whose total dose is within a factor of 3 of the maximum individual dose
* G11b is as G11, except that ^{210}Po and ^{210}Pb have been excluded from the assessment

Table 12 Summary of Assessed Annual Effective Doses to Individuals around Some Other Licensed Nuclear Sites in 1999 (mSv/y)

Site/Population group*	Total Dose Critical Group Mean	Terrestrial Food Critical Group Mean	Marine Food Critical Group Mean	Beach Occupancy Critical Group Mean	Inland Occupancy Critical Group Mean
Aldermaston (T)	1.80E-3	1.83E-3			
Amersham (T)	4.14E-3	4.14E-3			
Bradwell (M)	9.69E-1[$]		4.66E-3	3.24E-1	6.40E-1[#]
Cardiff (M)	2.32E-2		2.32E-2		
Cardiff (T)	8.53E-3	4.04E-3	1.20E-2		
Dungeness (M)	2.04E-2[$]		2.46E-3	1.80E-2	
Hartlepool (M)	8.27E-2[$]		5.72E-3	6.70E-2	1.00E-2[#]
Hartlepool (T)	8.34E-2[†]	6.42E-3	7.15E-4	6.70E-2	1.00E-2[#]
Harwell (T)	4.06E-3	4.06E-3			
Sizewell (T)	1.10E-2	1.06E-2	1.91E-3		
Springfields (T)	5.09E-2	7.29E-3	4.70E-2		

* T denotes population group based on high terrestrial food consumers. M denotes population group based on high marine food consumers.
[#] Critical group doses provided by the NII
[$] Total dose estimated from simple addition of pathways
[†] Inland occupancy and beach occupancy contributions to the total dose estimated through simple addition

Table 13 Non-Licensed Sites in the Thames Region (Non-Zero Returns for Gaseous Discharges)

ID	Name	ID	Name
AG7032	GE Lighting Ltd	AU1178	The Hillingdon Hospital Nhs Trust
AI5693	Radcliffe Infirmary NHS Trust	AU5165	Marconi Materials Technology
AJ1317	The Council For The Central Laboratory of The Research Councils	AU9144	Luton and Dunstable Hospital, Lewsey Road, Luton, LU4 0DZ
AK9909	University of Oxford Research Institute, Churchill Hospital	AV7945	National Radiological Protection Board
AK9925	University of Oxford, Institute of Molecular Medicine	AY1935	Wellhouse NHS Trust
AM8113	University of Oxford, Radcliffe Infirmary	AY6813	Glaxo Research and Development Ltd, Gunnels Wood Road
AM8121	University of Oxford, University Clinical Dept	AZ0713	Smithkline Beecham Pharmaceuticals
AO2957	Jet Joint Undertaking	AZ4808	Ashford and St Peters Hospitals NHS Trust, Guildford Road
AO7347	Rothamsted Experimental Station	AZ5286	Medical Research Council - Hammersmith
AO7592	Princess Alexandra Hospital Services	BA1001	Bbsrc Institute For Animal Health, Ash Road
AP9108	Veterinary Laboratories Agency	BA4019	Hammersmith Hospitals NHS Trust, Du Cane Road
AQ4039	Northwick Park and St Marks NHS Trust	BA7395	Glaxo Research and Development Ltd, Park Road
AQ7577	The Council For The Central Laboratory of The Research Councils	BB0779	Mount Vernon and Watford Hospitals NHS Trust, Watford Hospital
AS9984	Natural Environment Research Council	BB1481	Safeguard International Ltd
AT2870	Smithkline Beecham Plc	BB6793	University College London
AT5003	Guys and St Thomas Hospital Trust and GKT Medical	BB8621	Luton and Dunstable Hospital NHS Trust
AT5810	Brunel University	BB8729	Roche Products Ltd
AT5917	Nibsc	BE6919	Institute For Animal Health, Compton
AT7499	Merck Sharp and Dohme Laboratories		

Table 14 Non-Licensed Sites in the Thames Region (Non-zero Returns for Liquid Discharges)

ID	Name	ID	Name
AC1466	Bio Rad Laboratories Ltd	AX5633	Rhone Poulenc Rorer Ltd
AC1687	Birbeck College	AX6150	Celltech Therapeutics Ltd
AC5658	University of North London	AX7067	Glaxo Research and Development Ltd, Langley Court
AD2581	Zinsser Analytic Ltd	AX8349	Bibra International
AF5662	Imperial College of Science and Technology and Medicine	AX8616	Oxford Radcliffe Hospital NHS Trust
AG7032	GE Lighting Ltd	AY1617	Swindon and Marlborough NHS Trust
AG9841	The Royal Veterinary College	AY1935	Wellhouse NHS Trust
AI1434	Richmond,Twickenham and Roehampton Health Authority	AY2036	Bio Products Laboratory
AI4344	Royal Brompton and Harefield NHS Trust	AY2770	Redbridge Healthcare NHS Trust
AI5693	Radcliffe Infirmary NHS Trust	AY3997	The Oxford Radcliffe Hospital NHS Trust
AJ8346	Epsom Healthcare NHS Trust	AY4659	Bayer Plc
AK2564	North Hampshire Hospitals National Health Service	AY4918	The Forensic Science Service
AK5253	Bmi Health Care Group Plc	AY6813	Glaxo Research and Development Ltd, Gunnels Wood Road
AK9925	University of Oxford, Institute of Molecular Medicine	AY7020	Oxagen Ltd
AK9933	University of Oxford, Nuffield Orthopaedic Centre	AY7569	Hammersmith Hospitals NHS Trust
AL6387	Royal National Orthopaedic Hospital Trust	AY7712	Royal Brompton and Harefield NHS Trust
AM8091	Xenova Group Plc, Bath Road	AY7844	Oxford Brookes University
AM8113	University of Oxford, Radcliffe Infirmary	AY8000	Queen Charlottes and Chelsea Hospital

ID	Name	ID	Name
AM8121	University of Oxford, University Clinical Dept	AY8280	Novartis Institute For Medical Sciences
AN0754	National Blood Authority	AY8778	Yamanouchi UK Ltd
AN6370	WRC - NSF Ltd	AZ0713	Smithkline Beecham Pharmaceuticals
AO2957	Jet Joint Undertaking	AZ1256	PPP Columbia Healthcare Limited
AO4933	Ashford and St Peters Hospitals NHS Trust, London Road	AZ2767	Bromley Hospitals NHS Trust
AO5280	The London Hospital Medical College and The Royal Hospitals NHS Trust	AZ4093	Imperial Cancer Research Fund
AO7347	Rothamsted Experimental Station	AZ4107	Imperial Cancer Research Fund, South Mimms
AO7592	Princess Alexandra Hospital Services	AZ4735	Imperial College School of Medicine
AO7789	Kingston Hospital NHS Trust	AZ4808	Ashford and St Peters Hospitals NHS Trust, Guildford Road
AO8394	Medscreen Ltd	AZ5286	Medical Research Council - Hammersmith
AP0739	University of Greenwich	AZ5731	Oxford Glycosciences UK Ltd
AP7270	The Institute of Cancer Research	AZ8528	Royal Holloway University of London
AP7580	Dunbar Imaging Ltd	BA0757	University College London
AP8284	Eisai London Research Laboratories Ltd	BA0765	University College London
AP9108	Veterinary Laboratories Agency	BA0773	University College London
AP9612	East Hertfordshire NHS Trust	BA1001	BBSRC Institute For Animal Health, Ash Road
AQ1510	The Royal Veterinary College	BA1256	London University
AQ2966	Smithkline Beecham Plc	BA2407	National Heart and Lung Institute
AQ3920	The Institute of Cancer Research	BA2997	Prolifix Ltd
AQ4004	Stoke Mandeville Hospital NHS Trust	BA3560	Institute of Child Health
AQ4012	Guys and St Thomas Hospital Trust	BA3985	Imperial Cancer Research Fund, Du Cane Road
AQ4039	Northwick Park and St Marks NHS Trust	BA4019	Hammersmith Hospitals NHS Trust, Du Cane Road
AQ9405	Institute of Zoology	BA4027	Imperial College School of Medicine At Hammersmith
AR2562	Thames Water Utilities Ltd	BA4787	Forest Healthcare NHS Trust
AR3488	Institute of Neurology	BA6348	Chelsea and Westminster Healthcare Trust
AR7831	London School of Hygiene and Tropical Medicine	BA7395	Glaxo Research and Development Ltd, Park Road
AR9095	James Black Foundation	BA7522	British Biotech Pharmaceuticals Ltd
AS4885	Royal Berkshire and Battle Hospitals NHS Trust	BA9053	Lewisham Hospital NHS Trust
AS8210	University of Surrey	BA9614	Greenwich Healthcare NHS Trust
AS9984	Natural Environment Research Council	BA9843	London University
AT0087	South Buckinghamshire NHS Trust	BB0779	Mount Vernon and Watford Hospitals NHS Trust, Watford Hospital
AT2870	Smithkline Beecham Plc	BB1406	Havering Hospitals NHS Trust
AT5003	Guys and St Thomas Hospital Trust and GKT Medical	BB1481	Safeguard International Ltd
AT5810	Brunel University	BB2488	National Institute For Medical Research
AT5917	NIBSC	BB4952	Royal Brompton and Harefield NHS Trust
AT7499	Merck Sharp and Dohme Laboratories	BB5568	Therapeutic Antibodies UK Ltd
AT7596	Greenwich Healthcare Trust	BB5665	The Surrey and Sussex Healthcare NHS Trust
AT7910	Rhone Poulenc Agriculture Ltd	BB6793	University College London
AT8177	Cromwell Hospital	BB8621	Luton and Dunstable Hospital NHS Trust
AU0031	Institute of Ophthalmology	BB8729	Roche Products Ltd
AU0147	Unilabs Lister	BB9024	St Albans and Hemel Hempstead NHS Trust, Hillfield Road
AU0317	Zeneca Agrochemicals	BC1398	St Helier NHS Trust
AU1178	The Hillingdon Hospital NHS Trust	BC1592	University of Luton
AU3863	Eli Lilly and Co Ltd	BC2491	Newham Healthcare NHS Trust
AU5165	Marconi Materials Technology	BC4613	London Independent Hospital
AU5556	Barts and The London NHS Trust, West Smithfield	BE6889	The Edward Jenner Institute For Vaccine Research
AU9144	Luton and Dunstable Hospital, Lewsey Road, Luton, LU4 0DZ	BE6919	Institute For Animal Health, Compton
AV3044	Dr M Buxton, 126 Harley Street, London	BE8300	Kings Healthcare NHS Trust
AV4563	Smithkline Beecham Plc	BF0096	Glaxo Research and Development Ltd, Langley Court

ID	Name	ID	Name
AV5748	The Royal Marsden NHS Trust	BF3141	British Museum
AV6728	Chandos Clinical Research Ltd	BF4296	University of Oxford, Wellcome Trust
AV8011	Royal Free Hampstead NHS Trust	BF6400	Gray Laboratory Cancer Research Trust
AW0423	Pharmagene Laboratories Ltd	BF7821	University College London
AW1322	The Royal Veterinary College	BF9964	Therapeutic Antibodies UK Ltd
AW2329	Central Middlesex Hospital Trust	BG0440	Cerebrus Limited
AW3244	Frimley Park Hospital NHS Trust	BG1586	St Georges Healthcare NHS Trust
AW4054	The Mathilda and Terence Kennedy Institute	BG1667	Royal Surrey County Hospitals Trust
AW6561	Ortho Clinical Diagnostics	BG2051	North Middlesex Hospital NHS Trust
AW6731	Eastman Dental Institute and Hospital	BG2841	University College London
AW7673	Whittington Hospital NHS Trust	BG5085	Veterinary Laboratories Agency
AW8114	University of East London	BG6812	The Institute of Psychiatry
AW8220	University of Luton	BG7274	Barts and The London NHS Trust, Whitechapel
AW8289	St Albans and Hemel Hempstead NHS Trust, Waverley Road	BG7614	Vertex Pharmaceuticals Europe Ltd
AX3894	Oxford Biomedica Plc	BG7835	Graseby Dynamics Ltd
AX4211	Queen Mary and Westfield College	RW/RAL/889	London Independent Hospital

Table 15 List of Surrogate Radionuclides

Radionuclide	Surrogate	
	Liquid Discharges	**Gaseous Discharges**
Activation products	Cs-137	Co-60
C-11	-	Ar-41
Ca-45	-	Sr-90
Any other radionuclide	Cs-137	I-125
Beta emitters	Sr-90	-
Ni-63	Sr-90	-
Other non-alpha	Cs-137	-
Rb-83	Cs-137	-
Rb-84	Cs-137	-
Pu-241	C-14	
Cl-36	-	C-14
F-18	-	Ar-41
I-123	-	I-133
In-111	-	Nb-95
P-33	-	S-35
Tc-99m	-	Ar-41
Se-75	-	S-35

Table 16 1999 Discharges from Licensed Sites in the Thames Region (TBq)

UKAEA Harwell					
Discharge Route	**Alpha**	**Beta**	**^{3}H**	**^{60}Co**	**^{137}Cs**
Pipeline	2.69E-5	2.28E-3	4.84E-2	7.54E-5	4.32E-4
Lydebank	3.08E-5	2.30E-4	1.75E-2	-	-
Gaseous	1.15E-7	2.36E-6	2.55E+0	-	-

Nycomed Amersham									
Discharge Route	**Alpha**	**Beta**	**^{3}H**	**^{125}I**	**^{137}Cs**	**Other**	**^{75}Se**	**^{131}I**	**^{222}Rn**
Liquid	3.96E-5	8.65E-3	1.4E-3	6.03E-4	1.88E-5	4.45E-2	-	-	-
Gaseous	1.30E-7	-	-	6.90E-3	-	1.8E-2	2.70E-4	5.40E-4	1.6E+0

MoD Aldermaston						
Discharge Route	**Alpha**	**Beta**	**^{3}H**	**^{241}Pu**	**^{85}Kr**	**Other**
Pipeline	1.40E-5	-	1.05E-3	5.59E-5	-	9.42E-6
Silchester	6.77E-6	1.82E-5	-	-	-	-
Gaseous	1.01E-7	7.76E-8	6.25	-	4.69E-3	-

MoD Burghfield				
Discharge Route	**Alpha**	**^{3}H**	**^{85}Kr**	**Other**
Liquid	4.08E-8	-	-	8.16E-8
Gaseous	1.10E-9	1.00E-6	0	-

Table 17 Estimated Annual Individual Effective Doses from Sites that Passed the Preliminary Screening

Facility	Aerial Dose (uSv/yr)	River Dose[a] (uSv/yr)	STW Dose[b] (uSv/yr)	Total Dose (uSv/yr)	Receiving STW
AG7032	7.5E-01	N/A	6.3E+01	6.3E+01	Maple Lodge
AJ1317	1.6E+05[c]	N/A	N/A	1.6E+05[c]	N/A
AK9925	2.0E-01	N/A	1.6E+02	1.7E+02	Sandford
AM8113	1.5E-05	N/A	6.7E+01	7.1E+01	Sandford
AM8121	1.9E-03	N/A	7.7E+01	8.2E+01	Sandford
AO2957	1.2E+00	N/A	7.4E+01	7.5E+01	N/A
AQ4039	3.0E-01	N/A	9.5E+01	9.6E+01	Mogden
AT5003	4.4E-01	N/A	1.9E+03	2.0E+03	Cross Ness
AT7499	3.3E+01	N/A	4.1E+02	4.5E+02	Rye Meads
AY6813	1.0E+01	N/A	2.1E+02	2.4E+02	Rye Meads
AZ0713	1.2E+00	N/A	1.1E+02	1.2E+02	Rye Meads
AZ5286	N/A	N/A	5.8E+01	6.5E+01	Beckton
BA4019	N/A	N/A	8.1E+01	8.2E+01	Beckton
BB8729	2.9E-01	N/A	4.3E+02	4.4E+02	Rye Meads
Harwell	1.9E+00	2.5E+01	1.3E+02	1.5E+02	Private
Amersham	4.8E+02	N/A	2.8E+03	3.3E+03	Maple Lodge
AI4344	N/A	N/A	1.4E+02	1.4E+02	Beckton
AO5280	N/A	N/A	1.0E+02	1.1E+02	Beckton
AQ4012	N/A	N/A	1.6E+02	1.6E+02	Cross Ness
AS4885	N/A	N/A	1.2E+02	1.4E+02	Reading
AS8210	N/A	N/A	8.8E+02	9.9E+02	Guildford
AT7596	N/A	N/A	7.4E+01	7.6E+01	Cross Ness
AT8177	N/A	N/A	1.7E+02	2.0E+02	Beckton
AU5556	N/A	N/A	1.4E+03	1.8E+03	Beckton
AV8011	N/A	N/A	5.4E+02	5.9E+02	Beckton
AW2329	N/A	N/A	2.0E+02	2.0E+02	Beckton
AW3244	N/A	N/A	8.2E+01	8.4E+01	Camberley
AX5633	N/A	N/A	3.7E+02	4.1E+02	Beckton
AY1617	N/A	N/A	1.0E+02	1.0E+02	Swindon/S282
AY3997	N/A	N/A	2.1E+02	2.5E+02	Sandford
AY7569	N/A	N/A	2.5E+02	3.0E+02	Beckton
AY7712	N/A	N/A	9.6E+01	9.8E+01	Mogden
AZ4093	N/A	N/A	7.9E+01	1.0E+02	Beckton
AZ4735	N/A	N/A	1.2E+02	1.3E+02	Beckton
BA4787	N/A	N/A	5.5E+02	5.5E+02	Beckton
BA9614	N/A	N/A	9.3E+01	9.6E+01	Cross Ness
BB1406	N/A	N/A	1.2E+02	1.4E+02	Riverside
BB5665	N/A	N/A	6.8E+01	6.9E+01	Earlswood
BE8300	N/A	N/A	7.4E+02	7.9E+02	Cross Ness
BG1586	N/A	N/A	3.9E+03	4.0E+03	Cross Ness
BG1667	N/A	N/A	7.5E+02	8.2E+02	Guildford
BG2051	N/A	N/A	1.6E+02	1.8E+02	Deepham
BG5085	N/A	N/A	1.6E+02	1.8E+02	Chertsey
BG7614	N/A	N/A	6.0E+01	6.9E+01	Abingdon
BG7835	N/A	N/A	5.1E+03	5.2E+03	Maple Lodge

[a] River doses based on conservative estimation of river flow (1 m^3/s).

[b] STW doses based on conservative estimation of sewage flow rate through works (2 m^3/day per discharging site to the works).

[c] Dose estimate based on use of ^{60}Co as surrogate for "activation products". A more accurate breakdown is utilised in the generic regional assessment (see Section 9.4.2).

Table 18 Summary of Receiving Sewage Treatment Works in the Thames Region

STW	Easting	Northing	Sewage Flow (m^3/day)	Sludge application
Abingdon	449120	195120	1.00E+05[a]	Yes
Beckton	539540	180600	1068493	No
Camberley	484800	159500	1.00E+05[a]	Yes
Chertsey	501600	168000	1.00E+05[a]	Yes
Cross Ness	539540	180600	739726	No
Deepham	535660	193170	2.00E+05	Yes
Earlswood	526700	143600	1.00E+05[a]	Yes
Guildford	500300	151600	1.00E+05[a]	Yes
Maple Lodge	504200	192000	142465.8	Yes
Mogden	516800	175900	493150.7	Yes
Reading	467500	164500	1.00E+05[a]	Yes
Riverside	551520	181980	2.5E+05	No
Rye Meads	541650	216280	1.00E+05[a]	Yes
Sandford	454200	202200	49315.07	Yes
Swindon/S282	412700	185700	1.00E+05[a]	Yes

[a] Estimated value. Since the completion of the trial assessment actual data has been supplied by Thames Water which may be used by the EA in future assessments.

Table 19 River Reach System for Thames Region Assessment

Reach ID	Start	Easting	Northing	End	Easting	Northing	Length (km)	Flow (m^3/s)	Next reach
1	Swindon	412700	185700	Haydon wick	411700	188180	4.2	1.29	2
2	Haydon wick	411700	188180	Ray-Thames	412240	193950	7.8	1.29	3
3	Ray-Thames	412240	193950	Thames-Share ditch	416530	195980	7.3	9.15	4
4	Thames-Share Ditch	416530	195980	Thames-Bydemill Brook	419500	196810	3.8	9.15	5
5	Thames-Bydemill Brook	419500	196810	Thames-Colne	420490	198840	2.9	9.15	6
6	Thames-Coln	420490	198840	Thames-Shifford Weir	436350	200680	22.5	9.15	7
7	Thames-Shifford Weir	436350	200680	Thames-Bablock Hythe	443500	204240	12.4	9.15	8
8	Thames-Bablock Hythe	443500	204240	Thames-Evenlode	445780	209780	8	14.49	9
9	Thames-Evenlode	445780	209780	Thames-Castle Mill	450940	205520	9.3	14.49	10
10	Thames-Castle Mill	450940	205520	Thames-Cherwell	452000	205050	1.4	14.49	11
11	Thames-Cherwell	452000	205050	Thames-Sandford lock	453100	201240	4.4	14.49	12
12	Thames-Sandford lock	453100	201240	Thames-Ock	449670	196640	8.5	14.49	13
13	Thames-Ock	449670	196640	Thames-Sutton Bridge	450900	194800	3.7	14.49	14
14	Thames-Sutton Bridge	450900	194800	Thames-Thame	457800	193210	11.5	24.87	15
15	Thames-Thame	457800	193210	Thames-GoringSTW	459700	183000	14.2	27.89	16
16	Thames-GoringSTW	459700	183000	Thames-Whitchurch	463000	176900	8.5	27.89	17

Reach ID	Start	Easting	Northing	End	Easting	Northing	Length (km)	Flow (m^3/s)	Next reach
				STW					
17	Thames-Whitchurch STW	463000	176900	Thames-Kennet	473100	173880	12.6	27.89	18
18	Thames-Kennet	473100	173880	Thames-Loddon	477880	178680	7.9	36.42	19
19	Thames-Loddon	477880	178680	Thames-Fawley Court	477000	184600	7.6	58.21	20
20	Thames-Fawley Court	477000	184600	Thames-Cut	491640	178600	27.2	58.21	21
21	Thames-Cut	491640	178600	Thames-Boveney Weir	494460	177680	3.8	55.81	22
22	Thames-Boveney Weir	494460	177680	Thames-Romney Lock Cut	497320	178120	4.3	55.81	23
23	Thames-Romney Lock Cut	497320	178120	Thames-Windsor STW	499700	175000	5.8	55.81	24
24	Thames-Windsor STW	499700	175000	Thames-Wey	507420	165740	16	48.58	25
25	Thames-Wey	507420	165740	Thames-Mole	515680	168190	10.5	53.01	26
26	Thames-Mole	515680	168190	Thames-Hogsmill	517700	169190	4	65.31	27
27	Thames-Hogsmill	517700	169190	Thames-Teddington	517000	171400	2.7	65.31	28
28	Thames-Teddington	517000	171400	Thames-Lee	539540	180600	36	65.31	29
29	Thames-Lee	539540	180600	Thames-Ingebourne	551250	180760	17	65.31[#]	0
30	Odhay-Abingdon STW	449210	195120	Odhay-Ginge Brook	450210	194260	1.6	1[#]	31
31	Odhay-Ginge Brook	450210	194260	Ginge-Brook-Thames	450300	194400	0.1	1[#]	14
32	Foudry Brook-Steamafield STW	467500	164500	Holy Brook-Foudry Brook	471180	171180	10.5	1[#]	33
33	Holy Brook-Foudry Brook	471180	171180	Kennet-Holy Brook	472020	173440	2.8	9.52	34
34	Kennet-Holy Brook	472020	173440	Kennet-Thames	473100	173880	1.3	9.52	18
35	Blackwater-Camberley STW	484800	159500	Blackwater-Sandhurst STW	483600	160900	3.3	0.14	36
36	Blackwater-Sandhurst STW	483600	160900	Blackwater-Eversley	477500	162500	8.2	2.98	37
37	Blackwater-Eversley	477500	162500	Blackwater-Whitewater	474160	163560	4.3	2.98	38
38	Blackwater-Whitewater	474160	163560	Loddon-Blackwater	472580	165640	2.9	2.98	39
39	Loddon-Blackwater	472580	165640	Loddon-Barkham	475770	169510	5.6	5.8	40
40	Loddon-Barkham	475770	169510	Loddon-Wargrave	477900	177600	12.3	5.8	41
41	Loddon-Wargrave	477900	177600	Loddon-Thames	477880	178680	1.3	5.8	19
42	Colne-Grand Union Canal	504090	191660	Colne-Misbourne	505280	186050	6.8	3.98	43
43	Colne-	505280	186050	Colne-	503320	171460	18	3.98	24

[#] Estimated value.

Reach ID	Start	Easting	Northing	End	Easting	Northing	Length (km)	Flow (m^3/s)	Next reach
	Misbourne			Thames					
44	Bourne (N)-Chertsey STW	501600	168000	Bourne-Bourne (N)	506220	165720	6.3	1#	45
45	Bourne-Woburn	506220	165720	Thames-Bourne	507050	165510	1.1	1#	25
46	Wey-Guildford STW	500300	151600	Wey-Woking STW	503200	157200	12.1	3.19	47
47	Wey-Woking STW	503200	157200	Wey-Wisley STW	506100	159900	6.2	6.68	48
48	Wey-Wisley STW	506100	159900	Wey-Weybridge STW	506600	163200	5.2	6.68	49
49	Wey-Weybridge STW	506600	163200	Thames-Wey	507420	165740	3.7	6.68	25
50	Mole-Horley STW	526700	143600	Mole-Salford	526220	146560	5.5	2.09	51
51	Mole-Salford	526220	146560	Mole-Shag Brook	522280	149430	8.9	2.09	52
52	Mole-Shag Brook	522280	149430	Mole-Dorking STW	517700	150500	7.8	2.09	53
53	Mole-Dorking STW	517700	150500	Mole-River Lane	514870	157120	11.1	3.61	54
54	Mole-River Lane	514870	157120	Mole-Downside Mill Stream	511130	159330	8.1	3.61	55
55	Mole-Downside Mill Stream	511130	159330	Mole-Ember	515300	168180	21.8	5.3	56
56	Mole-Ember	515300	168180	Thames-Mole	507420	165740	0.5	5.3	26
57	Ingebourne-Riverside STW	551520	181980	Thames-Ingebourne	551250	180760	1.8	0.32	0
58	Ash-Wareside STW	541650	216280	Lee-Ash	537690	213020	7.9	0.32	59
59	Lee-Ash	537690	213020	Lee-Stort	539080	209200	4.1	2.74	60
60	Lee-Stort	539080	209200	Lee-Kings Weir	537310	205180	4.7	2.74	61
61	Lee-Kings Weir	537310	205180	Lee-Tottenham Lock	534770	189380	18.1	2.74	62
62	Lee-Tottenham Lock	534770	189380	Lee-Springhill	534860	187520	2.1	5.5	63
63	Lee-Springhill	534860	187520	Lee-Lea Bridge Weir	535620	186580	1.2	5.5	64
64	Lee-Lea Bridge Weir	535620	186580	Lee-Carpenters Road	537660	184520	3.7	5.5	65
65	Lee-Carpenters Road	537660	184520	Thames-Lee	539540	180600	6.8	5.5	29
66	Salmon Brook-Deephams	535660	193170	Pymmes Brook-Salmon Brook	535510	191780	1.4	0.16	67
67	Pymmes Brook-Salmon Brook	535510	191780	Lee-Tottenham Lock	534770	289380	2.8	0.16	62
68	Lydebank-	447790	187860	GingeBrook-	445340	188880	3	0.5#	69

Estimated value.

Reach ID	Start	Easting	Northing	End	Easting	Northing	Length (km)	Flow (m^3/s)	Next reach
	Harwell			Lydebank					
69	Ginge Brook-Lydebank	445340	188880	Odhay-Ginge Brook	450210	194260	9.6	0.5[#]	31

[#] Estimated value

Table 20 Summary of Maximum Annual Doses by Pathway in the Thames Region (μSv)

Pathway	Maximum Dose	Site
Aerial	58	Nycomed Amersham
River	65	Reach ID 66[a, b]
Sludge Application	17	Maple Lodge
STW Worker	2	Sandford

[a] See Table 19.

[b] Dose resultant from releases from Deephams STW which receives hospital discharges from North Middlesex Hospital (BG2051).

Table 21 Summary of Maximum Annual Doses in the Thames Region (μSv)

Non-STW Worker Doses					
Max Dose	**Grid Ref**	**Aerial Dose**	**River Dose**	**Sludge Appl Dose**	
78	499198	58	2.8	17	
STW Worker Doses					
Max Dose	**Grid Ref**	**Aerial Dose**	**River Dose**	**Sludge Appl. Dose**	**Worker**
78	499198	58	2.8	17	3.7E-6