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# RADIOLOGICAL ASSESSMENT OF RADIOACTIVE WASTE DISPOSAL FROM NON-NUCLEAR PREMISES IN ANGLIAN REGION

# VOLUME 1 - METHODOLOGY


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# FOREWORD

In the UK, premises keeping or using radioactive substances are required to be registered in accordance with the provisions of the Radioactive Substances Act 1993 (RSA 93). In addition, accumulation and disposal of radioactive waste, including direct discharges of liquid or gaseous effluent streams contaminated with radioactivity, can only be made in accordance with an authorisation under that Act. In England and Wales, the Environment Agency administers the Act.

In applying for an authorisation, the owner of the premises is required to carry out a radiological assessment of the consequences of the proposed disposal.. Such an assessment is usually given in terms of the maximum radiation dose to members of the public. The actual level of authorisation is then set by the Agency at a level which ensures that public exposure is within statutory dose limits and also that the disposals/discharges are no higher than necessary to meet operational needs.

The contributions to public exposure arising from discharges of radioactivity from the nuclear industry have been extensively assessed over a number of years. This has been based on both environmental monitoring and radiological assessments. The non-nuclear premises, such as industry, hospitals, universities and research institutions (who also use radioactive materials), have not been subject to such extensive assessment and monitoring.

Anglian Region of the Environment Agency therefore decided to carry out a more wide-ranging study of the impact of discharges from these premises. This is in keeping with our aspirations of looking at the environmental outcomes of the authorisations we issue. It also helps to give a more complete picture of the impact of authorised discharges of radioactive materials into the environment. This study also acts as a pilot for a methodology the Agency is considering adopting to look at radiation dose assessment for the public more generally.

The aim has been to assess the radiological impact that would result to the most exposed members of the public from each authorised premise in the Anglian Region. This volume contains the methodology and data used for the assessments. The results of the assessments are reported in a second volume.

This report has been prepared for the Anglian Region of the Environment Agency by Alan Martin Associates. Anglian Region is publishing the report in the spirit of openness and of making environmental information available to the public. It is hoped that it will help inform discussions on the impact of radioactive discharges from these categories of authorised processes.

The results of the study support the view that provided these discharges are properly assessed and authorised, then the level of risk for members of the general public is low.

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# SUMMARY

This Report has been prepared by Alan Martin Associates for the Anglian Region of the Environment Agency (EA) under Contract Ref. P0035/DOSE/CT. The objective of the work covered by the contract is to undertake an assessment of the radiation doses to critical groups from authorised disposals and discharges of radioactive waste from premises other than nuclear sites within the Anglian Region.

The results of the study are presented in three volumes as follows:

> Volume 1 - Methodology for assessment of the radiological impact of authorised releases from non-nuclear premises;
> Volume 2 – Radiological assessment of authorised releases from non-nuclear premises in the Anglian Region; and
> Volume 3 – Compiled data on authorised discharges from non-nuclear premises in the Anglian Region.

The present report comprises Volume 1 and sets out a detailed methodology on which the results reported in a separate volume (Volume 2) are based. After a discussion of the background to the study and of authorised disposals from non-nuclear premises, a summary and review of previous work is presented.

The general approach to the assessment of the radiological impact of disposals or discharges of wastes containing radioactivity are then described and reference results are presented, based on generic assessments. The disposal routes for which results are presented are:

- Release to atmosphere, considering the impacts at both residential and agricultural locations;
- Release to sewer, with subsequent discharge of treated effluent and use of sewage sludge;
- Release to river, including external exposure, drinking water, fish consumption and irrigation pathways;
- Release to coastal or estuarine waters, taking account of external exposure and fish consumption; and
- Disposal of solid waste to landfill.

In all cases, results are presented on a unit basis to facilitate their application to other locations or to variations of current authorisations.

An assessment of the radiological impact of sewer discharges on sewage plant workers and sewer maintenance workers is included.

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# 1. INTRODUCTION

This Report has been prepared by Alan Martin Associates for the Anglian Region of the Environment Agency (EA) under Contract Ref. P0035/DOSE/CT. The objective of the work covered by the report is to undertake an assessment of the radiation doses to critical groups from authorised disposals and discharges of radioactive waste from premises other than nuclear sites within the Anglian Region.

An interim report was issued in March 1998 (Ref. 1) and this included a review of previous work, the development of a general methodology and its application to a pilot area. The final results of the study are presented in three Volumes as follows:

> Volume 1 - Methodology for assessment of the radiological impact of authorised releases from non-nuclear premises;
> Volume 2 – Radiological assessment of authorised releases from non-nuclear premises in the Anglian Region; and
> Volume 3 – Compiled data on authorised discharges from non-nuclear premises in the Anglian Region.

The present report comprises Volume 1 and sets out a detailed methodology and presents estimates of radiological impact for unit releases. These unit estimates provide the basis for the results contained in Volume 2. Volume 3 contains detailed data extracted from the discharge and disposal authorisations effective in the Anglian Region as of summer 1998.

# 2. BACKGROUND TO STUDY

In the UK, premises keeping or using radioactive substances are required to be registered in accordance with the provisions of the Radioactive Substances Act 1993 (RSA 93). In addition, accumulation and disposal of radioactive waste, including direct discharges of liquid or gaseous effluent streams, can only be made in accordance with an authorisation under the Act. In England and Wales, RSA 93 is administered by the Environment Agency (EA) on behalf of the Secretary of State and registrations and authorisations are issued by the Agency.

In applying for an authorisation, the site operator is usually required to carry out a radiological assessment of the consequences of the proposed disposal, in terms of the maximum radiation dose to a member of the public that could result from the proposed level of authorisation. The actual level of authorisation is then set by the Agency at a level which ensures that public exposure remains within internationally accepted limits and also that the disposals and discharges are no higher than are necessary to meet operational needs.

Under, Article 14 of the EURATOM Basic Safety Standards (Council Directive 96/29/EURATOM ), there is a requirement for each member state to keep under review the levels of exposure of the public and to take reasonable steps to ensure that the contribution to the exposure of the population as a whole from practices is kept as low as reasonably achievable, economic and social factors being taken into account.

Within the UK, the contributions to public exposure arising from the nuclear industry have been extensively assessed over a number of years by means of both environmental monitoring programmes and of assessments based on appropriate methods of estimation of dose. The non-nuclear establishments, where the discharges of radioactive wastes are recognised as small, have not been subject to extensive assessment and monitoring.

A study was commissioned in the 1980s by Her Majesty's Inspectorate of Pollution (the predecessor of the Environment Agency) to assess the radiation exposure to members of the public arising from radioactive discharges from non-nuclear establishments in the City of Cambridge (Ref.2). The study was based mainly on the results of a programme of environmental measurements. The purpose of the present study is to extend the previous assessment to other areas within the Anglian Region. However, recognising that the levels of radioactivity discharged and disposed of are generally so low that the resulting levels of radioactivity in the environment are too small to be easily measured, the present study is based on methods of assessment involving the modelling of the pathways of exposure.

# 3. RADIOACTIVE DISPOSALS FROM NON-NUCLEAR SITES

The non-nuclear sites include hospitals, universities, research laboratories and commercial premises producing a wide variety of wastes containing a number of radionuclides. These solid, liquid or gaseous waste arisings may be disposed of by one or more of the following disposal routes, depending on the nature of the waste and the appropriate route available.

## 3.1 Solid waste disposal

Solid wastes may be disposed of by means of the following routes:

- disposal of very low level waste (VLLW) with normal refuse;
- incineration;
- burial at a specified location; and
- disposal via British Nuclear Fuels ( national LLW repository at Drigg ) or Safeguard International (at Culham - formerly to UKAEA , Harwell ).

Common sources of VLLW are hospitals and universities, and the waste consists of such items as absorbent paper, plastic gloves and used glassware contaminated with small amounts of radioactive materials. Such waste may be authorised for disposal in domestic refuse (dustbin disposals) when each 0.1 cubic metre of material contains less than 400 kBq of beta/gamma activity. In addition, various Exemption Orders under the Radioactive Substances Act allow the disposal, without authorisation, of wastes containing lower concentrations of radioactivity (exempt wastes).

Combustible solid wastes, together with small amounts of organic liquid wastes, may be disposed of by incineration, either on the premises or by transfer to an off-site incineration plant. This method of disposal is useful for wastes which are obnoxious or biologically toxic, such as clinical wastes. As well as discharging to atmosphere, the incineration plant will produce secondary wastes in the form of ash and either solid or liquid waste from off-gas scrubbing. Generally, the concentrations of radioactivity in these secondary wastes are sufficiently low that they can be disposed of as "exempt" wastes or with ordinary refuse (VLLW).

Within certain limits, solid wastes that are too radioactive for dustbin disposal may be authorised for disposal at suitable landfill sites (controlled burial). Authorisation for such disposal at a specified location is only granted where the disposal site has the necessary containment characteristics. Some low level solid wastes are not suitable for local disposal and may be transported to BNFL (national repository at Drigg) or to Safeguard International at Culham for processing and disposal.

### 3.2 Liquid waste disposal

Liquid wastes may be disposed of by means of one or more of the following routes:

- public sewer;
- direct to water course or water body;
- premises' own sewage treatment works; and
- septic tank or cesspit on premises.

Liquid wastes typically arise from general laboratory procedures involving the use of a variety of radioactive materials and may contain macerated organic matter. Hospitals may discharge the excreta of patients who have been given therapeutic or diagnostic doses of radioactive substances. For relatively small amounts of liquid radioactive waste, authorised disposal directly to the drains is a safe and convenient method of disposal. The waste is diluted immediately by the other effluent from the establishment and subsequently by effluent in the sewage collection system. The diluted waste passes through the sewage treatment works, before discharging into a river, an estuary or the sea. Secondary waste arises in the form of sewage sludge and subsequent use of the sludge as fertiliser can give rise to radiation exposure through consumption of crops.

In other cases, discharges of liquid wastes may be authorised directly to a water course or water body, such as a river, an estuary or the sea.

Alternative routes for the disposal of liquid wastes are to the premises' own sewage works or to a septic tank or cesspit on the premises, where secondary wastes may be produced. However, similar considerations apply since effluent and sludges will normally arise in the same way as from major sewage works.

### 3.3 Gaseous waste disposal

Atmospheric discharges of radioactive waste include wastes in the form of a gas, mist or dust. Authorisations for emissions to atmosphere by users of radioactive substances usually require discharges to be made directly from specific discharge points, in such a manner as to prevent re-entry into any part of the premises. Treatment techniques, such as filtration or absorption are likely to be employed at incineration plants and some laboratories.

## 4. PREVIOUS WORK

The EA and its predecessor HMIP have supported a number of studies over recent years to assist in the assessment of the radiological impact of authorised disposals from 'small' users of radioactive substances (*i.e.* non-nuclear industry premises). Among these is the Cambridge study, which included a programme of measurement and which is summarised in sub-section 4.1, and various other studies based on assessment methodologies, as discussed in sub-Sections 4.2 to 4.4.

An important recent development is the availability of a personal computer based assessment system, PC CREAM, which has been written by the National Radiological Protection Board under contract to the European Commission. This is intended to provide a user-friendly method of assessing the radiological impact of routine releases of radioactivity into the environment. The capabilities of the system are summarised in sub-Section 4.5 and its application to the present work is discussed.

## 4.1 The Cambridge study

This research study (Ref. 2) was designed to investigate the movements of radioactivity in the local environment around a small city in which there are numerous authorised discharges from non-nuclear establishments. The chosen study area was the City of Cambridge, where it was found that ten radionuclides were disposed of, seven of which were measured in the environment. In 1987, the three principal radionuclides, accounting for 90% of the total activity discharged, were tritium (H-3), Tc-99m and I-131. Additional radionuclides were P-32, S-35, I-125, In-111, Cr-51, C-14 and Ca-45 in decreasing order of activity. The predominant route of disposal was via the drains (92%) with atmospheric release (4%), incineration (2%) being minor routes in comparison. Details of the disposals were obtained from users of radionuclides but the primary emphasis was on the detection and measurement of the materials in the environment in order to obtain direct data on resulting concentrations.

There was no evidence in Cambridge of enhanced external radiation exposure to members of the public attributable to the disposal of radioactive wastes. The assessment of internal exposure was carried out in three different categories:

- Observed dose; calculated by inserting measured environmental concentrations into the modelled route or relationship considered to be most appropriate or applicable, representing an upper limit value;
- Estimated dose; calculated by inserting the reported quantities of radionuclide disposed of into the appropriate modelled route or relationship, again representing an upper limit value; and
- Actual dose; calculated after considering both the measured environmental concentration and the applicability of the modelled route or relationship to the actual habits or activities in that particular urban area.

The radiation exposure pathways considered were the use of river water for drinking or animal watering, the use of sewage sludge for agricultural purposes and the incineration of radioactive wastes. Calculated doses to members of the public were found to be extremely small compared with the average annual background dose from all sources for an individual in the UK.

## 4.2 Disposal of domestic and commercial wastes

Limited quantities of radioactivity are disposed of with non-radioactive domestic and commercial waste under the terms of Exemption Orders or authorisations granted by the Environment Agency. A review undertaken in the late 1980s considered the acceptability of authorised "dustbin disposal" (VLLW), special precautions (controlled) burial, disposal of demolition wastes and incineration of H-3 and C-14 (Ref. 3). The study also considered the acceptability of disposals under the various Exemption Orders, such as the Hospitals' Exemption Order and the Phosphatic Substances etc Exemption Order.

Maximum individual doses and collective doses to waste disposal workers and members of the public were estimated, using methods developed for the purpose and presented in the report. The exposure pathways that were considered for the waste disposal workers were external exposure and inhalation of dust and volatiles. For members of the public, external exposure, inhalation of fumes and ash, and consumption of contaminated water and food were considered.

The estimated individual and collective doses arising from dustbin disposal, controlled burial, disposal of demolition wastes and incineration were found to be very low for H-3 and C-14. Of the disposal practices under the then current Exemption Orders, only those under the Hospital Wastes, Luminous Articles, Gaseous Tritium Light Devices and the Phosphatic Substances *etc* were estimated to give rise to radiological impacts that might need to be kept under review.

Since the review discussed above, a number of changes have taken place in the regulation and practice of the disposal of controlled wastes and a further study was commissioned to confirm that the practices remained acceptable (Ref.4).

In order to assess the effective dose to individual waste management workers and to members of the public, it was necessary to make a number of simplifying assumptions concerning the amount of VLLW handled at a typical waste handling station and the operations carried out by individual workers. For each radionuclide, it was assumed that the maximum authorised activity was disposed of in a standard waste bag. For the majority of exposure scenarios, the doses to the most exposed individual waste management workers were of the order of 10 μSv per year or less, and doses in excess of 50 μSv per year occurred only for alpha emitters. The highest individual doses arose from those pathways involving the direct reuse of items with the maximum activity allowed for individual items in standard VLLW authorisation conditions and from the operation of, and disposal to landfill of ash from, a small clinical waste incinerator. The highest doses calculated for the general public were of the order of 0.2 μSv per year, for discharges from a small incinerator or landfill. The radiological assessment showed that the current standard conditions for disposal of waste as VLLW provide adequate protection of waste management workers and the general public.

Subsequently, NRPB published a memorandum setting out a methodology for preparing radiological assessments of disposals by small users via aqueous discharges to sewers or watercourses, incineration of radioactive wastes and direct disposal to atmosphere (Ref. 5). The methodology described in Ref. 5 is essentially that later implemented in PC Cream.

### 4.3 Discharges to sewer systems

The objective of this study (Ref. 6) was to assess the radiation doses that a sewer worker might receive in a typical sewerage system associated with a hospital involved in the diagnostic and therapeutic uses of radionuclides in medicine. Special attention was paid to discharges of iodine-131, which is used in the treatment of thyroid disorders. The hospital chosen for the study was the Royal Marsden Hospital at Sutton, where the sewers drain into the sewage treatment works (STW) near Kingston-upon-Thames, representing a typical combination of hospital/sewer system.

Details of the radionuclides likely to be discharged from a large hospital and the quantities involved were obtained from the literature and from discussions with personnel involved in the medical use of radionuclides. A model was developed for the dispersion and accumulation of radionuclides in a sewerage system, taking into account the accumulation of radionuclides on the sewer walls and the separation of crude sewage into primary (raw) sludge and settled sewage (effluent). Further models were developed to assess the exposure of sewer workers to radionuclides in the sewer system. The particular pathways assessed were external exposure at the sewer works, external irradiation from a sewer pipe and internal irradiation arising from inhalation of resuspended sewage material and from the inadvertent ingestion of sewage material. Measurements of radiation levels and radionuclide concentrations in the sewerage system associated with the chosen hospital were compared with the predictions of the theoretical models.

For a typical combination of hospital and sewer works, the estimated critical group doses arising from discharges of four selected radionuclides, P-32, Tc-99m, I-125 and I-131, were assessed. The estimated doses are 30 μSv per year and 20 μSv per year, respectively, for a worker at the sewage works and for a sewer maintenance worker exposed for prolonged periods in the region of the sewer system adjacent to the hospital discharge point.

### 4.4 Disposal of sewage sludge to agricultural land

In this study (Ref. 7) a review of options for the disposal of sewage sludge was used, in conjunction with historical discharge and environmental monitoring data relevant to the Amersham International site and the Maple Lodge sewage works, to assess the radiological impact of releases of radionuclides to sewers. In the course of undertaking that work, a new mathematical model for radionuclide transport in sewers was developed. However, the main limitation in applying the model to the assessment of the impact of the release of radionuclides to sewer was identified to be the lack of data on the particle reactivity of the radionuclides of interest. The disposal or use options for sewage sludge are:

- sea disposal (to be phased out);
- fertiliser for agricultural land, either in liquid or solid form;
- garden composting;
- landfill;
- land reclamation; and
- incineration or combined incineration with solid urban waste.

The study included an illustrative radiological assessment for the disposal of sewage sludge to agricultural land. The assessment considered the exposure pathways for external exposure, inhalation of re-suspended activity and ingestion of soil, contaminated plants and contaminated animal products. The upper bound estimates of annual effective dose per unit activity released were applied to current discharges from Amersham, giving a total effective dose of 79 μSv per year, arising mainly from the consumption of contaminated crops and animal products.

### 4.5 PC CREAM

PC CREAM (Ref. 8) is a computer-based implementation of a suite of models for performing radiological impact assessments for routine and continuous discharges of radioactivity to the environment. The models and data are set out in Ref. 9, which should be considered as part of the code documentation. The system allows assessment of the impact of releases to atmosphere, sea or rivers. Pathways that cannot be directly assessed are irrigation and application of sewage sludge to agricultural land.

The ASSESSOR module provides the main assessment role and this is designed to lead the user through the setting up and running of a case. This module provides the capability needed for assessment of discharges to atmosphere from non-nuclear premises but, where necessary, the more detailed models FARMLAND, PLUME and RESUS may be run to provide case-specific data for ASSESSOR. For liquid discharges to rivers, estuaries and the sea, the ASSESSOR module again provides the basic capability that can be supplemented by the GRANIS and DORIS modules.

## 5. METHODS FOR ASSESSMENT OF RADIOLOGICAL IMPACT

In general, the radiation exposure pathways that need to be considered in assessing the radiological impact of authorised disposals of wastes from non-nuclear premises are those arising from:

- release to atmosphere, including incineration;
- direct release to water;
- release to sewer; and
- disposal to landfill.

In the case of release to atmosphere, the exposure pathways can include inhalation, external dose and ingestion of radioactivity as a result of contamination of crops or animal products. Releases to water can lead to ingestion dose due to consumption of water, fish or agricultural produce irrigated by water from the receiving body. In the case of discharges to sewer drains, depending on the radionuclide, the activity is partitioned between sewage sludge and the liquid effluent from the sewage treatment plant, which is released to river, estuary or sea. The most important pathways for sewage sludge are those resulting from its use as agricultural fertiliser.

## 5.1 General approach

The assessment of the radiological impact of disposals or discharges of wastes containing radioactivity involves a number of stages, as follows:

- compilation of data on the authorised and/or actual rates of disposal and the characteristics of discharge;
- study of the receiving environment and compilation of the information and data needed for quantitative assessment;
- setting up of methodologies for assessment of the various disposal routes and exposure pathways;
- running of the assessments; and
- presentation and discussion of results.

## 5.2 Compilation of data on authorised disposals

The EA maintains a computerised database of registrations and authorisations under RSA 93 and the record may be searched by region, county, local authority, river catchment or by areas specified by National Grid Reference (GR) co-ordinates. This system allows identification of all premises within a defined study area holding authorisations for disposal. Detailed information on each of the identified premises may then be obtained from the files held in the Public Register, which is maintained at various EA regional offices. The information is mainly contained in the application form for authorisation (Form RSA3) and in the Certificate of Authorisation issued by the EA.

A complete list of authorised sites within the Anglian region , dated 30 April 1998, is shown in Appendix A. For the purposes of the present study a unique identification number was given to each of the non-nuclear sites. The current authorisation certificate for each site provided the annual disposal limit for each relevant radionuclide and any conditions specified for that disposal route. The current Form RSA 3, when available, provided further details of the site location and disposal arrangements. Actual disposals from each site were obtained from the annual report to the Environment Agency (emission inventories), where that was available.

The site information required for assessment purposes was compiled on data forms specific to each of the following disposal routes:

- disposals to atmosphere;
- liquid disposals to sewer or direct to watercourses;
- disposal by incineration;
- disposal to landfill (within the region).

The extracted data include details of the atmospheric discharge arrangements and distances to the nearest residence and point of public access, and information on the sewage discharge system. These summary data sheets are contained in a separate volume (Volume 3).

Within the Anglian region, as of summer 1998, there were 103 premises authorised to dispose of radioactive wastes, of which the following disposal routes are used:

- 83 sites discharging to sewer (discharges to sewer involve 28 municipal sewage treatment plants, 10 private sewage treatment plants and 6 sites discharging directly to an estuary or the sea);
- 38 sites discharging to atmosphere (including 6 sites with incinerators);
- one site disposing of solid waste to a landfill site.

The present assessment does not include radioactive wastes that are transported out of the region for disposal.

The following authorised sites were not included in the present assessment as the relevant data were not at that time available:

Mobil Oil, Coryton Refinery, Essex (Study Ref. 61);
Agricultural and Food Research Council, Bury St, Edmunds (Study Ref. 90);
Animal Health Trust, Balaton Lodge, Newmarket (Study Ref.91).

## 5.3 Compilation of data on the receiving environment

In compiling information on the receiving environment, the aim is to identify the groups of the population likely to receive the highest dose as a result of the disposals and to derive quantitative data for assessment purposes.

Although a visit to the sites and the general area is recommended, it is not generally feasible or necessary to compile complete sets of information either on the environment or on the occupancy factors and dietary habits of local population groups. Instead, stylised assessments are performed using generally conservative assumptions in order to obtain an upper bound estimate of dose. This type of assessment would generally confirm the low radiological significance of the authorised disposals but in any case where the dose appears to be unusually high, a more detailed assessment of the conditions of release and of the receiving environment would be indicated.

*Release to atmosphere*

For release to atmosphere, the relevant information is:

- the details of release that affect atmospheric dispersion, i.e. stack height, building dimensions, and release characteristics;
- the meteorological characteristics of the area, including windrose and stability category and rainfall frequencies (default meteorological data sets are available within PC CREAM and these are normally adequate for initial assessment);
- the location of the nearest normally occupied habitation; in this case, a distinction has been made between premises in urban and rural locations and for each type of location standard distances have been defined, see Section 6 below.

All of the pathways resulting from release to atmosphere can be assessed using PC-CREAM though not all radionuclides of interest to this study are contained in the default files supplied with the system.

*Release to water*

Where a release occurs to a water body, normally a river, the relevant characteristics of the river flow need to be established. Information on river flows in the UK is compiled by the Institute of Hydrology (NERC, Wallingford) in the form of the National Water Archive published as the Hydrological Yearbook (web site: www.nwl.ac.uk). River flow data are obtained from a network of gauging stations listed in the Concise Register of Gauging Stations and an extract from the list of gauging stations in the Anglian region is shown in Appendix B.

*Discharge to sewer*

Discharge to sewer results in release of treated water to the river, estuary or sea and the production of sludge from the sewage treatment process. Information on each sewage treatment works was obtained from the Water Quality/Pollution Control Register for the Anglian Region and included details of the sewage and sludge treatment processes and production rates; the relevant data are shown in Appendix C. In the case of premises discharging to their own private sewage treatment plant, the relevant information was obtained from the RSA3 application form.

For each sewage treatment plant, through which radioactive effluent is discharged, the data required for assessment purposes were assembled on the data forms that are compiled in Volume 3. Each form shows the total authorised input of radioactive waste arising from the premises discharging to that sewage treatment works and also the actual input, where that information is available.

The proportions of activity appearing in the liquid effluent and in the solid wastes depend largely on the distribution coefficient Kd for a particular radionuclide. Based on information in Refs. 6 and 7, a model representation of a sewage treatment works and of sludge utilisation has been derived to allow estimation of the quantity of sludge arising and the fractions of activity appearing in each phase. For radionuclides with a low Kd, almost all of the activity will remain in the aqueous phase and be discharged as treated sewer water, normally to a river. For nuclides with high Kd, the opposite is the case and almost all of the activity is retained in the solid phase. The approach adopted is to allocate each nuclide to one of three categories, as follows:

- low Kd, for which 100% release in liquid effluent is assumed, in addition to which it is conservatively assumed that 10% remains in sludge;
- high Kd, for which 100% retention in sludge is assumed, but with a conservative allowance for 10% to be released in liquid effluent; and
- intermediate or highly uncertain Kd, for which it is assumed that there is both 100% release and 100% retention in sludge.

For many of the radionuclides of interest, there is significant uncertainty over the Kd value that is appropriate to the conditions in a STW and the allocation to the three categories requires a large degree of judgement. Based on a compilation of data in Ref. 10 for distribution coefficients for organic material, the allocations are shown in the following table.

| Kd, $m^3\ kg^{-1}$ | Examples of elements | Fraction released in liquid phase | Fraction retained in sludge |
|---|---|---|---|
| < 3 | H, C, F, Na, P, S, Cl, Ca, Br, Sr, Tc, I, Cs, Ra, U | 1 | 0.1 |
| 3 - 30 | Cr, Fe, Co, Ru, In, Tl, | 1 | 1 |
| >30 | V, Mn, Ga, Se, Th | 0.1 | 1 |

## 5.4 Setting up and running the assessment

The setting up and running of the assessment is illustrated in the following sections in which estimates are made of the radiological impact of discharges from authorised premises at unit discharge rates.

## 5.5 Results

Results are presented in Sections 6, 7 and 8 of generic assessments of the radiological consequences of unit release rate, normally 1MBq per year, of radionuclides of interest. These unit data provide the basis for detailed estimates of the radiological impact of discharges at the limits of authorisation. The results of the detailed assessments for individual premises are presented in a separate volume (Volume 2).

# 6. ASSESSMENT OF RELEASES TO ATMOSPHERE

## 6.1 Assessment basis

Given the large number of sites to be assessed, the approach has been to undertake generic assessments and to estimate the radiological impact of unit release rate of the range of nuclides covered by the authorisations.

For the majority of premises, release to atmosphere occurs at low level, either from building vents or from low stacks. In such cases, entrainment of the airflow will affect radionuclide concentrations downwind of the building. At more than 100m downwind of a typical 15m high building the receptor point will lie within the "main wake" and a "virtual source" model may be used to predict airborne concentrations (Refs. 9, 11 and 12). For a continuous release, the annual averaged concentration may be obtained from equation 3.34 of Reference 9. For typical category D conditions and a wind speed of 4m/s, the effect of entrainment will be to increase the concentration at 300 m downwind by about 20%, as compared to that for a point release at from a stack height of 15 m, with the effect decreasing with increasing distance. Thus the effect is not significant compared with the quoted overall model uncertainty of ±50% (Ref. 11), and in all cases of low-level discharge, a release height of 15m is taken in the ASSESSOR module of PC-CREAM.

For a small number of premises, the release is from stacks of between 20 and 100m high. To cover all situations, generic CREAM runs were performed for four release heights – 15, 30, 60 and 100m – and all premises are considered to fit one of these cases.

Two types of exposure scenario are considered, corresponding to residential and agricultural locations. At the residential location, the exposure routes considered include external dose, inhalation and ingestion pathways as a result of consumption of limited quantities of garden produce. At the agricultural location, unless there is site-specific information to the contrary, it is usual to assume that a high proportion of food is produced on the farm. This could include fruit, vegetables, milk, and meat. For present purposes, in order to obtain bounding estimates, consumption at agricultural locations is taken to be at critical group consumption rate for all foodstuffs, see Table 1.

Generally, the nearest residential location is taken as 300m from the point of discharge and this distance is used for the lower elevation (15 and 30m) releases. For the higher elevation discharges, the peak impacts occur at longer ranges and the residential location is taken to be at 500m for a 60m-stack release and at 1000m for the 100m stack release.

For assessment of the impact at agricultural locations, a distinction is made between premises in urban and rural locations. For urban locations, the nearest farming is usually at least 1000m distant whilst for premises in rural locations, distances to the nearest farm could, more typically, be 500m. Again, the actual distance used for assessment purposes depends on the release height. Full details of the assessment basis for releases to atmosphere are shown in Table 1.

## 6.2 Results of generic assessments

The results of the generic assessments are shown in Tables 2 to 6 and show the contributions and total impacts for a release rate of 1 MBq per year at the reference locations.

Table 2 (a) and (b) give the results for a 15 m release from premises in an urban location. The results show the contributions of inhalation + external dose, ingestion dose and the total dose for the range of radionuclides covered by authorisations (24 radionuclides). The results are shown for three age groups - infant, child and adult. For the residential group, the doses to the three age groups are very similar for most radionuclides but for the agricultural scenario there are a few radionuclides for which the impact is significantly greater for the infant. Generally the factor is two or less but in a few cases the infant dose is larger by a factor of five to ten.

Tables 3 (a) and (b) show the equivalent results for premises located in a rural area and this also shows the doses to the three age groups.

Taking into account that most premises are authorised to discharge a number of radionuclides, the results in Tables 1 and 2 show that assessment of the impact to the adult age group is unlikely significantly to underestimate the dose to children or infants. In order to simplify their presentation, the subsequent tables give only the dose to adults. The results presented are as follows:

Table 4: 30 m stack; dose per unit discharge for urban and rural premises.

Table 5: 60 m stack; dose per unit discharge for urban and rural premises.

Table 6: 100 m stack; dose per unit discharge for urban and rural premises.

Tables 2 to 6 provide a set of data that can be used to assess the maximum radiological impact implied by any new authorisation or by a variation to an existing authorisation.

# 7. ASSESSMENT OF RELEASES TO WATER BODIES

## 7.1 Assessment basis

For release to river, as occurs from the majority of STW in the Anglian region, the key parameter is the river flow. As noted earlier, information on river flows in the UK is compiled by the Institute of Hydrology (NERC, Wallingford) in the form of the National Water Archive published as the Hydrological Yearbook (web site: www.nwl.ac.uk). The river flow rate at a particular discharge location is obtained by locating the nearest gauging station(s) upstream of that location and summing river flows where several tributaries contribute to the overall flow.

Within the Anglian region there are considerable variations in seasonal and annual-average river flow rates. For assessment purposes it was appropriate to use the long-term annual average flow (the values used are those corresponding to records preceding 1996).

Within the ASSESSOR module of PC-CREAM, there is a simple screening model and a dynamic model of radionuclide transport in rivers. Exploratory calculations showed that in terms of concentrations in river water, and therefore of pathways involving extraction of river water or consumption of fish, the two models give similar results. However, for external exposure to sediments on the riverbank, the screening method appears to over-estimate the impacts significantly. The majority of results are therefore based on the dynamic model. However, due to a simplification adopted in the modelling, for elements of low distribution coefficient (Kd), a value of zero is adopted in the code and this results in a zero contribution to external dose from radionuclides of these species. Where this has occurred for radionuclides with significant gamma emission (mainly I-125, I-131 and Ra-226), estimates of external dose from the screening model have been used.

The direct exposure pathways are external exposure to river sediment, use of filtered river water for drinking and, in principle, consumption of fish. These pathways are included in PC CREAM. In addition pathways resulting from irrigation of crops are considered; PC CREAM does not cover these and an assessment method has been developed as part of the current study. With regard to the fish consumption pathway, only coarse fish are caught in the rivers of the Anglian region and these are not generally considered edible. However, as there are some radionuclides for which fish consumption would be by far the dominant pathway, the approach has been to allow for fish consumption but at low rate of 2 kg/y (adults). From a small number of sites, release occurs either directly or via a STW to the sea or an estuary. In these cases, the pathways considered are external exposure to sediment and consumption of fish. The assessment basis for liquid releases is shown in Table 7.

As in the case of discharge to atmosphere, there is a large number of discharging locations and the approach has been to undertake a generic assessment, the results of which can be scaled to actual discharge situations. For rivers, reference results have, except for uranium and thorium, been derived for unit release rate (1 MBq per year) of each radionuclide for an annual average river flow of 1 $m^3$ per second. For uranium and thorium, the results are given in terms of the mass release (1 gram per year) since the authorisations are expressed in this way. The receptor point is taken at 1 km downstream from the discharge but tests show that the results are not very sensitive to this assumption. A similar approach is used for sea or estuarine discharges, and reference results are based on an exchange/dilution flow of 1 $m^3$ per second from the local compartment.

## 7.3 Results of generic assessment – river pathways

The results of the generic assessments are shown in Tables 8 and 9. Table 8 gives results for a small selection of radionuclides for the three age groups. This shows that there are not extreme differences in the radiological impact on the three age groups and that, for the purposes of the study, it is sufficient to present detailed results for the adult group only.

The reference results, which are for unit discharge rate and unit river flow rate, are presented in Table 9 (a) and (b). In Volume 2 of the report of the study, these results are used as a basis for calculating the impact that would result from discharges into rivers at the limits of authorisation. To obtain the dose from an authorised discharge, the relevant impact from Table 8 should be multiplied by the authorised discharge for the nuclide, in MBq, and divided by the average annual river flow, in $m^3$ per second.

The final column of Table 9 shows the proposed reduction factor to be applied when assessing the impact of discharges via a STW, see discussion in sub-Section 5.3.

## 7.4 Results of generic assessment – river water irrigation pathways

A further pathway to be considered is the use of river water for irrigation of crops. This pathway is not available within PC-CREAM and a spreadsheet method has been set up.

Considering the same reference release case as for the river pathways, i.e. a unit release rate of

1 MBq per year into an average annual flow of 1 $m^3$ per second, the average concentration in irrigation water will be 3.2 x $10^{-2}$ Bq m-3. Conservatively, spray irrigation is assumed to be applied daily to crops for fraction f of the year (taken to be 0.25) immediately before harvest. The soil concentration $c_1$ (Bq $kg^{-1}$) at harvest in Year 1 is then:

$$c_1 = \frac{c_w \cdot r \cdot 365 \; (1 - \exp(-\lambda_e f))}{\rho \; d \; \lambda_e}$$

where $c_w$ is the concentration in the irrigation water, (0.032 Bq $m^{-3}$);
r is the irrigation rate, (0.005 m $d^{-1}$);
$\rho$ is the soil density, (1300 kg $m^{-3}$);
d is the mixed soil depth, (0.2 m);
$\lambda_e$ is the effective removal constant in soil $= \lambda + \lambda_s$ where $\lambda_s$ is taken as 0.04 $y^{-1}$ and $\lambda$ is the radioactive decay constant.

After t years (taken as 50) of discharge, the concentration $c_t$ in soil is the sum of the series

$$c_t = \Sigma_t \, c_1 \exp(-\lambda_e t)$$

which is $c_1 (1 - \exp(-\lambda_e t)) / (1 - \exp(-\lambda_e))$

It is assumed that irrigation using river water would only be undertaken on farms and that it would be used for irrigation of green vegetables, root vegetables and fruit. The concentrations in these products are then calculated using plant to soil concentration factors. Allowance is made for direct interception of activity on plants and for soil adhesion on harvesting. The contributions to exposure from external exposure to the soil and from resuspension are also included. The relevant nuclide-dependent parameter values are shown in Table 10.

On this basis, the results of the generic assessment are shown in Table 11 (a) and (b). As in the case of the river pathways, the dose from an authorised discharge is obtained by multiplying the relevant impact from Table 11 by the authorised discharge for the nuclide, in MBq, and dividing by the average annual river flow, in $m^3$ per second. Where the discharge is from a STW, account should be taken of the reduction factors shown in Table 9.

## 7.5 Results of generic assessment – marine and estuarine release

Within the Anglian region, one site is authorised to discharge to sea and four to estuaries. The marine discharge is from CEFAS at Lowestoft. For this site, the dispersion conditions may be taken to be similar to those for Sizewell, for which a model representation is included in PC-CREAM. For Sizewell, the volume of the local compartment and the annual exchange rate with the regional compartment are given in Ref. 9 as 2.0 x $10^8$ $m^3$ and 1.1 x $10^{10}$ $m^3$ $y^{-1}$, the latter value corresponding to a dilution flow of about 320 $m^3$ $s^{-1}$. Thus for a conservative species, such as H-3, the concentration in sea water in the local compartment for a release rate of 1 MBq per year will be 9 x $10^{-5}$ Bq $m^{-3}$. For consistency with the approaches adopted in Sections 7.1 to 7.3, the method adopted for marine discharges has been to run the PC-Cream model for Sizewell with the discharge rate adjusted to give the concentrations that would result from a discharge rate of 1 MBq per year into a compartment with an exchange or dilution rate of 1 $m^3$ $s^{-1}$. The results are shown in Table 12. For assessing the impact of discharges to sea from any part of the coast covered by the Anglian region, it is considered that an exchange/dilution flow of 300 $m^3$ $s^{-1}$ can reasonably be adopted.

Estuarine environments are more complex and variable than marine environments because of the presence of both fresh water run-off from rivers and the tidal incursions of saline water. Of the discharge locations for which assessment is required for the purposes of this study, most are located such that they are clearly predominantly saline. The reference results presented in Table 12 are therefore applicable in these cases, subject to deriving an exchange/dilution flow rate appropriate to each discharge location. Suitable values are derived in the Volume 2 report for the specific locations. Where the discharge is from a STW, account should be taken of the reduction factors shown in Table 9.

### 7.6 Discharge to sewer - sewage sludge application

For the purposes of the study, a reference Sewage Treatment Works (STW) has been defined, based on information on the STW in the Anglian region, on the characteristics and use of sewage sludge discussed in Ref. 13, and on general information and discussion in Ref. 7. The reference plant has a raw sewage input of $10^5$ $m^3$ per day with a typical solids content after removal of large debris by screening of 0.2 kg $m^{-3}$. After dewatering and digestion, this results in a daily liquid sludge production of 800 $m^3$ containing 25 kg $m^{-3}$ of solids, dry weight (dw). The total annual sludge production is then 7.3 x $10^6$ kg dw. The sludge can be used in this form or as sludge cake at 25-30% loading, i.e. at about 250 kg $m^{-3}$, for which the production would be 80 $m^3$ per day.

The rate of application for liquid sludge is, at most 100 t/ha (about 5 t solids dw per hectare), whilst for cake a typical application rate is about 50 t/ha (about 15 t solids dw per hectare). For the purposes of assessment an application rate of 10 t dw per hectare is assumed for both types and this corresponds to 1 kg dw per $m^2$. Cake is usually applied at the time of ploughing whilst liquid sludge is applied in spring. The Sludge (Use in Agriculture) Regulations prohibit the harvesting of vegetable or fruit crops for a period of 10 months after sludge application.

On the above basis, and assuming that all activity disposed of into the sewage system remains in the sludge, a 1 MBq/y input would give a concentration in sludge of 0.14 Bq/kg and for an application rate of 1 kg $m^{-2}$ the activity application rate would be 0.14 Bq $m^{-2}$ $y^{-1}$. Allowing for a delay period of p (taken as 5 days) between disposal of waste to sewer and the spreading of the associated sludge on land , the concentration in soil immediately after the first application is given by:

$$c_1 = \frac{0.14 \ . \ \exp(-\lambda \ p/365))}{\rho \ d} \quad \text{Bq kg}^{-1}$$

As in the case of irrigation, the concentration in soil after time t (50 years) is represented by an exponential series and, taking account of a delay d (taken to be 0.83 y) between application of sludge and harvesting, the soil concentration at the time of harvesting is given by:

$$c_h = c_1 \exp(-\lambda_e \, d) \ (1 - \exp(-\lambda_e \, t)) \ / \ (1 - \exp(-\lambda_e \,))$$

As for the irrigation model, this approach has been implemented in a spreadsheet. The dose factors obtained from the spreadsheet are shown in Table 13 (a) and (b), which also take account of the fraction of activity remaining in sludge, see Section 5.3.

To apply the results in Table 13 to the use of sludge from a particular STW, the results should be scaled by multiplying by the activity input in MBq per year and dividing by the size of the STW relative to the reference plant ($10^5$ $m^3$ per day raw sewage input). Thus for a STW with a daily raw sewage input of 5 x $10^4$ $m^3$ per day and an input of 100 MBq/y of I-125, the impact would be obtained from the reference value in Table 13a of 1.7 x $10^{-7}$ μSv/y as follows:

$$\text{Dose} = 1.7 \times 10^{-7} \times 100 \times 10^5 / (5 \times 10^4) \ \mu\text{Sv/y}.$$

### 7.7 Dose to workers from sewer disposal

Discharge of liquid radioactive effluents to sewerage systems can also result in the exposure of workers at the STW and those engaged in the maintenance of the system. The exposure of a typical worker at the sewage treatment plant and that of a sewer maintenance worker have been assessed using the simple calculational models of Ref. 4, in which the inhalation, ingestion and external radiation pathways are considered. In view of low doses expected, simple exposure models, together with fairly pessimistic occupancy factors, have been employed, which may be scaled according to the particular radionuclide concentration in the sewage sludge. The same models may be extended to estimate doses to the agricultural workers involved in the use of sewage products. The results of this assessment are contained in Appendix D.

## 8. ASSESSMENT OF DISPOSAL TO LANDFILL

The assessment of the radiological impact of disposal of low-level radioactive waste cannot be undertaken directly using PC-CREAM. However, estimates of the doses to workers and to members of the public have been reported in the results of studies for the then HMIP. These included the review undertaken by Associated Nuclear Services in 1987 (Ref. 3) and the later study by the NRPB (Ref. 4). For the purposes of the present study, the data from Ref. 4 have been employed since they are based on the most recent dosimetric information.

For waste management workers, the impacts covered in Ref. 4 include those arising at the various management stages, including collection, transport, sorting and disposal operations. The results in Ref. 4 are for a programme of annual disposals of 100 GBq of H-3 and C-14, 1 GBq of Ra-226, Th-232 and natural uranium, and 10 GBq of other radionuclides to a number of disposal facilities.

Based on the results in Ref.4, radiological impacts to disposal workers and members of the public have been derived for disposals of 1 MBq per year of selected radionuclides to a single disposal facility. These are shown in Table 14. For workers the impact shown in the table is that from the operation giving the highest dose. For members of the public, the pathways included in the assessment in Ref. 4 include inhalation of landfill gases (H-3, C-14 and S-35 only), dust inhalation, external exposure, ingestion of food grown on a disturbed landfill, and ingestion of leachate water.

The results in Table 14 are used in Volume 2 to assess the potential radiological impact of authorised disposals to landfill

## 9. DISCUSSION

The undertaking of the radiological assessment is inevitably complex, involving a number of premises, typically two to ten radionuclides per premise, a variety of exposure pathways, and several potential critical groups. PC CREAM has proved to be easy to use for assessing the impacts of releases to atmosphere and for simple river release cases. However, there are several important aspects that cannot be directly represented by PC CREAM, including use of river water for irrigation, use of sewage sludge as agricultural fertiliser and disposal of low-level solid waste to landfill. The approach that has been adopted for the purposes of the present study has been to use PC-Cream where this was feasible and to supplement the results by means of other methods.

In order to provide data of general application, the approach has been to estimate the radiological impact for unit disposal rate (1 MBq per year) and, where appropriate, to a defined environment. The results can then be scaled to actual or authorised levels of disposal, and to the particular environment into which the radioactivity is disposed.

In Volume 2, estimates are presented of the radiological impact that would result from disposals at the limits of the authorisations for all premises in the Anglian region for which the necessary data are available.

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| a) Distance from release point to assessment location | | | |
|---|---|---|---|
| Location of premises | Release height, m | Distance to reference habitation, m | |
| | | Residential | Agricultural |
| Urban | 15 | 300 | 500 |
| | 30 | 300 | 1000 |
| | 60 | 500 | 1000 |
| | 100 | 1000 | 1000 |
| Rural | 15 | 300 | 500 |
| | 30 | 300 | 500 |
| | 60 | 500 | 500 |
| | 100 | 1000 | 1000 |
| b) Occupancy and inhalation factors | | | |
| Pathway | | Residential | Agricultural |
| Inhalation (incl resus) | $m^3/h$ | 7300 | 7300 |
| External $\beta$ and $\gamma$ | Hours per year | 8760 | 8760 |
| | Fraction indoors | 0.8 | 0.7 |
| | Loc. factor, cloud $\gamma$ | 0.2 | 0.2 |
| | Loc factor, depos $\gamma$ | 0.1 | 0.1 |
| c) Annual consumption rates of locally grown produce | | | |
| Cow meat | kg/y | - | 45 |
| Cow milk | l/y | - | 240 |
| Cow milk products | kg/y | - | 60 |
| Cow liver | kg/y | - | 10 |
| Green vegetables | kg/y | 40 | 80 |
| Root vegetables | kg/y | 65 | 130 |
| Fruit | kg/y | 37.5 | 75 |

**TABLE 1 BASIS OF ASSESSMENT OF RADIOLOGICAL IMPACT - ATMOSPHERIC RELEASE**

| Nuclide | Age group | Dose per unit release, µSv $y^{-1}$ per MBq $y^{-1}$ | | | | | |
|---|---|---|---|---|---|---|---|
| | | Residential location at 300m | | | Agricultural location at 1000m | | |
| | | Inh + ext | Ingestion | Total | Inh + ext | Ingestion | Total |
| H-3 | Infant | 1.7E-08 | 2.2E-08 | 3.9E-08 | 4.8E-09 | 6.2E-08 | 6.7E-08 |
| | Child | 2.4E-08 | 2.0E-08 | 4.4E-08 | 6.7E-09 | 3.1E-08 | 3.8E-08 |
| | Adult | 2.5E-08 | 2.5E-08 | 5.0E-08 | 6.9E-09 | 3.1E-08 | 3.8E-08 |
| C-14 | Infant | 7.4E-07 | 3.6E-06 | 4.3E-06 | 2.1E-07 | 9.1E-06 | 9.3E-06 |
| | Child | 9.4E-07 | 3.3E-06 | 4.2E-06 | 2.6E-07 | 5.3E-06 | 5.6E-06 |
| | Adult | 9.0E-07 | 3.6E-06 | 4.5E-06 | 2.5E-07 | 5.1E-06 | 5.4E-06 |
| O-15 | Infant | 2.1E-08 | <1.0E-12 | 2.1E-08 | 4.7E-09 | <1.0E-12 | 4.7E-09 |
| | Child | 2.7E-08 | <1.0E-12 | 2.7E-08 | 6.0E-09 | <1.0E-12 | 6.0E-09 |
| | Adult | 2.7E-08 | <1.0E-12 | 2.7E-08 | 7.2E-09 | <1.0E-12 | 7.2E-09 |
| Na-24 | Infant | 2.2E-06 | <1.0E-12 | 2.2E-06 | 5.9E-07 | <1.0E-12 | 5.9E-07 |
| | Child | 3.1E-06 | <1.0E-12 | 3.1E-06 | 8.3E-07 | <1.0E-12 | 8.3E-07 |
| | Adult | 3.0E-06 | <1.0E-12 | 3.0E-06 | 1.0E-06 | <1.0E-12 | 1.0E-06 |
| P-32 | Infant | 2.1E-06 | 2.8E-05 | 3.0E-05 | 5.7E-07 | 2.5E-04 | 2.5E-04 |
| | Child | 2.4E-06 | 1.6E-05 | 1.8E-05 | 6.6E-07 | 7.1E-05 | 7.2E-05 |
| | Adult | 2.0E-06 | 1.0E-05 | 1.2E-05 | 7.4E-07 | 4.0E-05 | 4.1E-05 |
| P-33 | Infant | 1.5E-07 | 5.0E-06 | 5.2E-06 | 3.8E-08 | 4.5E-05 | 4.5E-05 |
| | Child | 1.0E-07 | 2.8E-06 | 2.9E-06 | 2.9E-08 | 1.3E-05 | 1.3E-05 |
| | Adult | 6.4E-08 | 1.8E-06 | 1.9E-06 | 1.8E-08 | 7.2E-06 | 7.2E-06 |
| S-35 | Infant | 8.1E-07 | 2.7E-06 | 3.5E-06 | 2.2E-07 | 1.5E-03 | 1.5E-03 |
| | Child | 1.0E-06 | 1.6E-06 | 2.6E-06 | 2.9E-07 | 4.1E-04 | 4.1E-04 |
| | Adult | 9.7E-07 | 1.2E-06 | 2.2E-06 | 2.7E-07 | 2.5E-04 | 2.5E-04 |
| A-41 | Infant | 2.5E-08 | <1.0E-12 | 2.5E-08 | 5.5E-09 | <1.0E-12 | 5.5E-09 |
| | Child | 3.2E-08 | <1.0E-12 | 3.2E-08 | 7.0E-09 | <1.0E-12 | 7.0E-09 |
| | Adult | 3.2E-08 | <1.0E-12 | 3.2E-08 | 8.5E-09 | <1.0E-12 | 8.5E-09 |
| Cr-51 | Infant | 9.2E-08 | 1.7E-08 | 1.1E-07 | 2.6E-08 | 2.7E-07 | 3.0E-07 |
| | Child | 1.1E-07 | 1.3E-08 | 1.2E-07 | 3.2E-08 | 9.0E-08 | 1.2E-07 |
| | Adult | 1.1E-07 | 1.3E-08 | 1.2E-07 | 3.7E-08 | 5.8E-08 | 9.5E-08 |
| Br-82 | Infant | 1.9E-06 | 5.8E-07 | 2.5E-06 | 4.9E-07 | 2.5E-05 | 2.5E-05 |
| | Child | 2.5E-06 | 3.7E-07 | 2.9E-06 | 6.7E-07 | 7.9E-06 | 8.6E-06 |
| | Adult | 2.4E-06 | 3.9E-07 | 2.8E-06 | 7.9E-07 | 5.2E-06 | 6.0E-06 |
| Kr-85 | Infant | 4.2E-10 | <1.0E-12 | 4.2E-10 | 1.1E-10 | <1.0E-12 | 1.1E-10 |
| | Child | 4.3E-10 | <1.0E-12 | 4.3E-10 | 1.2E-10 | <1.0E-12 | 1.2E-10 |
| | Adult | 4.3E-10 | <1.0E-12 | 4.3E-10 | 1.2E-10 | <1.0E-12 | 1.2E-10 |
| Kr-79 | Infant | 1.9E-08 | <1.0E-12 | 1.9E-08 | 4.9E-09 | <1.0E-12 | 4.9E-09 |
| | Child | 1.9E-08 | <1.0E-12 | 1.9E-08 | 5.2E-09 | <1.0E-12 | 5.2E-09 |
| | Adult | 1.9E-08 | <1.0E-12 | 1.9E-08 | 5.2E-09 | <1.0E-12 | 5.2E-09 |

**TABLE 2a ATMOSPHERIC RELEASE - 15m DISCHARGE: - DOSE PER UNIT DISCHARGE DATA FOR URBAN SITE**

| Nuclide | Age group | Dose per unit release, $\mu Sv\ y^{-1}$ per $MBq\ y^{-1}$ | | | | | |
|---|---|---|---|---|---|---|---|
| | | Residential location at 300m | | | Agricultural location at 1000m | | |
| | | Inh + ext | Ingestion | Total | Inh + ext | Ingestion | Total |
| Kr-85m | Infant | 4.0E-09 | <1.0E-12 | 4.0E-09 | 9.0E-10 | <1.0E-12 | 9.0E-10 |
| | Child | 5.0E-09 | <1.0E-12 | 5.0E-09 | 1.1E-09 | <1.0E-12 | 1.1E-09 |
| | Adult | 5.0E-09 | <1.0E-12 | 5.0E-09 | 1.3E-09 | <1.0E-12 | 1.3E-09 |
| Rb-81/Kr-81m | Infant | 4.6E-08 | <1.0E-12 | 4.6E-08 | 4.9E-09 | <1.0E-12 | 4.9E-09 |
| | Child | 3.8E-08 | <1.0E-12 | 3.8E-08 | 5.2E-09 | <1.0E-12 | 5.2E-09 |
| | Adult | 2.3E-08 | <1.0E-12 | 2.3E-08 | 5.2E-09 | <1.0E-12 | 5.2E-09 |
| Sr-90 | Infant | 2.0E-05 | 7.6E-05 | 9.6E-05 | 5.5E-06 | 3.1E-04 | 3.2E-04 |
| | Child | 2.7E-05 | 1.3E-04 | 1.6E-04 | 7.4E-06 | 2.7E-04 | 2.8E-04 |
| | Adult | 2.5E-05 | 1.2E-04 | 1.4E-04 | 7.0E-06 | 1.8E-04 | 1.9E-04 |
| Tc-99 | Infant | 2.4E-06 | 4.3E-04 | 4.3E-04 | 6.5E-07 | 2.4E-04 | 2.4E-04 |
| | Child | 3.0E-06 | 1.9E-04 | 1.9E-04 | 8.2E-07 | 1.1E-04 | 1.1E-04 |
| | Adult | 2.8E-06 | 1.5E-04 | 1.5E-04 | 7.7E-07 | 8.3E-05 | 8.4E-05 |
| Tc-99m | Infant | 2.0E-08 | <1.0E-12 | 2.0E-08 | 5.4E-09 | <1.0E-12 | 5.4E-09 |
| | Child | 2.1E-08 | <1.0E-12 | 2.1E-08 | 5.6E-09 | <1.0E-12 | 5.6E-09 |
| | Adult | 1.6E-08 | <1.0E-12 | 1.6E-08 | Tc-99m | <1.0E-12 | 4.5E-09 |
| In-111 | Infant | 2.8E-07 | <1.0E-8 | 2.8E-07 | 6.1E-08 | <1.0E-8 | 6.1E-08 |
| | Child | 2.2E-07 | <1.0E-8 | 2.2E-07 | 6.2E-08 | <1.0E-8 | 6.2E-08 |
| | Adult | 1.5E-07 | <1.0E-8 | 1.5E-07 | 4.7E-08 | <1.0E-8 | 4.7E-08 |
| I-125 | Infant | 4.1E-06 | 1.9E-04 | 1.9E-04 | 1.1E-06 | 1.1E-03 | 1.1E-03 |
| | Child | 5.7E-06 | 2.0E-04 | 2.1E-04 | 1.5E-06 | 5.3E-04 | 5.3E-04 |
| | Adult | 3.5E-06 | 1.6E-04 | 1.6E-04 | 9.3E-07 | 3.1E-04 | 3.1E-04 |
| I-131 | Infant | 1.5E-05 | 1.8E-04 | 1.9E-04 | 4.0E-06 | 1.5E-03 | 1.5E-03 |
| | Child | 1.3E-05 | 9.5E-05 | 1.1E-04 | 3.5E-06 | 3.8E-04 | 3.8E-04 |
| | Adult | 8.3E-06 | 7.1E-05 | 7.9E-05 | 2.5E-06 | 1.9E-04 | 1.9E-04 |
| Xe-133 | Infant | 1.0E-09 | <1.0E-12 | 1.0E-09 | 2.4E-10 | <1.0E-12 | 2.4E-10 |
| | Child | 1.3E-09 | <1.0E-12 | 1.3E-09 | 2.9E-10 | <1.0E-12 | 2.9E-10 |
| | Adult | 1.3E-09 | <1.0E-12 | 1.3E-09 | 3.5E-10 | <1.0E-12 | 3.5E-10 |
| Ba-140 | Infant | 5.7E-06 | 1.2E-06 | 6.9E-06 | 1.6E-06 | 3.1E-06 | 4.7E-06 |
| | Child | 7.1E-06 | 7.7E-07 | 7.9E-06 | 2.0E-06 | 9.8E-07 | 3.0E-06 |
| | Adult | 6.7E-06 | 7.3E-07 | 7.4E-06 | 2.1E-06 | 6.0E-07 | 2.7E-06 |
| La-140 | Infant | 1.9E-06 | <1.0E-8 | 1.9E-06 | 5.3E-07 | 6.8E-08 | 6.0E-07 |
| | Child | 2.4E-06 | <1.0E-8 | 2.4E-06 | 6.8E-07 | 3.9E-08 | 7.2E-07 |
| | Adult | 2.2E-06 | <1.0E-8 | 2.2E-06 | 7.7E-07 | 3.7E-08 | 8.1E-07 |
| Po-210 | Infant | 2.0E-03 | 4.4E-03 | 6.4E-03 | 5.5E-04 | 2.3E-03 | 2.9E-03 |
| | Child | 2.4E-03 | 2.5E-03 | 4.9E-03 | 6.7E-04 | 1.3E-03 | 2.0E-03 |
| | Adult | 2.3E-03 | 1.9E-03 | 4.2E-03 | 6.3E-04 | 9.7E-04 | 1.6E-03 |

**TABLE 2b ATMOSPHERIC RELEASE - 15m DISCHARGE: - DOSE PER UNIT DISCHARGE DATA FOR URBAN SITE**

| Nuclide | Age Group | Dose per unit release, µSv y-1 per MBq y-1 | | | | | |
|---|---|---|---|---|---|---|---|
| | | Residential location at 300m | | | Agricultural location at 500m | | |
| | | Inh + ext | Ingestion | Total | Inh + ext | Ingestion | Total |
| H-3 | Infant | 1.7E-08 | 2.2E-08 | 3.9E-08 | 1.1E-08 | 1.4E-07 | 1.5E-07 |
| | Child | 2.4E-08 | 2.0E-08 | 4.4E-08 | 1.5E-08 | 7.1E-08 | 8.6E-08 |
| | Adult | 2.5E-08 | 2.5E-08 | 5.0E-08 | 1.6E-08 | 7.1E-08 | 8.7E-08 |
| C-14 | Infant | 7.4E-07 | 3.6E-06 | 4.3E-06 | 4.7E-07 | 2.1E-05 | 2.1E-05 |
| | Child | 9.4E-07 | 3.3E-06 | 4.2E-06 | 6.0E-07 | 1.2E-05 | 1.3E-05 |
| | Adult | 9.0E-07 | 3.6E-06 | 4.5E-06 | 5.8E-07 | 1.2E-05 | 1.3E-05 |
| O-15 | Infant | 2.1E-08 | <1.0E-12 | 2.1E-08 | 1.1E-08 | <1.0E-12 | 1.1E-08 |
| | Child | 2.7E-08 | <1.0E-12 | 2.7E-08 | 1.4E-08 | <1.0E-12 | 1.4E-08 |
| | Adult | 2.7E-08 | <1.0E-12 | 2.7E-08 | 1.8E-08 | <1.0E-12 | 1.8E-08 |
| Na-24 | Infant | 2.2E-06 | <1.0E-8 | 2.2E-06 | 1.3E-06 | <1.0E-8 | 1.3E-06 |
| | Child | 3.1E-06 | <1.0E-8 | 3.1E-06 | 1.9E-06 | <1.0E-8 | 1.9E-06 |
| | Adult | 3.0E-06 | <1.0E-8 | 3.0E-06 | 2.4E-06 | <1.0E-8 | 2.4E-06 |
| P-32 | Infant | 2.1E-06 | 2.8E-05 | 3.0E-05 | 1.3E-06 | 5.7E-04 | 5.7E-04 |
| | Child | 2.4E-06 | 1.6E-05 | 1.8E-05 | 1.5E-06 | 1.6E-04 | 1.6E-04 |
| | Adult | 2.0E-06 | 1.0E-05 | 1.2E-05 | 1.7E-06 | 9.0E-05 | 9.2E-05 |
| P-33 | Infant | 1.5E-07 | 5.0E-06 | 5.2E-06 | 8.9E-08 | 1.0E-04 | 1.0E-04 |
| | Child | 1.0E-07 | 2.8E-06 | 2.9E-06 | 6.6E-08 | 2.9E-05 | 2.9E-05 |
| | Adult | 6.4E-08 | 1.8E-06 | 1.9E-06 | 4.1E-08 | 1.6E-05 | 1.6E-05 |
| S-35 | Infant | 8.1E-07 | 2.7E-06 | 3.5E-06 | 5.2E-07 | 3.4E-03 | 3.4E-03 |
| | Child | 1.0E-06 | 1.6E-06 | 2.6E-06 | 6.7E-07 | 9.2E-04 | 9.2E-04 |
| | Adult | 9.7E-07 | 1.2E-06 | 2.2E-06 | 6.2E-07 | 5.5E-04 | 5.5E-04 |
| A-41 | Infant | 2.5E-08 | <1.0E-12 | 2.5E-08 | 1.3E-08 | <1.0E-12 | 1.3E-08 |
| | Child | 3.2E-08 | <1.0E-12 | 3.2E-08 | 1.7E-08 | <1.0E-12 | 1.7E-08 |
| | Adult | 3.2E-08 | <1.0E-12 | 3.2E-08 | 2.1E-08 | <1.0E-12 | 2.1E-08 |
| Cr-51 | Infant | 9.2E-08 | 1.7E-08 | 1.1E-07 | 5.8E-08 | 6.1E-07 | 6.7E-07 |
| | Child | 1.1E-07 | 1.3E-08 | 1.2E-07 | 7.2E-08 | 2.0E-07 | 2.7E-07 |
| | Adult | 1.1E-07 | 1.3E-08 | 1.2E-07 | 8.3E-08 | 1.3E-07 | 2.1E-07 |
| Br-82 | Infant | 1.9E-06 | 5.8E-07 | 2.5E-06 | 1.2E-06 | 6.0E-05 | 6.1E-05 |
| | Child | 2.5E-06 | 3.7E-07 | 2.9E-06 | 1.6E-06 | 1.9E-05 | 2.1E-05 |
| | Adult | 2.4E-06 | 3.9E-07 | 2.8E-06 | 1.9E-06 | 1.2E-05 | 1.4E-05 |
| Kr-85 | Infant | 4.2E-10 | <1.0E-12 | 4.2E-10 | 2.6E-10 | <1.0E-12 | 2.6E-10 |
| | Child | 4.3E-10 | <1.0E-12 | 4.3E-10 | 2.7E-10 | <1.0E-12 | 2.7E-10 |
| | Adult | 4.3E-10 | <1.0E-12 | 4.3E-10 | 2.7E-10 | <1.0E-12 | 2.7E-10 |
| Kr-79 | Infant | 1.9E-08 | <1.0E-12 | 1.9E-08 | 1.1E-08 | <1.0E-12 | 1.1E-08 |
| | Child | 1.9E-08 | <1.0E-12 | 1.9E-08 | 1.2E-08 | <1.0E-12 | 1.2E-08 |
| | Adult | 1.9E-08 | <1.0E-12 | 1.9E-08 | 1.2E-08 | <1.0E-12 | 1.2E-08 |

**TABLE 3a ATMOSPHERIC RELEASE - 15m DISCHARGE: - DOSE PER UNIT DISCHARGE DATA FOR RURAL SITE**

| Nuclide | Age group | Dose per unit release, $\mu Sv\ y^{-1}$ per $MBq\ y^{-1}$ | | | | | |
|---|---|---|---|---|---|---|---|
| | | Residential location at 300m | | | Agricultural location at 500m | | |
| | | Inh + ext | Ingestion | Total | Inh + ext | Ingestion | Total |
| Kr-85m | Infant | 4.0E-09 | <1.0E-12 | 4.0E-09 | 2.2E-09 | <1.0E-12 | 2.2E-09 |
| | Child | 5.0E-09 | <1.0E-12 | 5.0E-09 | 2.7E-09 | <1.0E-12 | 2.7E-09 |
| | Adult | 5.0E-09 | <1.0E-12 | 5.0E-09 | 3.2E-09 | <1.0E-12 | 3.2E-09 |
| Rb-81/ Kr-81m | Infant | 4.6E-08 | <1.0E-12 | 4.6E-08 | 2.8E-08 | <1.0E-12 | 2.8E-08 |
| | Child | 3.8E-08 | <1.0E-12 | 3.8E-08 | 2.4E-08 | <1.0E-12 | 2.4E-08 |
| | Adult | 2.3E-08 | <1.0E-12 | 2.3E-08 | 1.5E-08 | <1.0E-12 | 1.5E-08 |
| Sr-90 | Infant | 2.0E-05 | 7.6E-05 | 9.6E-05 | 1.3E-05 | 7.0E-04 | 7.1E-04 |
| | Child | 2.7E-05 | 1.3E-04 | 1.6E-04 | 1.7E-05 | 6.2E-04 | 6.4E-04 |
| | Adult | 2.5E-05 | 1.2E-04 | 1.4E-04 | 1.6E-05 | 4.1E-04 | 4.3E-04 |
| Tc-99 | Infant | 2.4E-06 | 4.3E-04 | 4.3E-04 | 1.5E-06 | 5.4E-04 | 5.4E-04 |
| | Child | 3.0E-06 | 1.9E-04 | 1.9E-04 | 1.9E-06 | 2.4E-04 | 2.4E-04 |
| | Adult | 2.8E-06 | 1.5E-04 | 1.5E-04 | 1.8E-06 | 1.9E-04 | 1.9E-04 |
| Tc-99m | Infant | 2.0E-08 | <1.0E-12 | 2.0E-08 | 1.2E-08 | <1.0E-12 | 1.2E-08 |
| | Child | 2.1E-08 | <1.0E-12 | 2.1E-08 | 1.3E-08 | <1.0E-12 | 1.3E-08 |
| | Adult | 1.6E-08 | <1.0E-12 | 1.6E-08 | 1.1E-08 | <1.0E-12 | 1.1E-08 |
| In-111 | Infant | 2.8E-07 | <1.0E-9 | 2.8E-07 | 1.4E-07 | <1.0E-9 | 1.4E-07 |
| | Child | 2.2E-07 | <1.0E-9 | 2.2E-07 | 1.5E-07 | <1.0E-9 | 1.5E-07 |
| | Adult | 1.5E-07 | <1.0E-9 | 1.5E-07 | 1.1E-07 | <1.0E-9 | 1.1E-07 |
| I-125 | Infant | 4.1E-06 | 1.9E-04 | 1.9E-04 | 2.6E-06 | 3.7E-03 | 3.7E-03 |
| | Child | 5.7E-06 | 2.0E-04 | 2.1E-04 | 3.6E-06 | 2.0E-03 | 2.0E-03 |
| | Adult | 3.5E-06 | 1.6E-04 | 1.6E-04 | 2.2E-06 | 1.2E-03 | 1.2E-03 |
| I-131 | Infant | 1.5E-05 | 1.8E-04 | 1.9E-04 | 9.4E-06 | 5.0E-03 | 5.0E-03 |
| | Child | 1.3E-05 | 9.5E-05 | 1.1E-04 | 8.3E-06 | 1.4E-03 | 1.4E-03 |
| | Adult | 8.3E-06 | 7.1E-05 | 7.9E-05 | 6.0E-06 | 7.3E-04 | 7.4E-04 |
| Xe-133 | Infant | 1.0E-09 | <1.0E-12 | 1.0E-09 | 5.7E-10 | <1.0E-12 | 5.7E-10 |
| | Child | 1.3E-09 | <1.0E-12 | 1.3E-09 | 7.1E-10 | <1.0E-12 | 7.1E-10 |
| | Adult | 1.3E-09 | <1.0E-12 | 1.3E-09 | 8.4E-10 | <1.0E-12 | 8.4E-10 |
| Ba-140 | Infant | 5.7E-06 | 1.2E-06 | 6.9E-06 | 3.6E-06 | 1.0E-05 | 1.4E-05 |
| | Child | 7.1E-06 | 7.7E-07 | 7.9E-06 | 4.5E-06 | 3.5E-06 | 8.0E-06 |
| | Adult | 6.7E-06 | 7.3E-07 | 7.4E-06 | 4.9E-06 | 2.3E-06 | 7.2E-06 |
| La-140 | Infant | 1.9E-06 | <1.0E-8 | 1.9E-06 | 1.2E-06 | 2.8E-07 | 1.5E-06 |
| | Child | 2.4E-06 | <1.0E-8 | 2.4E-06 | 1.5E-06 | 1.7E-07 | 1.7E-06 |
| | Adult | 2.2E-06 | <1.0E-8 | 2.2E-06 | 1.8E-06 | 1.7E-07 | 2.0E-06 |
| Po-210 | Infant | 2.0E-03 | 4.4E-03 | 6.4E-03 | 1.3E-03 | 9.7E-03 | 1.1E-02 |
| | Child | 2.4E-03 | 2.5E-03 | 4.9E-03 | 1.5E-03 | 5.5E-03 | 7.0E-03 |
| | Adult | 2.3E-03 | 1.9E-03 | 4.2E-03 | 1.5E-03 | 4.3E-03 | 5.8E-03 |

**TABLE 3b ATMOSPHERIC RELEASE - 15m DISCHARGE: - DOSE PER UNIT DISCHARGE DATA FOR RURAL SITE**

| Nuclide | Age Group | Dose per unit release, µSv y-1 per MBq y-1 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Residential location at 300m | | | Agricultural location at 500m | | | Agricultural location at 1000m | | |
| | | Inh + ext | Ingestion | Total | Inh + ext | Ingestion | Total | Inh + ext | Ingestion | Total |
| H-3 | Adult | 5.8E-09 | 5.9E-09 | 1.2E-08 | 4.9E-09 | 2.2E-08 | 2.7E-08 | 3.1E-09 | 1.4E-08 | 1.7E-08 |
| C-14 | Adult | 2.1E-07 | 8.4E-07 | 1.1E-06 | 1.8E-07 | 3.6E-06 | 3.8E-06 | 1.1E-07 | 2.3E-06 | 2.4E-06 |
| O-15 | Adult | 1.5E-08 | 0.0 | 1.5E-08 | 1.2E-08 | 0.0 | 1.2E-08 | 5.2E-09 | 0.0 | 5.2E-09 |
| Na-24 | Adult | | | | | | | | | |
| P-32 | Adult | 6.1E-07 | 3.6E-06 | 4.2E-06 | 6.4E-07 | 3.6E-05 | 3.7E-05 | 3.8E-07 | 2.1E-05 | 2.1E-05 |
| P-33 | Adult | | | | | | | | | |
| S-35 | Adult | 2.3E-07 | 4.3E-07 | 6.6E-07 | 1.9E-07 | 2.2E-04 | 2.2E-04 | 1.2E-07 | 1.3E-04 | 1.3E-04 |
| Ar-41 | Adult | 1.8E-08 | 0.0 | 1.8E-08 | 1.4E-08 | 0.0 | 1.4E-08 | 6.1E-09 | 0.0 | 6.1E-09 |
| Cr-51 | Adult | 3.4E-08 | 4.6E-09 | 3.9E-08 | 3.2E-08 | 5.2E-08 | 8.4E-08 | 1.9E-08 | 3.0E-08 | 4.9E-08 |
| Br-82 | Adult | 6.1E-07 | 9.6E-08 | 7.1E-07 | 6.3E-07 | 4.0E-06 | 4.6E-06 | 3.8E-07 | 2.5E-06 | 2.9E-06 |
| Kr-85 | Adult | 1.2E-10 | 0.0 | 1.2E-10 | 9.9E-11 | 0.0 | 9.9E-11 | 5.8E-11 | 0.0 | 5.8E-11 |
| Kr-79 | Adult | 5.3E-09 | 0.0 | 5.3E-09 | 4.4E-09 | 0.0 | 4.4E-09 | 2.6E-09 | 0.0 | 2.6E-09 |
| Sr-90 | Adult | 5.9E-06 | 4.0E-05 | 4.6E-05 | 5.0E-06 | 1.6E-04 | 1.7E-04 | 3.2E-06 | 9.5E-05 | 9.8E-05 |
| Tc-99 | Adult | | | | | | | | | |
| Tc-99m | Adult | | | | | | | | | |
| In-111 | Adult | 4.0E-08 | 0.0 | 4.0E-08 | 3.8E-08 | 0.0 | 3.8E-08 | 2.2E-08 | 0.0 | 2.2E-08 |
| I-125 | Adult | 8.3E-07 | 4.0E-05 | 4.1E-05 | 7.0E-7 | 4.0E-04 | 4.0E-04 | 4.4E-07 | 2.5E-04 | 2.5E-04 |
| I-131 | Adult | 2.0E-06 | 1.8E-05 | 2.0E-05 | 1.9E-6 | 2.3E-04 | 2.3E-04 | 1.2E-06 | 1.5E-04 | 1.5E-04 |
| Xe-133 | Adult | 6.7E-10 | 0 | 6.7E-10 | 4.9E-10 | 0.0 | 4.9E-10 | 2.3E-10 | 0 | 2.3E-10 |
| Ba-140 | Adult | 1.9E-06 | 2.5E-07 | 2.2E-06 | 1.8E-06 | 9.3E-07 | 2.7E-06 | 1.1E-06 | 5.4E-07 | 1.6E-06 |
| La-140 | Adult | 6.7E-07 | 0.0 | 6.7E-07 | 6.7E-07 | 6.7E-08 | 7.4E-07 | 3.9E-07 | 3.9E-08 | 4.3E-07 |
| Po-210 | Adult | 5.4E-04 | 6.6E-04 | 1.2E-03 | 4.5E-04 | 1.7E-03 | 2.1E-03 | 2.9E-04 | 1.0E-03 | 1.3E-03 |

**TABLE 4 ATMOSPHERIC RELEASE - 30m DISCHARGE: - DOSE PER UNIT DISCHARGE DATA FOR URBAN AND RURAL SITES**

| Nuclide | Age Group | Dose per unit release, μSv y⁻¹ per MBq y⁻¹ | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Residential location at 500m | | | Agricultural location at 500m | | | Agricultural location at 1000m | | |
| | | Inh + ext | Ingestion | Total | Inh + ext | Ingestion | Total | Inh + ext | Ingestion | Total |
| H-3 | Adult | 1.0E-09 | 1.1E-09 | 2.1E-09 | 1.0E-09 | 4.6E-09 | 5.6E-09 | 9.1E-10 | 4.0E-09 | 4.9E-09 |
| C-14 | Adult | 3.8E-08 | 1.5E-07 | 1.9E-07 | 3.8E-08 | 7.7E-07 | 8.1E-07 | 3.3E-08 | 6.7E-07 | 7.0E-07 |
| O-15 | Adult | 6.1E-09 | 0.0 | 6.1E-09 | 6.1E-09 | 0.0 | 6.1E-09 | 3.1E-09 | 0.0 | 3.1E-09 |
| Na-24 | Adult | | | | | | | | | |
| P-32 | Adult | 2.6E-07 | 1.2E-06 | 1.5E-06 | 2.6E-07 | 1.6E-05 | 1.6E-05 | 1.6E-07 | 9.7E-06 | 9.9E-06 |
| P-33 | Adult | | | | | | | | | |
| S-35 | Adult | 4.1E-08 | 1.4E-07 | 1.8E-07 | 4.1E-08 | 9.8E-05 | 9.8E-05 | 3.5E-08 | 6.0E-05 | 6.0E-05 |
| Ar-41 | Adult | 7.2E-09 | 0.0 | 7.2E-09 | 7.2E-09 | 0.0 | 7.2E-09 | 3.7E-09 | 0.0 | 3.7E-09 |
| Cr-51 | Adult | 1.3E-08 | 1.5E-09 | 1.5E-08 | 1.3E-08 | 2.3E-08 | 3.6E-08 | 8.1E-09 | 1.4E-08 | 2.2E-08 |
| Br-82 | Adult | 1.6E-07 | 1.9E-08 | | 1.6E-07 | 9.9E-07 | 1.2E-06 | 1.2E-07 | 7.9E-07 | 9.1E-07 |
| Kr-85 | Adult | 2.9E-11 | 0.0 | 2.9E-11 | 2.9E-11 | 0.0 | 2.9E-11 | 2.0E-11 | 0 | 2.0E-11 |
| Kr-79 | Adult | | | | | | | | | |
| Sr-90 | Adult | 1.1E-06 | 1.3E-05 | 1.4E-05 | 1.1E-06 | 7.2E-05 | 7.3E-05 | 9.1E-07 | 4.4E-05 | 4.5E-05 |
| Tc-99 | Adult | | | | | | | | | |
| Tc-99m | Adult | | | | | | | | | |
| In-111 | Adult | 8.8E-09 | 0.0 | 8.8E-09 | 8.8E-09 | 0.0 | 8.8E-09 | 6.8E-09 | 0.0 | 6.8E-09 |
| I-125 | Adult | 1.5E-07 | 8.1E-06 | 8.3E-06 | 1.5E-07 | 9.8E-05 | 9.8E-05 | 1.3E-07 | 7.8E-05 | 7.8E-05 |
| I-131 | Adult | 4.3E-07 | 3.6E-06 | 4.0E-06 | 4.3E-07 | 5.8E-05 | 5.8E-05 | 3.6E-07 | 4.6E-05 | 4.6E-05 |
| Xe-133 | Adult | 2.3E-10 | 0.0 | 2.3E-10 | 2.3E-10 | 0.0 | 2.3E-10 | 1.2E-10 | 0.0 | 1.2E-10 |
| Ba-140 | Adult | 6.1E-07 | 8.1E-08 | 6.9E-07 | 6.1E-07 | 4.1E-07 | 1.0E-06 | 4.1E-07 | 2.5E-07 | 6.6E-07 |
| La-140 | Adult | 2.6E-07 | 0.0 | 2.6E-07 | 2.6E-07 | 2.9E-08 | 2.9E-07 | 1.7E-07 | 1.8E-08 | 1.9E-07 |
| Po-210 | Adult | 9.6E-05 | 2.1E-04 | 3.1E-04 | 9.6E-05 | 7.6E-04 | 8.6E-04 | 8.3E-05 | 4.7E-04 | 5.5E-04 |

**TABLE 5 ATMOSPHERIC RELEASE - 60m DISCHARGE: - DOSE PER UNIT DISCHARGE DATA FOR URBAN AND RURAL SITES**

| Nuclide | Age group | Dose per unit release, µSv y⁻¹ per MBq y⁻¹ | | | | | |
|---|---|---|---|---|---|---|---|
| | | Residential location at 1000m | | | Agricultural location at 1000m | | |
| | | Inh + ext | Ingestion | Total | Inh + ext | Ingestion | Total |
| H-3 | Adult | 3.1E-10 | 3.0E-10 | 6.1E-10 | 3.1E-10 | 1.3E-09 | 1.6E-09 |
| C-14 | Adult | 1.1E-08 | 4.3E-08 | 5.4E-08 | 1.1E-08 | 2.2E-07 | 2.3E-07 |
| O-15 | Adult | 2.0E-09 | <1.0E-12 | 2.0E-09 | 2.0E-09 | <1.0E-12 | 2.0E-09 |
| Na-24 | Adult | 7.0E-08 | <1.0E-9 | 7.0E-08 | 7.0E-08 | <1.0E-9 | 7.0E-08 |
| P-32 | Adult | 9.9E-08 | 4.5E-07 | 5.5E-07 | 9.9E-08 | 6.2E-06 | 6.3E-06 |
| P-33 | Adult | | | | | | |
| S-35 | Adult | 1.2E-08 | 5.4E-08 | 6.6E-08 | 1.2E-08 | 3.8E-05 | 3.8E-05 |
| Ar-41 | Adult | 2.3E-09 | <1.0E-12 | 2.3E-09 | 2.3E-09 | <1.0E-12 | 2.3E-09 |
| Cr-51 | Adult | 4.9E-09 | 5.9E-10 | 5.5E-09 | 4.9E-09 | 9.0E-09 | 1.4E-08 |
| Br-82 | Adult | 5.0E-08 | 6.2E-09 | 5.6E-08 | 5.0E-08 | 3.1E-07 | 3.6E-07 |
| Kr-85 | Adult | 8.5E-12 | <1.0E-12 | 8.5E-12 | 8.5E-12 | <1.0E-12 | 8.5E-12 |
| Kr-79 | Adult | 3.8E-10 | <1.0E-12 | 3.8E-10 | 3.8E-10 | <1.0E-12 | 3.8E-10 |
| Sr-90 | Adult | 3.1E-07 | 5.1E-06 | 5.4E-06 | 3.1E-07 | 2.8E-05 | 2.8E-05 |
| Tc-99 | Adult | | | | | | |
| Tc-99m | Adult | | | | | | |
| In-111 | Adult | 2.6E-09 | 0.0 | 2.6E-09 | 2.6E-09 | 0.0 | 2.6E-09 |
| I-125 | Adult | 4.3E-08 | 2.6E-06 | 2.6E-06 | 4.3E-08 | 3.1E-05 | 3.1E-05 |
| I-131 | Adult | 1.3E-07 | 1.1E-06 | 1.2E-06 | 1.3E-07 | 1.8E-05 | 1.8E-05 |
| Xe-133 | Adult | 5.6E-11 | <1.0E-12 | 5.6E-11 | 5.6E-11 | <1.0E-12 | 5.6E-11 |
| Ba-140 | Adult | 2.3E-07 | 3.2E-08 | 2.6E-07 | 2.3E-07 | 1.6E-07 | 3.9E-07 |
| La-140 | Adult | 9.8E-08 | <1.0E-08 | 9.8E-08 | 9.8E-08 | 1.1E-08 | 1.1E-07 |
| Po-210 | Adult | 2.8E-05 | 8.3E-05 | 1.1E-04 | 2.8E-05 | 3.0E-04 | 3.3E-04 |

**TABLE 6 ATMOSPHERIC RELEASE - 100m DISCHARGE: - DOSE PER UNIT DISCHARGE DATA FOR URBAN AND RURAL SITES**

| Nuclide | Age group | Dose for discharge of 1 MBq per year into river flow of 3 cu metres per second, $\mu Sv\ y^{-1}$ | | | |
|---|---|---|---|---|---|
| | | External | Ingestion - fish | Ingestion – water | Total |
| H-3 | Infant | 0.0 | 4.6E-11 | 1.3E-07 | 1.3E-07 |
| | Child | 0.0 | 1.1E-10 | 8.5E-08 | 8.5E-08 |
| | Adult | 0.0 | 3.4E-10 | 1.1E-07 | 1.1E-07 |
| C-14 | Infant | 0.0 | 7.4E-06 | 4.2E-06 | 1.2E-05 |
| | Child | 0.0 | 1.9E-05 | 2.8E-06 | 2.2E-05 |
| | Adult | 0.0 | 5.4E-05 | 3.5E-06 | 5.7E-05 |
| P-32 | Infant | 0.0 | 9.7E-12 | 5.1E-05 | 5.1E-05 |
| | Child | 0.0 | 1.4E-11 | 1.9E-05 | 1.9E-05 |
| | Adult | 0.0 | 2.4E-11 | 1.5E-05 | 1.5E-05 |
| Co-58 | Infant | 6.6E-07 | 9.8E-07 | 8.5E-06 | 9.5E-06 |
| | Child | 1.1E-05 | 1.9E-06 | 4.4E-06 | 6.3E-06 |
| | Adult | 1.1E-05 | 3.3E-06 | 3.3E-06 | 1.7E-05 |
| Sr-90 | Infant | 2.7E-13 | 4.5E-06 | 1.8E-04 | 1.8E-04 |
| | Child | 4.5E-12 | 1.8E-05 | 2.0E-04 | 2.2E-04 |
| | Adult | 4.5E-12 | 3.4E-05 | 1.6E-04 | 1.9E-04 |
| I-131 | Infant | 1.0E-06 | 3.7E-06 | 1.7E-04 | 1.7E-04 |
| | Child | 1.0E-06 | 5.3E-06 | 6.5E-05 | 7.0E-04 |
| | Adult | 1.0E-06 | 9.0E-05 | 4.7E-05 | 1.4E-04 |

Notes: 1. Dose at 1 km downstream of release.
2. Flow rate is mean annual value; doses may be scaled inversely to flow rate.

**TABLE 8 RELEASE TO RIVER: DOSE PER UNIT DISCHARGE DATA FOR SELECTED RADIONUCLIDES**

| | | |
|---|---|---|
| a) River pathways - direct | | |
| Pathway | | |
| Drinking water | Litres per year | 600 |
| Freshwater fish consumption | Kg per year | 2 |
| Occupancy on river bank | Hours per year | 500 |
| b) Sewage sludge application and irrigation by river water | | |
| Sludge application rate | Kg (dry weight) per $m^2$ per year | 1 |
| Irrigation rate | Mm per day | 5 |
| Occupancy on irrigated / fertilised land | Hours per year | 1000 |
| Consumption rates of locally grown produce | | |
| Green vegetables | Kg per year | 80 |
| Root vegetables | Kg per year | 130 |
| Fruit | Kg per year | 75 |
| c) Marine / estuarine pathways | | |
| Fish consumption - local | Kg per year | 50 |
| Fish consumption – regional | Kg per year | 50 |
| Occupancy on sediments | Hours per year | 1000 |
| Inhalation of sea spray | Hours per year | 2000 |

**TABLE 7 BASIS OF ASSESSMENT OF RADIOLOGICAL IMPACT FOR PATHWAYS FROM LIQUID RELEASES**

| Nuclide | Half-life | Dose to adult for discharge of 1 MBq per year into river flow of 1 cubic metre per second, µSv y-1 (1, 2) | | | | Reduction factor for discharge via STW (3) |
|---|---|---|---|---|---|---|
| | | External | Ingestion – fish | Ingestion - water | Total | |
| H-3 | 12y | 0.0 | 1.03E-09 | 3.4E-07 | 3.4E-07 | 1 |
| C-14 | 5,700y | 0.0 | 1.6E-04 | 1.1E-05 | 1.7E-04 | 1 |
| F-18 | 1.8h | 0.0 | 0.0 | 3.0E-07 | 3.0E-07 | 1 |
| Na-24 | 15h | 0.0 | 0.0 | 4.0E-06 | 4.0-06 | 1 |
| P-32 | 14d | 0.0 | 7.4E-10 | 4.4E-05 | 4.4E-05 | 1 |
| P-33 | 25d | 0.0 | 7.4E-11 | 4.4E-06 | 4.4E-06 | 1 |
| S-35 | 87d | 0.0 | 9.2E-06 | 1.4E-05 | 2.3E-05 | 1 |
| Cl-36 | 3E+05y | 0.0 | 1.1E-06 | 5.9E-06 | 7.0E-06 | 1 |
| Ca-45 | 163d | 0.0 | 2.5E-06 | 1.2E-05 | 1.5E-05 | 1 |
| V-48 | 16d | 6.0E-06 | 3.6E-06 | 2.7E-05 | 3.7E-05 | 0.1 |
| Cr-51 | 28d | 1.2E-07 | 6.8E-08 | 5.1E-07 | 7.0E-07 | 1 |
| Mn-54 | 312d | 5.3E-04 | 2.1E-06 | 6.3E-06 | 5.4E-04 | 0.1 |
| Mn-56 | 2.6h | 0.0 | 0.0 | 2.2E-06 | 2.2E-06 | 0.1 |
| Co-57 | 271d | 2.0E-05 | 2.8E-06 | 2.8E-06 | 2.6E-05 | 1 |
| Co-58 | 71d | 3.3E-05 | 9.9E-06 | 9.9E-06 | 5.3E-05 | 1 |
| Fe-59 | 44d | 4.2E-06 | 9.5E-06 | 2.8E-05 | 4.2E-05 | 1 |
| Ga-67 | 3.3d | 0.0 | 0.0 | 3.4E-06 | 3.4E-06 | 0.1 |
| Se-75 | 120d | 1.9E-07 | 1.9E-04 | 2.8E-04 | 4.7E-04 | 0.1 |
| Br-82 | 1.4d | 1.8E-04 | 0.0 | 3.5E-06 | 1.8E-04 | 1 |
| Sr-89 | 50d | 6.1E-11 | 9.5E-06 | 4.5E-05 | 5.5E-05 | 1 |
| Sr –90 | 29y | 1.3E-11 | 1.0E-04 | 4.9E-04 | 5.9E-04 | 1 |
| Tc-99m | 6.0h | 0.0 | 0.0 | 3.6E-07 | 3.6E-07 | 1 |
| Ru-103 | 39d | 1.1E-06 | 4.1E-07 | 6.1E-06 | 7.6E-06 | 1 |
| In-111 | 2.8d | 1.5E-07 | 0.0 | 5.4E-06 | 5.6E-06 | 1 |
| In-113m | 1.7h | 0.0 | 0.0 | 3.4E-07 | 3.4E-07 | 1 |
| I-123 | 13h | 0.0 | 0.0 | 1.4E-06 | 1.4E-06 | 1 |
| I-125 | 60d | 3.0E-07 | 1.9E-05 | 9.9E-05 | 1.2E-04 | 1 |
| I-131 | 8d | 3.0E-06 | 2.7E-05 | 1.4E-04 | 1.7E-04 | 1 |
| Cs-137/Ba-137m | 30y | 4.9E-05 | 1.6E-03 | 1.1E-04 | 1.7E-03 | 1 |
| Tl-201 | 3.0d | 3.0E-10 | 2.6E-06 | 1.8E-06 | 4.4E-06 | 1 |
| Ra-226 | 1.6E+03 | 3.6E-03 | 8.8E-04 | 5.3E-03 | 9.8E-03 | 1 |
| U and Th | See following table for factors for uranium and thorium | | | | | |

Notes:
1. Dose at 1 km downstream of release and based on fish consumption rate of 2 kg/y.
2. To obtain dose estimates for other flow rates, divide tabulated values by annual average flow.
3. If release is from a STW, the release should be corrected by the factors in this column.

**TABLE 9a RELEASE TO RIVER: REFERENCE DATA - DOSE TO ADULT PER MBq RELEASE INTO MEAN ANNUAL FLOW OF 1 $m^3/s$**

| Nuclide | Half-life | Dose to adult for discharge of 1 gram per year into river flow of 1 cubic metre per second, $\mu Sv \cdot y^{-1}$ (1, 2, 3, 4) | | | | Reduction factor for discharge via STW (5) |
|---|---|---|---|---|---|---|
| | | External | Ingestion – fish | Ingestion - water | Total | |
| Natural U | Various | 4.51E-05 | 4.55E-05 | 1.19E-04 | 2.09E-04 | 1 |
| Natural Th | Various | 3.63E-06 | 5.42E-05 | 3.25E-04 | 3.83E-04 | 0.1 |

Notes:
1. Uranium assumed to be in secular equilibrium with decay chain.
2. For Th, includes Th-232 chain plus Th-230 at 59kBq/g Th.
3. Dose at 1 km downstream of release and based on fish consumption rate of 2 kg/y.
4. To obtain dose estimates for other flow rates, divide tabulated values by annual average flow.
5. If release is from a STW, the release should be corrected by the factors in this column.

**TABLE 9b RELEASE TO RIVER: REFERENCE DATA - DOSE TO ADULT PER GRAM RELEASE INTO MEAN ANNUAL FLOW OF 1 $m^3$/s**

| Nuclide | Half-life | Plant to soil concentration factor (WW:dw) | | | External dose rate |
|---|---|---|---|---|---|
| | | Green vegetables | Root vegetables | Fruit | µSv y⁻¹ per Bq kg⁻¹ |
| H-3 | 12y | 5.0E+00 | 5.0E+00 | 5.0E+00 | 0.0E+00 |
| C-14 | 5,700y | 2.0E-01 | 2.0E-01 | 2.0E-01 | 0.0E+00 |
| F-18 | 1.8h | 5.0+00 | 5.0E+00 | 5.0E+00 | 2.3E+00 |
| Na-24 | 15h | 3.0E-02 | 3.0E-02 | 3.0E-02 | 9.3E+00 |
| P-32 | 14d | 1.0E+00 | 1.0E+00 | 1.0E+00 | 0.0E+00 |
| P-33 | 25d | 1.0E+00 | 1.0E+00 | 1.0E+00 | 0.0E+00 |
| S-35 | 87d | 6.0E-01 | 6.0E-01 | 6.0E-01 | 0.0E+00 |
| Cl-36 | 3E+05y | 5.0E+00 | 5.0E+00 | 5.0E+00 | 0.0E+00 |
| Ca-45 | 163d | 1.0E-02 | 5.0E-03 | 1.0E-02 | 0.0E+00 |
| V-48 | 16d | 3.0E-04 | 3.0E-04 | 3.0E-04 | 6.4E+00 |
| Cr-51 | 28d | 3.0E-04 | 3.0E-04 | 3.0E-04 | 7.4E-02 |
| Mn-54 | 312d | 1.0E-01 | 1.0E-01 | 1.0E-01 | 1.9E+00 |
| Mn-56 | 2.6h | 1.0E-01 | 1.0E-01 | 1.0E-01 | 3.7E+00 |
| Co-57 | 271d | 1.0E-02 | 1.0E-02 | 1.0E-02 | 2.9E-01 |
| Co-58 | 71d | 1.0E-02 | 1.0E-02 | 1.0E-02 | 2.2E+00 |
| Fe-59 | 44d | 2.0E-04 | 3.0E-04 | 2.0E-04 | 2.7E+00 |
| Ga-67 | 3.3d | 1.0E-02 | 1.0E-02 | 1.0E-02 | 3.6E-01 |
| Se-75 | 120d | 1.0E-02 | 1.0E-02 | 1.0E-02 | 8.8E-01 |
| Br-82 | 1.4d | 1.0E+00 | 1.0E+00 | 1.0E+00 | 4.6E+00 |
| Sr-89 | 50d | 3.0E-01 | 1.0E-01 | 3.0E-01 | 0.0E+00 |
| Sr –90 | 29y | 3.0E-01 | 1.0E-01 | 3.0E-01 | 0.0E+00 |
| Tc-99m | 6.0h | 5.0E+00 | 5.0E+00 | 5.0E+00 | 2.0E-01 |
| Ru-103 | 39d | 1.0E-02 | 1.0E-02 | 1.0E-02 | 1.1E+00 |
| In-111 | 2.8d | 1.0E-02 | 1.0E-02 | 1.0E-02 | 9.6E-01 |
| In-113m | 1.7h | 1.0E-02 | 1.0E-02 | 1.0E-02 | 6.0E-01 |
| I-123 | 13h | 2.0E-02 | 2.0E-02 | 2.0E-02 | 3.9E-01 |
| I-125 | 60d | 2.0E-02 | 2.0E-02 | 2.0E-02 | 2.6E-02 |
| I-131 | 8d | 2.0E-02 | 2.0E-02 | 2.0E-02 | 8.7E-01 |
| Cs-137/Ba- | 30y | 7.0E-03 | 5.0E-03 | 7.0E-03 | 1.2E+00 |
| Tl-201 | 3.0d | 1.0E-02 | 1.0E-02 | 1.0E-02 | 2.1E-01 |
| Ra-226 | 1.6E+03 | 1.0E-02 | 1.0E-02 | 1.0E-02 | 3.5E+00 |
| Th-232 | 1.4E+10 y | 1.0E-02 | 1.0E-03 | 1.0E-02 | 2.5E+00 |
| Th-230 | 7.7E+04y | 1.0E-02 | 1.0E-03 | 1.0E-02 | 0.0E+00 |
| U-238 | | 1.0E-02 | 1.0E-02 | 1.0E-02 | 5.0E-02 |

Notes: Data taken mainly from Ref.4.

**TABLE 10 INPUT DATA FOR AGRICULTURAL PATHWAYS**

| Nuclide | Half-life | Dose to adult from irrigation for discharge of 1 MBq per year into river flow of 1 cubic metre per second, µSv y⁻¹ | | |
|---|---|---|---|---|
| | | Ext. + resus | Food pathways | Total |
| H-3 | 12y | 8.7E-11 | 1.6E-05 | 1.6E-05 |
| C-14 | 5,700y | 1.3E-08 | 5.8E-05 | 5.8E-05 |
| F-18 | 1.8h | 1.9E-12 | 2.4E-12 | 4.4E-12 |
| Na-24 | 15h | 1.9E-07 | 4.6E-07 | 6.4E-07 |
| P-32 | 14d | 7.4E-11 | 5.7E-05 | 5.7E-05 |
| P-33 | 25d | 1.5E-11 | 7.1E-06 | 7.1E-06 |
| S-35 | 87d | 4.7E-10 | 4.5E-06 | 4.5E-06 |
| Cl-36 | 3E+05y | 7.2E-08 | 1.7E-03 | 1.7E-03 |
| Ca-45 | 163d | 1.3E-09 | 2.0E-05 | 2.0E-05 |
| V-48 | 16d | 9.5E-06 | 4.3E-05 | 5.2E-05 |
| Cr-51 | 28d | 1.7E-07 | 9.2E-07 | 1.1E-06 |
| Mn-54 | 312d | 1.8E-05 | 2.2E-05 | 4.1E-05 |
| Mn-56 | 2.6h | 6.2E-11 | 2.5E-10 | 3.1E-10 |
| Co-57 | 271d | 2.5E-06 | 6.1E-06 | 8.6E-06 |
| Co-58 | 71d | 9.1E-06 | 2.0E-05 | 2.9E-05 |
| Fe-59 | 44d | 8.8E-06 | 4.7E-05 | 5.6E-05 |
| Ga-67 | 3.3d | 9.3E-08 | 1.8E-06 | 1.9E-06 |
| Se-75 | 120d | 4.7E-06 | 7.3E-05 | 7.8E-05 |
| Br-82 | 1.4d | 4.1E-07 | 2.3E-06 | 2.7E-06 |
| Sr-89 | 50d | 1.5E-09 | 7.3E-05 | 7.3E-05 |
| Sr-90 | 29y | 2.5E-07 | 2.3E-03 | 2.3E-03 |
| Tc-99m | 6.0h | 4.5E-10 | 1.1E-09 | 1.5E-09 |
| Ru-103 | 39d | 3.3E-06 | 1.9E-05 | 2.2E-05 |
| In-111 | 2.8d | 2.1E-07 | 5.8E-05 | 5.8E-05 |
| In-113m | 1.7h | <1.0E-12 | <1.0E-12 | <1.0E-12 |
| I-123 | 13h | 6.0E-09 | 1.7E-07 | 1.8E-07 |
| I-125 | 60d | 1.0E-07 | 4.1E-04 | 4.1E-04 |
| I-131 | 8d | 6.3E-07 | 3.6E-04 | 3.7E-04 |
| Cs-137/Ba-137m | 30y | 1.2E-04 | 4.0E-04 | 5.2E-04 |
| Tl-201 | 3.0d | 5.0E-08 | 8.4E-07 | 8.8E-07 |
| Ra-226 | 1.6E+03 | 5.1E-04 | 9.3E-03 | 9.8E-03 |
| U and Th | | See following table | | |

Notes:
1. Irrigation rate of 5 mm per day. Water extracted 1km downstream of release.
2. To obtain estimates for other river flow rates, divide tabulated values by annual average flow.
3. If release is from STW, the activity release should be reduced by the factor from Table 9.

**TABLE 11a SPRAY IRRIGATION FROM RIVER: REFERENCE DATA - DOSE TO ADULT PER MBq RELEASE INTO MEAN ANNUAL FLOW OF 1 $m^3/s$**

| Nuclide | Half-life | Dose to adult from irrigation for discharge of 1 gram per year into river flow of 1 cubic metre per second, μSv $y^{-1}$ | | |
|---|---|---|---|---|
| | | Ext. + resus | Food pathways | Total |
| Natural U | Various | 1.9E-05 | 2.4E-04 | 2.6E-04 |
| Natural Th | Various | 5.9E-06 | 5.4E-04 | 5.5E-04 |

Notes:
1. Uranium assumed to be in secular equilibrium with decay chain.
2. For Th. includes Th-232 chain plus Th-230 at 59kBq/g Th.
3. Irrigation rate of 5mm per day. Water extracted 1km downstream of release.
4. To obtain estimates for other river flow rates, divide tabulated values by annual average flow.
5. If release is from STW, the activity release should be reduced by the factor from Table 9.

**TABLE 11b SPRAY IRRIGATION FROM RIVER: REFERENCE DATA - DOSE TO ADULT PER GRAM RELEASE INTO MEAN ANNUAL FLOW OF 1 $m^3/s$**

| Nuclide | Half-life | Dose to adult from release of 1 MBq per year into sea or estuary for a nominal exchange/ dilution flow of 1 cubic metre per second, µSv y$^{-1}$ | | |
|---|---|---|---|---|
| | | Fish consumption | Gamma exposure from sediment | Total |
| H-3 | 12y | 5.3E-08 | 0.0 | 5.3E-08 |
| C-14 | 5700y | 3.0E-02 | 0.0 | 3.0E-02 |
| Na-24 | 15h | 1.0E-08 | 9.9E-09 | 2.0E-08 |
| S-35 | 87d | 4.1E-06 | 0.0 | 4.1E-06 |
| Mn-56 | 2.6h | 5.0E-09 | 2.0E-10 | 5.2E-09 |
| Co-58 | 71d | 1.2E-04 | 2.3E-06 | 1.2E-04 |
| Br-82 | 1.4d | 3.0E-06 | 1.0E-09 | 3.0E-06 |
| Sr-89 | 50d | 1.2E-05 | 1.2E-11 | 1.2E-05 |
| Sr-90 | 29y | 1.5E-04 | 2.5E-11 | 1.5E-04 |
| Tc-99m | 6.0h | 5.0E-09 | 2.0E-10 | 5.2E-09 |
| In-113m | 1.7h | <1.0E-12 | <1.0E-12 | <1.0E-12 |
| I-125 | 60d | 3.9E-04 | 9.3E-09 | 3.9E-04 |
| I-131 | 8d | 3.4E-04 | 7.2E-09 | 3.4E-04 |
| Cs-137/Ba-137m | 30y | 3.1E-03 | 2.3E-05 | 3.1E-03 |
| Pb-210 | 22.3y | 0.2 | 1.9E-7 | 0.2 |
| Po-210 | 138d | 0.4 | Neg | 0.4 |
| Ra-226 | 1620y | 3.0E-01 | 1.6E-04 | 3.0E-01 |

1. To obtain dose estimates for other flow rates, divide tabulated values by estimated exchange/dilution flow from local region. For coastal region of SW North Sea, a reasonable value is 300 m$^3$/s. The same value can be used for discharges into major estuaries such as Thames and Humber. For other tidal waters, the local conditions need to be examined.
2. If release is from STW, the activity release should be reduced by the factor from Table 9.

**TABLE 12 RELEASE TO SEA OR ESTUARY: REFERENCE DATA - DOSE TO ADULT PER MBq RELEASE INTO REGION WITH DILUTION/EXCHANGE RATE OF 1 m$^3$/s**

| Nuclide | Half-life | Fractions to water / sludge | | Dose to adult from discharge of 1 MBq per year into reference STW taking 1.0E5 cubic metre per day raw sewage, µSv y⁻¹ | | |
|---|---|---|---|---|---|---|
| | | W | S | Ext. + resus | Food pathways | Total |
| H-3 | 12y | 1 | 0.1 | 8.1E-11 | 1.4E-05 | 1.4E-05 |
| C-14 | 5,700y | 1 | 0.1 | 1.2E-08 | 3.8E-05 | 3.8E-05 |
| F-18 | 1.8h | 1 | 0.1 | <1.0E-12 | <1.0E-12 | <1.0E-12 |
| Na-24 | 15h | 1 | 0.1 | 6.3E-10 | <1.0E-12 | 6.3E-10 |
| P-32 | 14d | 1 | 0.1 | 1.8E-11 | 1.1E-11 | 2.9E-11 |
| P-33 | 25d | 1 | 0.1 | 4.2E-12 | 7.8E-10 | 7.8E-10 |
| S-35 | 87d | 1 | 0.1 | 2.3E-10 | 1.1E-07 | 1.1E-07 |
| Cl-36 | 3E+05y | 1 | 0.1 | 6.8E-08 | 1.5E-03 | 1.5E-03 |
| Ca-45 | 163d | 1 | 0.1 | 8.0E-10 | 3.0E-08 | 3.1E-08 |
| V-48 | 16d | 0.1 | 1 | 2.3E-05 | <1.0E-12 | 2.3E-05 |
| Cr-51 | 28d | 1 | 1 | 5.1E-07 | 2.6E-12 | 5.1E-07 |
| Mn-54 | 312d | 0.1 | 1 | 1.4E-04 | 9.3E-06 | 1.5E-04 |
| Mn-56 | 2.6h | 0.1 | 1 | <1.0E-12 | 0.0E+00 | <1.0E-12 |
| Co-57 | 271d | 1 | 1 | 1.9E-05 | 2.4E-07 | 1.9E-05 |
| Co-58 | 71d | 1 | 1 | 4.0E-05 | 5.9E-08 | 4.0E-05 |
| Fe-59 | 44d | 1 | 1 | 3.1E-05 | 2.1E-09 | 3.1E-05 |
| Ga-67 | 3.3d | 0.1 | 1 | 1.1E-07 | <1.0E-12 | 1.1E-07 |
| Se-75 | 120d | 0.1 | 1 | 2.7E-05 | 7.9E-07 | 2.7E-05 |
| Br-82 | 1.4d | 1 | 0.1 | 1.8E-08 | <1.0E-12 | 1.8E-08 |
| Sr-89 | 50d | 1 | 0.1 | 5.8E-10 | 1.2E-07 | 1.2E-07 |
| Sr-90 | 29y | 1 | 0.1 | 2.4E-07 | 1.3E-03 | 1.3E-03 |
| Tc-99m | 6.0h | 1 | 0.1 | <1.0E-12 | 0.0E+00 | <1.0E-12 |
| Ru-103 | 39d | 1 | 1 | 1.1E-05 | 5.1E-09 | 1.1E-05 |
| In-111 | 2.8d | 1 | 1 | 2.2E-07 | <1.0E-12 | 2.2E-07 |
| In-113m | 1.7h | 1 | 1 | <1.0E-12 | <1.0E-12 | <1.0E-12 |
| I-123 | 13h | 1 | 0.1 | 1.1E-11 | <1.0E-12 | 1.1E-11 |
| I-125 | 60d | 1 | 0.1 | 4.1E-08 | 1.3E-07 | 1.7E-07 |
| I-131 | 8d | 1 | 0.1 | 1.3E-07 | <1.0E-12 | 1.3E-07 |
| Cs-137/Ba-137m | 30y | 1 | 0.1 | 1.1E-04 | 2.0E-05 | 1.3E-04 |
| Tl-201 | 3.0d | 1 | 1 | 5.7E-08 | <1.0E-12 | 5.7E-08 |
| Ra-226 | 1.6E+03 | 1 | 0.1 | 4.8E-04 | 9.8E-04 | 1.5E-03 |
| U and Th | See following table | | | | | |

Notes: 1. The estimates include allowance for the fraction in sludge
2. To obtain estimates for other STW input rates, scale values inversely to capacity of plant.

**TABLE 13a SEWAGE SLUDGE APPLICATION TO AGRICULTURAL LAND - DOSE TO ADULT PER MBq RELEASE INTO STW OF $10^5$ m³/day**

| Nuclide | Half-life | Fractions to water / sludge | | Dose to adult from sludge application for input of 1 gram per year into reference STW taking 1.0E5 cubic metre per day raw sewage, μSv $y^{-1}$ | | |
|---|---|---|---|---|---|---|
| | | W | S | Ext. + resus | Food pathways | Total |
| Natural U | Various | 1 | 0.1 | 1.8E-05 | 2.2E-05 | 4.0E-05 |
| Natural Th | Various | 0.1 | 1 | 5.6E-05 | 3.7E-04 | 4.3E-04 |

1. The estimates include allowance for the fraction in sludge
2. To obtain estimates for other STW input rates, scale values inversely to capacity of plant.
3. For U includes U-238, Th-234, Pa-234, U-234, U-235 and Th-231.
4. For Th, includes Th-232 chain plus contribution from Th-230.

**TABLE 13b SEWAGE SLUDGE APPLICATION TO AGRICULTURAL LAND - DOSE TO ADULT PER GRAM RELEASE INTO STW OF $10^5$ $m^3$/day**

| Nuclide | Dose to adult from landfill disposal of 1 MBq per year, µSv y-1 | |
|---|---|---|
| | Disposal worker | Member of public |
| H-3 | 5.7E-09 | 9.7E-09 |
| C-14 | 8.1E-08 | 1.5E-07 |
| P-32 | 5.0E-04 | 2.7E-09 |
| S-35 | 9.8E-08 | 5.6E-06 |
| Cr-51 | 1.2E-03 | 2.0E-09 |
| Co-60 | 7.8E-02 | 1.1E-06 |
| Sr-90 | 9.1E-04 | 6.9E-06 |
| Tc-99m | 4.8E-03 | 2.5E-10 |
| I-125 | 3.3E-03 | 2.1E-07 |
| I-131 | 1.30E-02 | 2.9E-07 |
| Cs-137 | 1.9E-02 | 1.9E-07 |
| Ra-226 | 4.9E-02 | 1.3E-04 |
| Th-232 (1) | 8.0E-02 | 5.9E-03 |
| Nat. U (2) | 6.8E-02 | 3.7E-03 |

1. Includes dose contributions from Th decay chain, plus contribution from Th-230 which is taken to be present to extent of 59kBq/g of Th. The 1 MBq refers only to the Th-232 activity.
2. The uranium decay chain is assumed to be in secular equilibrium but the activity refers only to U-238.

**TABLE 14 LANDFILL DISPOSAL - DOSE RATE TO ADULT FOR ANNUAL DISPOSAL OF 1 MBq**

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# APPENDIX A - LIST OF AUTHORISED SITES IN ANGLIAN REGION

(Hand-written numbers in left margin are reference numbers for study)

ADDRAS 30/04/98 10:31

# RSA93 S.13 - Effective Anglian Region

| | Operator Name | Operator Complete Address | Permiss... | Local Authority Co... |
|---|---|---|---|---|
| 01 | BEDFORD HOSPITAL NHS TRUST | SOUTH WING , KEMPSTON ROAD BEDFORD MK42 9DJ | AT3957 | BEDFORDSHIRE |
| 02 | CHEMEX INTERNATIONAL PLC | 74 SUNDERLAND ROAD SANDY BEDFORDSHIRE SG19 1QY | AY9103 | BEDFORDSHIRE |
| 03 | CRANFIELD BIOTECHNOLOGY CENTRE | CRANFIELD UNIVERSITY CRANFIELD BEDFORD BEDFORDSHIRE MK43 0AL | AC2314 | BEDFORDSHIRE |
| 04 | SOIL SURVEY AND LAND RESEARCH CENTRE | CRANFIELD UNIVERSITY , SILSOE BEDFORD MK45 4DT | AL4163 | BEDFORDSHIRE |
| 05 | UNILEVER RESEARCH COLWORTH LABORATORY | COLWORTH HOUSE SHARNBROOK BEDFORD BEDFORDSHIRE MK44 1LQ | AT1920 | BEDFORDSHIRE |
| 06 | EG AND G LTD | 20 VINCENT AVENUE CROWNHILL MILTON KEYNES BUCKINGHAMSHIRE MK8 0AB | AE4628 | BUCKINGHAMSHI... |
| 07 | HOECHST MARION ROUSSEL LTD | WALTON MANOR, WALTON MILTON KEYNES MK7 7AJ | AW3252 | BUCKINGHAMSHI... |
| 08 | MILTON KEYNES GENERAL NHS TRUST | MILTON KEYNES GENERAL HOSPITAL, STANDING WAY, EAGLESTONE MILTON KEYNES MK6 5LD | BA2768 | BUCKINGHAMSHI... |
| 09 | PHARMACIA AND UPJOHN LTD | DAVY AVENUE, KNOWLHILL MILTON KEYNES BUCKINGHAMSHIRE MK5 8PH | AV4652 | BUCKINGHAMSHI... |
| 10 | THE OPEN UNIVERSITY | OPEN UNIVERSITY CAMPUS , WALTON HALL MILTON KEYNES MK7 6AA | AS8457 | BUCKINGHAMSHI... |
| 11 | ADDENBROOKES NHS TRUST HOSPITAL | ADDENBROOKES HOSPITAL, HILLS ROAD CAMBRIDGE CB2 2QQ | AY6767 | CAMBRIDGESHIRE |
| 12 | ADVANCED TECHNOLOGIES (CAMBRIDGE) LTD | 210 CAMBRIDGE SCIENCE PARK, MILTON ROAD CAMBRIDGE CAMBRIDGESHIRE CB4 4WA | AX3932 | CAMBRIDGESHIRE |
| 13 | AFFINITY SENSORS | SAXON WAY BAR HILL CAMBRIDGE CAMBRIDGESHIRE CB3 8SL | AV4920 | CAMBRIDGESHIRE |
| 14 | AGREVO UK LTD | THE REDLANDS, OAKINGTON ROAD COTTENHAM CAMBRIDGE CAMBRIDGESHIRE CB4 4TW | AM6455 | CAMBRIDGESHIRE |
| 15 | AI QUALITEK LTD | LONDON ROAD PAMPISFORD CAMBRIDGE CAMBRIDGESHIRE CB2 4EF | AY7941 | CAMBRIDGESHIRE |
| 16 | AXIS GENETICS PLC | BABRAHAM CAMBRIDGE CB2 4AZ | AX5471 | CAMBRIDGESHIRE |
| 17 | BRITISH GAS PLC | EASTERN DIVISION, NENE WEST AGI, FERRY LANE NEWTON WISBECH CAMBRIDGESHIRE PE13 ... | AJ0647 | CAMBRIDGESHIRE |
| 18 | ~~CAMBRIDGE ANTIBODY TECHNOLOGY LTD~~ | ~~THE SCIENCE PARK MELBOURN ROYSTON HERTFORDSHIRE SG8 6JJ~~ | ~~AQ0081~~ | ~~CAMBRIDGESHIRE~~ |
| | CAMBRIDGE ANTIBODY TECHNOLOGY LTD | THE SCIENCE PARK MELBOURN ROYSTON HERTFORDSHIRE SG8 6JJ | AX6826 | CAMBRIDGESHIRE |
| 19 | CAMBRIDGE SCIENTIFIC INSTRUMENTS LTD | UNITS 7 AND 8, SEDGEWAY BUSINESS PARK, WITCHFORD ELY CAMBRIDGESHIRE CB6 2HY | AT3833 | CAMBRIDGESHIRE |
| 20 | CANTAB PHARMACEUTICALS LTD | 184 CAMBRIDGE SCIENCE PARK, MILTON ROAD CAMBRIDGE CB4 4GN | AT4287 | CAMBRIDGESHIRE |
| 21 | CHIROSCIENCE LTD | UNIT 252/254 CAMBRIDGE SCIENCE PARK, MILTON ROAD CAMBRIDGE CB4 4WE | AY5167 | CAMBRIDGESHIRE |
| 22 | DALGETY FOOD INGREDIENTS LTD | FOOD INGREDIENTS DEVELOPMENT CENTRE, BLOCK B, STATION ROAD CAMBRIDGE CB1 2JN | AZ2422 | CAMBRIDGESHIRE |
| 23 | GENOME RESEARCH LTD | THE SANGER CENTRE, WELLCOME TRUST GENOME CAMPUS HINXTON SAFFRON WALDEN ESS... | AN2862 | CAMBRIDGESHIRE |
| 24 | HEXAGEN TECHNOLOGY LTD | 214 CAMBRIDGE SCIENCE PARK, MILTON ROAD CAMBRIDGE CAMBRIDGESHIRE CB4 4WA | AW8564 | CAMBRIDGESHIRE |
| 25 | ~~HINCHINGBROOKE HEALTH CARE NHS TRUST~~ | ~~HINCHINGBROOKE HOSPITAL , HINCHINGBROOKE PARK HUNTINGDON CAMBRIDGESHIRE PE18...~~ | AM8032 | CAMBRIDGESHIRE |
| | HINCHINGBROOKE HEALTH CARE NHS TRUST | HINCHINGBROOKE HOSPITAL , HINCHINGBROOKE PARK HUNTINGDON CAMBRIDGESHIRE PE18... | AZ8439 | CAMBRIDGESHIRE |
| 26 | HORSERACING FORENSIC LABORATORY LTD | NEWMARKET ROAD, FORDHAM ELY CAMBRIDGESHIRE CB7 5WW | AX3878 | CAMBRIDGESHIRE |
| 27 | HUNTINGDON LIFE SCIENCES LTD | WOOLLEY ROAD , ALCONBURY HUNTINGDON CAMBRIDGESHIRE PE18 6ES | AW9714 | CAMBRIDGESHIRE |
| 28 | IMUTRAN LIMITED | DOUGLAS HOUSE, 18 TRUMPINGTON ROAD CAMBRIDGE CB2 2AH | BA2750 | CAMBRIDGESHIRE |
| 29 | ~~INSTITUTE OF TERRESTRIAL ECOLOGY~~ | ~~MONKS WOOD ABBOTS RIPTON HUNTINGDON CAMBRIDGESHIRE PE17 2LS~~ | ~~AO7634~~ | ~~CAMBRIDGESHIRE~~ |
| | INSTITUTE OF TERRESTRIAL ECOLOGY | MONKS WOOD ABBOTS RIPTON HUNTINGDON CAMBRIDGESHIRE PE17 2LS | AS2157 | CAMBRIDGESHIRE |
| 30 | LCG CLINICAL LABORATORY UNIT | 211 CAMBRIDGE SCIENCE PARK, MILTON ROAD CAMBRIDGE CB4 4ZA | BA2636 | CAMBRIDGESHIRE |
| 31 | MARSHALL OF CAMBRIDGE AEROSPACE LTD | THE AIRPORT CAMBRIDGE CB5 8RX | AZ4891 | CAMBRIDGESHIRE |
| 32 | ~~MEDICAL RESEARCH COUNCIL~~ | ~~MRC CENTRE, HILLS ROAD CAMBRIDGE CAMBRIDGESHIRE CB2 2QH~~ | ~~AE5128~~ | ~~CAMBRIDGESHIRE~~ |
| 33 | MEDICAL RESEARCH COUNCIL | STRANGEWAYS RESEARCH LABORATORY, WORTS CAUSEWAY CAMBRIDGE CAMBRIDGESHIRE... | AI4573 | CAMBRIDGESHIRE |
| 34 | MEDICAL RESEARCH COUNCIL | MRC CENTRE, HILLS ROAD CAMBRIDGE CAMBRIDGESHIRE CB2 2QH | AZ2236 | CAMBRIDGESHIRE |
| 35 | MRC DUNN NUTRITION CENTRE | DUNN NUTRITIONAL LABORATORY, DOWNHAMS LANE, MILTON ROAD CAMBRIDGE CB4 1XJ | AN4156 | CAMBRIDGESHIRE |
| 36 | MRC HUMAN GENOME MAPPING PROJECT RESO... | HINXTON CAMBRIDGE CB10 1SB | AZ0896 | CAMBRIDGESHIRE |
| 37 | NAPP RESEARCH CENTRE | UNITS 127 AND 137, CAMBRIDGE SCIENCE PARK, MILTON RD CAMBRIDGE CB4 4GW | AC8967 | CAMBRIDGESHIRE |
| 38 | NIAB | HUNTINGDON ROAD CAMBRIDGE CAMBRIDGESHIRE CB3 0LE | AC9203 | CAMBRIDGESHIRE |
| 39 | PAPWORTH HOSPITAL NHS TRUST | PAPWORTH EVERARD CAMBRIDGE CB3 8RE | AO3872 | CAMBRIDGESHIRE |

| | | | | |
|---|---|---|---|---|
| | PARKE-DAVIS NEUROSCIENCE RESEARCH CENT... | CAMBRIDGE UNIVERSITY FORVIE SITE , ROBINSON WAY CAMBRIDGE CB2 2QB | AR8943 | CAMBRIDGESHIRE |
| 41 | PARKE-DAVIS NEUROSCIENCE RESEARCH CENT... | CAMBRIDGE UNIVERSITY FORVIE SITE , ROBINSON WAY CAMBRIDGE CB2 2QB | AY9740 | CAMBRIDGESHIRE |
| 42 | PEPTIDE THERAPEUTICS LTD | 324 CAMBRIDGE SCIENCE PARK, MILTON ROAD CAMBRIDGE CB4 4WG | AZ3143 | CAMBRIDGESHIRE |
| 43 | PETERBOROUGH HOSPITALS NHS TRUST | PETERBOROUGH DISTRICT HOSPITAL, THORPE ROAD PETERBOROUGH CAMBRIDGESHIRE PE... | AV4245 | CAMBRIDGESHIRE |
| 44 | PLANT BREEDING INTERNATIONAL | MARIS LANE, TRUMPINGTON CAMBRIDGE CB2 2LQ | AO0849 | CAMBRIDGESHIRE |
| 45 | QUADRANT HOLDINGS CAMBRIDGE LTD | MARIS LANE CAMBRIDGE CAMBRIDGESHIRE CB2 2JB | AA6327 | CAMBRIDGESHIRE |
| — | ~~SCL BIOSCIENCE SERVICES LTD~~ | ~~211 CAMBRIDGE SCIENCE PARK, MILTON ROAD CAMBRIDGE CB4 4ZA~~ | ~~AC0010~~ | ~~CAMBRIDGESHIRE~~ |
| 46 | SCL BIOSCIENCE SERVICES LTD | 211 CAMBRIDGE SCIENCE PARK, MILTON ROAD CAMBRIDGE CB4 4ZA | AX9132 | CAMBRIDGESHIRE |
| 47 | THE BABRAHAM INSTITUTE | BABRAHAM HALL BABRAHAM CAMBRIDGE CB2 4AT | AO3694 | CAMBRIDGESHIRE |
| 48 | THOROUGHBRED BREEDERS ASSOCIATION | EQUINE FERTILITY UNIT, WOODDITTON ROAD NEWMARKET SUFFOLK CB8 9BH | AD8075 | CAMBRIDGESHIRE |
| 49 | UNIVERSITY OF CAMBRIDGE | WASTE STORE, HIGH CROSS, MADINGLEY ROAD CAMBRIDGE CAMBRIDGESHIRE CB3 0HB | AG4289 | CAMBRIDGESHIRE |
| 50 | UNIVERSITY OF CAMBRIDGE | ADDENBROOKES HOSPITAL SITE, HILLS ROAD CAMBRIDGE CAMBRIDGESHIRE CB2 2QQ | AW3589 | CAMBRIDGESHIRE |
| 51 | UNIVERSITY OF CAMBRIDGE | CENTRAL SITE PREMISES CAMBRIDGE CB2 3DY | BA3748 | CAMBRIDGESHIRE |
| 52 | UNIVERSITY OF CAMBRIDGE | WEST SITES CAMBRIDGE CB3 0ES | AW3619 | CAMBRIDGESHIRE |
| 53 | UNIVERSITY OF CAMBRIDGE | DEPARTMENT OF ZOOLOGY MADINGLEY CAMBRIDGE CAMBRIDGESHIRE CB3 8AQ | AM7664 | CAMBRIDGESHIRE |
| 54 | WOLFSON BRAIN IMAGING CENTRE | ADDENBROOKE S NHS TRUST, HILLS ROAD CAMBRIDGE CB2 2QQ | AR6126 | CAMBRIDGESHIRE |
| 55 | AGREVO UK LTD | CHESTERFORD PARK LITTLE CHESTERFORD SAFFRON WALDEN ESSEX CB10 1XL | AV8712 | ESSEX |
| — | ~~AGREVO UK LTD~~ | ~~CHESTERFORD PARK LITTLE CHESTERFORD SAFFRON WALDEN ESSEX CB10 1XL~~ | ~~AO4321~~ | ~~ESSEX~~ |
| 56 | BASILDON AND THURROCK GENERAL HOSPITAL... | BASILDON HOSPITAL, NETHER MAYNE BASILDON ESSEX SS16 5NL | AT1202 | ESSEX |
| 57 | CARLESS REFINING AND MARKETING LTD | REFINERY ROAD HARWICH ESSEX CO12 4QG | AE7228 | ESSEX |
| 58 | ESSEX RIVERS HEALTHCARE NHS TRUST | COLCHESTER GENERAL HOSPITAL, TURNER ROAD COLCHESTER CO4 5JL | AR1701 | ESSEX |
| 59 | ESSEX RIVERS HEALTHCARE NHS TRUST | ESSEX COUNTY HOSPITAL, LEXDEN ROAD COLCHESTER CO3 3NB | AR1710 | ESSEX |
| — | ~~HUNTING BRAE LTD~~ | ~~ATOMIC WEAPONS ESTABLISHMENT, FOULNESS SOUTHEND-ON-SEA ESSEX SS3 9XE~~ | ~~AI2759~~ | ~~ESSEX~~ |
| — | ~~MAGNOX ELECTRIC PLC~~ | ~~BRADWELL NUCLEAR POWER STATION , GASEOUS DISPOSAL AUTHORISATION , BRADWELL-ON...~~ | ~~AB0804~~ | ~~ESSEX~~ |
| — | ~~MAGNOX ELECTRIC PLC~~ | ~~BRADWELL NUCLEAR POWER STATION , LIQUID DISPOSAL AUTHORISATION REVISION , BRADW...~~ | ~~AB0812~~ | ~~ESSEX~~ |
| — | ~~MAGNOX ELECTRIC PLC~~ | ~~BRADWELL NUCLEAR POWER STATION BRADWELL-ON-SEA SOUTHMINSTER ESSEX CM0 7HP~~ | ~~AB1142~~ | ~~ESSEX~~ |
| — | ~~MAGNOX ELECTRIC PLC~~ | ~~DISTRICT SURVEY LABORATORY (PEAKES), WATERSIDE ROAD, BRADWELL-ON-SEA SOUTHMIN...~~ | ~~AX8438~~ | ~~ESSEX~~ |
| — | ~~MAGNOX ELECTRIC PLC~~ | ~~BRADWELL POWER STATION , , BRADWELL ON SEA SOUTHMINSTER ESSEX CM0 7HP~~ | ~~AE8194~~ | ~~ESSEX~~ |
| — | ~~MAGNOX ELECTRIC PLC~~ | ~~BRADWELL NUCLEAR POWER STATION BRADWELL-ON-SEA SOUTHMINSTER ESSEX CM0 7HP~~ | ~~AP9005~~ | ~~ESSEX~~ |
| 60 | MID ESSEX HOSPITALS NHS TRUST | BROOMFIELD HOSPITAL, COURT ROAD CHELMSFORD CM1 5ET | AR8218 | ESSEX |
| 61 | MOBIL OIL CO LTD | CORYTON REFINERY , THE MANORWAY CORYTON STANFORD-LE-HOPE ESSEX SS17 9LL | AC8169 | ESSEX |
| — | ~~MOD~~ | ATOMIC WEAPONS ESTABLISHMENT , FOULNESS SOUTHEND-ON-SEA SS3 9XE | AI8617 | ESSEX |
| 62 | NICHOLS INSTITUTE DIAGNOSTICS LTD | WHITE HOUSE, HIGH STREET NEWPORT SAFFRON WALDEN ESSEX CB11 3PQ | AF9854 | ESSEX |
| 63 | RHONE POULENC AGRICULTURE LTD | ALDHAMS FARM , DEAD LANE LAWFORD MANNINGTREE ESSEX CO11 2NF | AH8816 | ESSEX |
| 64 | SHELL UK LTD DOWNSTREAM OIL | SHELL HAVEN REFINERY STANFORD-LE-HOPE ESSEX SS17 9LD | AQ8026 | ESSEX |
| 65 | SOUTHEND HEALTH CARE NHS TRUST | SOUTHEND HOSPITAL, PRITTLEWELL CHASE WESTCLIFF-ON-SEA ESSEX SS0 0RY | AT9548 | ESSEX |
| 66 | UNIVERSITY OF ESSEX | WIVENHOE PARK COLCHESTER ESSEX CO4 3SQ | AM4428 | ESSEX |
| 67 | CONOCO LTD | HUMBER REFINERY , SOUTH KILLINGHOLME GRIMSBY SOUTH HUMBERSIDE DN40 3DW | AW7258 | HUMBERSIDE |
| 68 | LINDSEY OIL REFINERY LTD | NORTH KILLINGHOLME IMMINGHAM GRIMSBY SOUTH HUMBERSIDE DN40 3LW | AZ0357 | HUMBERSIDE |
| 69 | MILLENNINIUM INORGANIC CHEMICALS | LAPORTE ROAD IMMINGHAM GRIMSBY SOUTH HUMBERSIDE DN40 2PR AN4032 | AE0207 | HUMBERSIDE |
| 70 | ~~MILLENNINIUM INORGANIC CHEMICALS~~ | ~~PO BOX 26 GRIMSBY NORTH HUMBERSIDE DN37 8DP~~ | ~~AE0215~~ | ~~HUMBERSIDE~~ |
| 71 | NORTH EAST LINCOLNSHIRE NHS TRUST | GRIMSBY HOSPITAL, SCARTHO ROAD GRIMSBY SOUTH HUMBERSIDE DN33 2BA | AZ2112 | HUMBERSIDE |
| 72 | CONOCO (UK) LTD | PICKERILL DUNES VALVE PIT, THEDDLETHORPE GAS TERMINAL, THEDDLETHORPE MABLETHO... | AV3567 | LINCOLNSHIRE |
| | CONOCO (UK) LTD | PICKERILL DUNES VALVE PIT, THEDDLETHORPE GAS TERMINAL, THEDDLETHORPE MABLETHO... | AW9471 | LINCOLNSHIRE |
| 73 | GRANTHAM AND DISTRICT HOSPITAL NHS TRUST | 101 MANTHORPE ROAD GRANTHAM LINCOLNSHIRE NG31 8DG | AR2058 | LINCOLNSHIRE |

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| | | | | |
|---|---|---|---|---|
| 74 | LINCOLN AND LOUTH NHS TRUST ✓ | ST GEORGE S HOSPITAL , LONG LEYS ROAD LINCOLN LN1 1EF | AM8474 | LINCOLNSHIRE |
| 75 | LINCOLN AND LOUTH NHS TRUST ✓ | COUNTY HOSPITAL, GREETWELL ROAD LINCOLN LN2 5QY | AU0678 | LINCOLNSHIRE |
| 76 | PILGRIM HEALTH NHS TRUST ✓ | PILGRIM HOSPITAL, SIBSEY ROAD BOSTON LINCOLNSHIRE PE21 9QS | AP7245 | LINCOLNSHIRE |
| 77 | BRITISH SUGAR PLC ✓ | BRITISH SUGAR TECHNICAL CENTRE, NORWICH RESEARCH PARK COLNEY NORWICH NORFOL... | AE0142 | NORFOLK |
| 78 | INSTITUTE OF FOOD RESEARCH ✓ | NORWICH LABORATORY, NORWICH RESEARCH PARK, COLNEY LANE NORWICH NR4 7UA | AE4130 | NORFOLK |
| 79 | JOHN INNES CENTRE ✓ | NORWICH RESEARCH PARK COLNEY NORWICH NR4 7UH | AS5946 | NORFOLK |
| 80 | KING S LYNN AND WISBECH HOSPITALS NHS TR... ✓ | QUEEN ELIZABETH HOSPITAL, GAYTON ROAD KING S LYNN NORFOLK PE30 4ET | AX2430 | NORFOLK |
| 81 | MAFF ✓ | FOOD SCIENCE LABORATORY , COLNEY LANE NORWICH NR4 7UQ | AB5628 | NORFOLK |
| 82 | NORFOLK AND NORWICH HEALTH CARE NHS TR... ✓ | NORFOLK AND NORWICH HOSPITAL, BRUNSWICK ROAD NORWICH NR1 3SR | AU4789 | NORFOLK |
| 83 | SHELL UK EXPLORATION AND PRODUCTION ✓ | GAS TERMINAL, PASTON ROAD, BACTON NORWICH NR12 0JE | AL1261 | NORFOLK |
| 84 | UNIVERSITY OF EAST ANGLIA ✓ | EARLHAM , NORWICH NR4 7TJ | AS8694 | NORFOLK |
| 85 | KETTERING GENERAL HOSPITAL NHS TRUST ✓ | KETTERING GENERAL HOSPITAL, ROTHWELL ROAD KETTERING NORTHAMPTONSHIRE NN16 8UZ | AT2659 | NORTHAMPTONS... |
| 86 | MALLINCKRODT MEDICAL UK LTD ✓ | 11 NORTH PORTWAY CLOSE, ROUND SPINNEY NORTHAMPTON NN3 8RQ | AR3259 | NORTHAMPTONS... |
| 87 | NORTHAMPTON GENERAL HOSPITAL NHS TRUST ✓ | CLIFTONVILLE NORTHAMPTON NORTHAMPTONSHIRE NN1 5BD | AW9552 | NORTHAMPTONS... |
| 88 | SURELITE LTD ✓ | PRIORS HAW ROAD CORBY NORTHAMPTONSHIRE NN17 5JG | AE0274 | NORTHAMPTONS... |
| 89 | WOODLAND HOSPITAL ✓ | ROTHWELL ROAD KETTERING NORTHAMPTONSHIRE NN16 8XF | BA2008 | NORTHAMPTONS... |
| 90 | ~~AGRICULTURAL AND FOOD RESEARCH COUNCIL~~ ✓ | ~~BROOMS BARN HIGHAM BURY ST. EDMUNDS SUFFOLK IP28 6NP~~ | AH8158 | SUFFOLK |
| 91 | ANIMAL HEALTH TRUST ✓ | BALATON LODGE SNAILWELL ROAD , NEWMARKET SUFFOLK CB8 7DW | AD0147 | SUFFOLK |
| 92 | ANIMAL HEALTH TRUST ✓ | LANWADES PARK , KENTFORD NEWMARKET SUFFOLK CB8 7UU | AZ8447 | SUFFOLK |
| 93 | CENTRE FOR ENVIRONMENT, FISHERIES AND AQ... | LOWESTOFT LABORATORY, PAKEFIELD ROAD LOWESTOFT SUFFOLK NR33 0HT | AJ6823 | SUFFOLK |
| 94 | GREENWOOD ELLIS AND PARTNERS ✓ | REYNOLDS HOUSE, 166 HIGH STREET NEWMARKET SUFFOLK CB8 9AH | AC3582 | SUFFOLK |
| 95 | HUNTINGDON LIFE SCIENCES LTD | , EYE SUFFOLK IP23 7PX | AY1838 | SUFFOLK |
| – | ~~MAGNOX ELECTRIC PLC~~ | ~~SIZEWELL A POWER STATION LEISTON SUFFOLK IP16 4UE~~ | ~~AA3565~~ | ~~SUFFOLK~~ |
| – | ~~MAGNOX ELECTRIC PLC~~ | ~~DISTRICT SURVEY LABORATORY , LOVER S LANE LEISTON SUFFOLK~~ | ~~AJ7994~~ | SUFFOLK |
| – | ~~MAGNOX ELECTRIC PLC~~ | ~~SIZEWELL A NUCLEAR POWER STATION LEISTON SUFFOLK IP16 4UE~~ | ~~AA8176~~ | ~~SUFFOLK~~ |
| – | ~~MAGNOX ELECTRIC PLC~~ | ~~SIZEWELL A POWER STATION , LEISTON SUFFOLK IP16 4UE~~ | ~~AF6642~~ | ~~SUFFOLK~~ |
| – | ~~MAGNOX ELECTRIC PLC~~ | ~~SIZEWELL A POWER STATION , AUTHORISATION TO DISCHARGE GASES LEISTON SUFFOLK~~ | ~~AE7538~~ | ~~SUFFOLK~~ |
| – | ~~MAGNOX ELECTRIC PLC~~ | ~~SIZEWELL C SITE , LEISTON SUFFOLK IP16~~ | ~~AH5027~~ | ~~SUFFOLK~~ |
| – | ~~NUCLEAR ELECTRIC LTD~~ | ~~SIZEWELL B SITE , LEISTON SUFFOLK IP16 4UR~~ | ~~AB5580~~ | ~~SUFFOLK~~ |
| – | ~~NUCLEAR ELECTRIC LTD~~ | ~~SIZEWELL B POWER STATION , LEISTON SUFFOLK IP16 4UR~~ | ~~AX4190~~ | ~~SUFFOLK~~ |
| – | ~~NUCLEAR ELECTRIC LTD~~ | ~~SIZEWELL B POWER STATION , LEISTON SUFFOLK IP16 4UR~~ | ~~AS3846~~ | ~~SUFFOLK~~ |
| – | ~~NUCLEAR ELECTRIC LTD~~ | ~~SIZEWELL B POWER STATION , LEISTON SUFFOLK IP16 4UR~~ | ~~AS3820~~ | ~~SUFFOLK~~ |
| – | ~~NUCLEAR ELECTRIC LTD~~ | ~~SIZEWELL B POWER STATION , LEISTON SUFFOLK IP16 4UR~~ | ~~AS3466~~ | ~~SUFFOLK~~ |
| – | ~~NUCLEAR ELECTRIC LTD~~ | ~~SIZEWELL B POWER STATION LEISTON SUFFOLK IP16 4UR~~ | ~~AL0648~~ | ~~SUFFOLK~~ |
| – | ~~NUCLEAR ELECTRIC LTD~~ | ~~SIZEWELL B POWER STATION , LEISTON SUFFOLK IP16 4UR~~ | ~~AJ3930~~ | SUFFOLK |
| – | ~~NUCLEAR ELECTRIC LTD~~ | ~~SIZEWELL B POWER STATION , LEISTON SUFFOLK IP16 4UR~~ | ~~AJ3921~~ | ~~SUFFOLK~~ |
| – | ~~NUCLEAR ELECTRIC LTD~~ | ~~GEC SITE , SIZEWELL B POWER STATION LEISTON SUFFOLK IP16 4UE~~ | ~~AF6634~~ | ~~SUFFOLK~~ |
| 96 | ROSSDALE AND PARTNERS | BEAUFORT COTTAGE, LABORATORIES, HIGH STREET NEWMARKET SUFFOLK CB8 8JS | AL0419 | SUFFOLK |
| 97 | ROSSDALE AND PARTNERS | BEAUFORT COTTAGE DIAGNOSTIC CENTRE, COTTON END STABLES, EXNING NEWMARKET SU... | AS4273 | SUFFOLK |
| 98 | SUFFOLK COLLEGE ✓ | ROPE WALK IPSWICH SUFFOLK IP4 1LT | AE0100 | SUFFOLK |
| 99 | THE IPSWICH HOSPITAL NHS TRUST ✓ | THE IPSWICH HOSPITAL, HEATH ROAD IPSWICH IP4 5PD | AP3126 | SUFFOLK |
| 100 | VCH LTD | UNIT 5, HIGHBURY ROAD BRANDON SUFFOLK IP27 0ND | AV7589 | SUFFOLK |
| 101 | WARDLE STOREYS PLC | STOREYS INDUSTRIAL PRODUCTS LTD, BRANTHAM WORKS, BRANTHAM MANNINGTREE ESSEX... | AL2136 | SUFFOLK |
| 102 | WEST SUFFOLK HOSPITALS NHS TRUST | WEST SUFFOLK HOSPITAL , HARDWICK LANE BURY ST. EDMUNDS SUFFOLK IP33 2QZ | AW0725 | SUFFOLK |
| 103 | WHITE ROSE ENVIRONMENTAL ✓ | THE IPSWICH HOSPITAL, HEATH ROAD IPSWICH IP4 5PD | BA2776 | SUFFOLK |

## APPENDIX B – ABBREVIATED LIST OF GAUGING STATIONS

| Station Number | Station Name | Mean Flow ($m^3/3$) | Period of Record |
|---|---|---|---|
| 030001 | Witham at Claypole Mill | 1.755 | 1959 - 1995 |
| 030002 | Barlings Eau at Langworth Bridge | 1.284 | 1960 - 1995 |
| 030003 | Bain at Fulsby Lock | 1.264 | 1962 - 1995 |
| 030005 | Witham at Saltersford total | 0.779 | 1973 - 1995 |
| 030006 | Slea at Leasingham Bridge | 0.589 | 1974 - 1995 |
| 032001 | Nene at Orton | 9.385 | 1939 - 1995 |
| 032002 | Willow Brook at Fotheringhay | 0.784 | 1938 - 1995 |
| 032004 | Ise Brook at Harrowden Old Mill | 1.350 | 1943 - 1995 |
| 032006 | Nene/Kislingbury at Upton | 1.379 | 1939 - 1995 |
| 032007 | Nene Brampton at St Andrews | 1.162 | 1939 - 1995 |
| 032008 | Nene/Kislingbury at Dodford | 0.612 | 1945 - 1995 |
| 032811 | Nene/Kislingbury at Upton Bypass | 0.480 | 1969 - 1995 |
| 032813 | Nene/Brampton at St Andrews Mill Bypass | 0.616 | 1971 - 1995 |
| 033002 | Bedford Ouse at Bedford | 10.200 | 1933 - 1995 |
| 033003 | Cam at Bottisham | 3.616 | 1936 - 1987 |
| 033007 | Nar at Marham | 1.156 | 1953 - 1995 |
| 033009 | Bedford Ouse at Harrold Mill | 9.460 | 1955 - 1993 |
| 033014 | Lark at Temple | 1.279 | 1960 - 1995 |
| 033015 | Ouzel at Willen | 2.049 | 1962 - 1995 |
| 033016 | Cam at Jesus Lock | 2.860 | 1959 - 1983 |
| 033020 | Alconbury Brook at Brampton | 0.760 | 1963 - 1993 |
| 033022 | Ivel at Blunham | 3.033 | 1965 - 1995 |
| 033023 | Lea Brook at Beck Bridge | 0.249 | 1962 - 1995 |
| 033026 | Bedford Ouse at Offord | 14.140 | 1970 - 1995 |
| 033028 | Flit at Shefford | 0.829 | 1966 - 1995 |
| 033035 | Ely Ouse at Denver Complex | 14.140 | 1958 - 1995 |
| 033037 | Bedford Ouse at Newport Pagnell | 4.870 | 1969 - 1995 |
| 033039 | Bedford Ouse at Roxton | 11.380 | 1972 - 1995 |
| 033050 | Snail at Fordham | 0.302 | 1974 - 1995 |
| 033051 | Cam at Chesterford | 0.601 | 1964 - 1995 |
| 033055 | Granta at Babraham | 0.242 | 1976 - 1995 |
| 033060 | Kings Dike at Stanground | 0.445 | 1969 - 1995 |

| Station Number | Station Name | Mean Flow (m$^3$/3) | Period of Record |
|---|---|---|---|
| 034001 | Yare at Colney | 1.400 | 1959 - 1995 |
| 034002 | Tas at Shotesham | 0.725 | 1957 - 1995 |
| 034004 | Wensum at Costessey Mill | 4.029 | 1960 - 1995 |
| 034005 | Tud at Costessey Park | 0.349 | 1961 - 1995 |
| 034007 | Dove at Oakley Park | 0.654 | 1966 - 1995 |
| 035001 | Gipping at Constantine Wier | 1.384 | 1961 - 1995 |
| 037002 | Chelmer at Rushes Lock | 1.879 | 1932 - 1995 |
| 037005 | Colne at Lexden | 1.036 | 1959 - 1995 |

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# APPENDIX C - DETAILS OF LOCATIONS RELEASING LIQUID EFFLUENTS IN ANGLIAN REGION

C.1 Direct discharge to water body

C.2 Discharge via Public STW

C.3 Discharge via Private STW

| Name of premises | Receiving water body | Flow / dilution rate in receiving body, $m^3$ per second |
|---|---|---|
| **C.1 Direct discharge to water body** | | |
| Carless Refinery (57ESS) | Stour Estuary | |
| Conoco (72LIN) | North Sea | 300 (estimated) |
| MAFF (93SUF) | North Sea | 300 (estimated) |
| Millenium Inorganic (69/70HUM) * | Humber Estuary | 300 (estimated) |
| Mobil Oil (61ESS) | Thames Estuary | 300 (estimated) |
| Shell (64ESS) | Thames Estuary | 300 (estimated) |

| Name of sewage treatment works | Raw sewage input, m³ per day | Receiving water body | Flow / dilution rate in receiving body, m³ per second |
|---|---|---|---|
| **C.2 Discharge via Public STP:** | | | |
| Basildon | 28,400 | Pitsea Creek (tidal) (no GS) | 1 (assumed) |
| Bedford | 35,000 | R Great Ouse | 10.2 |
| Boston | 10,000 | R Witham | 4.9 |
| Broadholme | 46,500 | R Nene | 4.5 |
| Bury St. Edmunds | 11,000 | R Lark | 1.28 |
| Camwick | 29,400 | R Witham (via South Delph) | 1.78 |
| Chelmsford | 52,050 | R Chelmer | 1.04 |
| Cliff Quay | 10,760 | R Orwell (tidal) | 0.78 |
| Corby | 28,500 | R Nene (via Willow Brook) | 1.38 |
| Cotton Valley | 54,610 | R Great Ouse | 6.9 |
| Flag Fen | 58,000 | R Nene | 9.4 |
| Grantham | 14,300 | R Witham | 0.78 |
| Great Billing | 50,000 | R Nene | 3.2 |
| Great Chesterford | 432 | R Cam | 0.60 |
| Haven | 27,300 | R Colne | 1.04 |
| Huntingdon | 10,700 | R Ouse | 14.9 |
| Kentford | 350 | R Kennett (via Lea Brook) | 0.249 |
| Kings Lynn | 26,000 | R Ouse | 15.3 |
| Melbourn | 1,800 | R Mel | 0.5 (assumed) |
| Milton | 36,000 | R Cam | 3.2 |
| Newmarket | 6,100 | R Snail (via Public No.1 Drain) | 0.3 |
| Papworth Everard | 500 | R Great Ouse (via West Brook) | 0.5 (assumed) |
| Pyewipe (pumping station) | | Humber Estuary (no GS) | 300 (estimated) |
| Sandy | 1,800 | R Ivel | 3.0 |
| Silsoe | 1,800 | R Flitt | 0.83 |
| Southend | 36,500 | Thames Estuary (no GS) | 300 (estimated) |
| Uttons Drove | 3,550 | Tributary (no name) of R Great Ouse | 0.5 (assumed) |
| Whittlingham | 73,000 | R Yare (tidal) | 6.5 |

| Name of sewage treatment works | Raw sewage input, m3 per day | Receiving water body | Flow / dilution rate in receiving body, $m^3$ per second |
| --- | --- | --- | --- |
| **C.3 Discharge via Private Sewage Treatment Works** | | | |
| Agrevo | 180 | R Cam (via un-named stream) | 0.60 |
| Babraham Institute | 250 | R Granta | 0.242 |
| Conoco | 12,000 | Humber Estuary (via S Killingholme main drain) (no GS) | 300 (estimated) |
| Cranfield | 333 | R Great Ouse (via Chicheley Brook) | 6.9 |
| Huntingdon Life Sciences, Alconbury | 300 | Alconbury Brook (via Cock Brook) | 0.76 |
| Huntingdon Life Sciences, Eye | 300 | R Dove | 0.65 |
| Inst. Terrestrial Ecology | 10 | Kings Dyke (via Ewingswode Stream) | 0.45 |
| Lindsey Oil | 6,000 | Humber Estuary (via N Killingholme Drain) (no GS) | 300 (estimated) |
| Unilever Research | 600 | R Great Ouse (via Sharn Brook) | 9.5 |
| Woodland Hospital | 20 | Soakaway on site (no GS) | Not applicable |

# APPENDIX D - EXPOSURE OF SEWAGE WORKERS

By

**G D Burholt**

D.1 Introduction

D.2 Exposure of a worker at the sewage works

D.3 Exposure of a sewer maintenance worker

D.4 Discussion

D.5 References

## D1 Introduction

The exposure of waste disposal workers, such as those at the sewage treatment plant, sewer maintenance workers and workers involved in the agricultural use of sewage products is subject to the principles of occupational dose control and addressed by the implementation of the Ionising Radiations Regulations 1985.

The exposure of a typical worker at the sewage treatment plant and that of a sewer maintenance have been assessed using the simple calculational models of Reference D1, in which the inhalation, ingestion and external radiation pathways have been considered. The exact modeling of each sewage treatment plant and work activity would require extensive effort and would not be justified in view of the low doses expected. Thus, simple exposure models, together with fairly pessimistic occupancy factors, have been employed, which may be scaled according to the particular radionuclide concentration in the sewage sludge. The same models may be extended to estimate doses to the agricultural workers involved in the use of sewage products.

## D2 Exposure of a worker at the sewage works

Assessment of internal exposure is carried out by considering inhalation and inadvertent ingestion of raw sewage. External exposure from gamma radiation depends on the geometry of the tank or pipe containing the raw sewage.

Ingestion doses are calculated using equation (5) of Reference D1, involving:

- the concentration of a radionuclide in untreated sewage (assuming a density of 1 tonne per cubic metre);
- the intake rate for inadvertent ingestion of sewage;
- the committed effective dose equivalent per unit intake by ingestion, and;
- the occupancy factor.

Appropriate values for the above parameters are listed in Table D1. Committed effective dose equivalent factors for adults were obtained from ICRP 72 [Reference D2].

Inhalation doses are calculated using equation (6) of Reference D1, involving:

- the re-suspended sewage load;
- the breathing rate for an adult worker;
- the committed effective dose equivalent per unit intake by inhalation, and;
- the occupancy factor.

External doses arising from gamma emitting radionuclides in sewage are assessed by assuming a semi-infinite slab source representing the open tank of sewage (equation (7) of Reference D1). External doses are calculated using equation (8) of Reference A.1, involving:
the absorbed dose rate above a slab contaminated at a level of 1 Bq per tonne (Table 11 of Reference D1 together with the factors for additional radionuclides calculated by the same method);

- a general factor of 0.9 used to relate absorbed dose rate (Gy per hour) to effective dose equivalent rate (Sv per hour);
- the radionuclide concentration in unfiltered sewage, and;
- the occupancy factor.

Table D2 lists the dose factors for each exposure pathway for unit input of each radionuclide and normalised to a sewage flow of 1,000 m3 per day. The total annual doses to sewage plant workers at each of the sewage treatment plants, to which site discharges flow, were obtained from the total authorised radionuclide input per year and the plant flow (see Annex C of Volume 2). Table D3 lists the total annual dose for workers at each of the sewage treatment plants. The assessment model is not likely to be applicable at the private sewage treatment plants, which are mainly closed systems; in those cases the assessment model for maintenance workers (see below) is likely to be more relevant.

## D3 Exposure of a sewer maintenance worker

The maximum exposure of a sewer maintenance worker is likely to occur much closer to the disposal point or indeed on the site itself. The above equations are suitable for assessing internal doses, except that different values of some of the parameters are appropriate (Table D1) and the concentration of radionuclides in the liquid effluent leaving the site should be used rather than the concentration in raw sewage at the sewage works.

A particular sewer maintenance worker is likely to work within the area covered by one sewage treatment plant. The maximum dose to that individual may be obtained conveniently by summing all the radionuclides discharged to that treatment plant and assuming an occupancy of 200 hours per year (ie. 10% of total working time at each discharge site).

Ingestion and inhalation doses are calculated using equations (5) and (6) respectively of Reference D1, with the appropriate parameters. External gamma exposure from the sewer pipe may be assessed by considering a line source, having a source strength determined by the average rate at which the radioactivity is discharged and the linear flow rate through the sewer pipe. For a typical site, such as a hospital or university, the average effluent flow from the site is likely to be about 10,000 m3 per month, corresponding to a linear flow of 0.5 metres per second in a pipe of 0.1 metre diameter. Due to the lack of data on site effluent flows, this nominal flow rate has been used for each of the sites. It is also assumed that there is no significant contribution from radioactivity adsorbed onto the sewer pipe walls. External doses are calculated using equation (11) of Reference D1.

Table D3 lists the dose factors for each exposure pathway for unit input of each radionuclide and normalised to a site effluent flow of 10,000 m3 per month. The total annual doses to sewer maintenance workers working in the area of each of the sewage treatment plants were obtained from the total authorised radionuclide input per year (See Volume 3 Report)

## D4 Discussion

On the basis of the unit estimates contained in Tables D2 and D3, the total annual doses to sewage plant workers and sewer maintenance workers that would result from discharges from all premises at their authorised limits are presented in Table D4.

Doses to sewage plant workers are generally less than 10 μSv per year, with maximum values at Milton STP, Cambridge (13 μSv per year) and Papworth Everard STP (65 μSv per year). All these doses are well below the appropriate "dose objective" of 500 μSv per year.

Doses to sewer maintenance workers are all less than 4 μSv per year. A fairly pessimistic estimate of occupancy was used for those calculations, as discharges are unlikely to be uniform in practice, it being more likely that the occur as a series of "spikes" one or more of which may occur during the maintenance period.

The agricultural use of sewage sludge and other products will result in exposure scenarios similar to those applying to sewage plant workers. However, doses to agricultural workers are likely to be smaller due to the radioactive decay of short-lived radionuclides, such as Tc-99m and I-131, during the process time within the sewage treatment plant (typically several weeks).

## D5 References


D1. McDonnell, C E. Assessment of the radiological consequences of accumulation and disposal of radioactive wastes by small users of radioactive materials. NRPB-M744, 1996.

D2. ICRP Publication 72. Age-dependent doses to members of the public from intake of radionuclides: Part 5 – compilation of ingestion and inhalation dose coefficients. Annals of the ICRP Vol.26, No. 1, 1996

| **Parameter** | **Value** |
|---|---|
| Occupancy at sewage plant -inhalation<br>-ingestion and external gamma | 2000 h $y^{-1}$<br>1000 h $y^{-1}$ |
| Occupancy for sewer maintenance (all pathways) | 200 h $y^{-1}$ |
| Breathing rate | 1.2 m3 $h^{-1}$ |
| Intake rate for inadvertent ingestion of sewage | $5 \times 10^{-5}$ kg $h^{-1}$ |
| Resuspended sewage concentration -sewage plant<br>-maintenance | mg $m^{-3}$<br>1.0 mg $m^{-3}$ |

**Table D1 Parameter values for exposure of sewage plant workers and sewer maintenance workers**

| Nuclide | Dose per unit input, µSv y⁻¹ per MBq y-1 | | | |
|---|---|---|---|---|
| | Ingestion | Inhalation | External | Total |
| H-3 | 5.7E-09 | 1.7E-10 | 0.0 | 5.9E-09 |
| C-14 | 7.8E-08 | 3.8E-09 | 0.0 | 8.2E-08 |
| F-18 | 6.6E-09 | 3.8E-11 | 6.9E-04 | 6.9E-04 |
| Na-24 | 5.8E-08 | 1.8E-10 | 2.9E-03 | 2.9E-03 |
| P-32 | 3.2E-07 | 2.2E-09 | 0.0 | 3.2E-07 |
| P-33 | 3.2E-08 | 9.7E-10 | 0.0 | 3.3E-08 |
| S-35 | 1.0E-07 | 1.2E-09 | 0.0 | 1.0E-07 |
| Cl-36 | 1.2E-07 | 4.7E-09 | 0.0 | 1.2E-07 |
| Ca-45 | 9.6E-08 | 2.4E-09 | 0.0 | 9.8E-08 |
| V-48 | 2.7E-07 | 1.6E-09 | 2.8E-04 | 2.8E-04 |
| Cr-51 | 5.1E-09 | 2.4E-11 | 2.3E-05 | 2.3E-05 |
| Mn-54 | 9.6E-08 | 9.7E-10 | 5.9E-04 | 5.9E-04 |
| Mn-56 | 3.3E-08 | 7.8E-11 | 1.1E-03 | 1.1E-03 |
| Co-57 | 2.8E-08 | 6.5E-10 | 9.1E-05 | 9.1E-05 |
| Co-58 | 1.0E-07 | 1.4E-09 | 6.8E-04 | 6.8E-04 |
| Fe-59 | 2.4E-07 | 2.6E-09 | 8.4E-04 | 8.4E-04 |
| Ga-67 | 2.6E-08 | 1.6E-10 | 1.1E-04 | 1.1E-04 |
| Se-75 | 3.5E-07 | 8.4E-10 | 2.7E-04 | 2.7E-04 |
| Br-82 | 7.3E-08 | 4.1E-10 | 9.8E-04 | 9.8E-04 |
| Sr-89 | 3.5E-07 | 5.1E-09 | 0.0 | 3.5E-07 |
| Sr-90+Y-90 | 4.1E-06 | 1.0E-07 | 0.0 | 4.2E-06 |
| Y-90 | 3.6E-07 | 9.7E-10 | 0.0 | 3.6E-07 |
| Tc-99m | 3.0E-09 | 1.3E-11 | 9.1E-05 | 9.1E-05 |
| Mo-99+Tc-99m | 8.4E-08 | 6.5E-10 | 2.0E-04 | 2.0E-04 |
| Ru-103+Rh-103m | 9.8E-08 | 2.0E-09 | 3.4E-04 | 3.4E-04 |
| In-111 | 3.9E-08 | 1.5E-10 | 2.9E-04 | 2.9E-04 |
| In-113m | 3.8E-09 | 1.3E-11 | 1.7E-04 | 1.7E-04 |
| I-123 | 2.8E-08 | 4.8E-11 | 1.2E-04 | 1.2E-04 |
| I-125 | 2.0E-06 | 3.3E-09 | 2.9E-05 | 3.1E-05 |
| I-131 | 2.9E-06 | 4.8E-09 | 2.7E-04 | 2.7E-04 |
| Ba-137m | 1.7E-06 | 2.5E-08 | 3.9E-04 | 3.9E-04 |
| Tl-201 | 1.3E-08 | 2.9E-11 | 6.5E-05 | 6.5E-05 |
| U-238+ | 3.2E-04 | 9.1E-05 | 2.1E-03 | 2.4E-03 |
| Th-232+ | 1.5E-04 | 1.1E-04 | 1.3E-03 | 1.6E-03 |
| Any alpha (Ra-226) | 3.8E-05 | 6.2E-06 | 5.2E-06 | 4.9E-05 |

Note. The above dose factors are normalised to a sewage flow of 1,000 m3 per day.

**Table D2 Sewage plant workers; dose per unit input data**

| Nuclide | Dose per unit input, µSv $y^{-1}$ per MBq y-1 | | | |
|---|---|---|---|---|
| | **Ingestion** | **Inhalation** | **External** | **Total** |
| H-3 | 3.3E-09 | 4.9E-10 | 0.0 | 3.8E-09 |
| C-14 | 4.6E-08 | 1.1E-08 | 0.0 | 5.7E-08 |
| F-18 | 3.9E-09 | 1.1E-10 | 4.4E-06 | 4.4E-06 |
| Na-24 | 3.4E-08 | 5.1E-10 | 1.8E-05 | 1.8E-05 |
| P-32 | 1.9E-07 | 6.5E-09 | 0.0 | 2.0E-07 |
| P-33 | 1.9E-08 | 2.8E-09 | 0.0 | 2.2E-08 |
| S-35 | 6.1E-08 | 3.6E-09 | 0.0 | 6.5E-08 |
| Cl-36 | 7.3E-08 | 1.4E-08 | 0.0 | 8.7E-08 |
| Ca-45 | 5.6E-08 | 7.0E-09 | 0.0 | 6.3E-08 |
| V-48 | 1.5E-07 | 4.6E-09 | 1.8E-06 | 1.9E-06 |
| Cr-51 | 3.0E-09 | 7.0E-11 | 1.4E-07 | 1.4E-07 |
| Mn-54 | 5.6E-08 | 2.8E-09 | 3.7E-06 | 3.7E-06 |
| Mn-56 | 2.0E-08 | 2.3E-10 | 7.2E-06 | 7.2E-06 |
| Co-57 | 1.7E-08 | 1.9E-09 | 5.8E-07 | 6.0E-07 |
| Co-58 | 5.8E-08 | 4.0E-09 | 4.4E-06 | 4.4E-06 |
| Fe-59 | 1.4E-07 | 7.6E-09 | 5.4E-06 | 5.5E-06 |
| Ga-67 | 1.5E-08 | 4.6E-10 | 7.2E-07 | 7.3E-07 |
| Se-75 | 2.0E-07 | 2.5E-09 | 1.7E-06 | 1.9E-06 |
| Br-82 | 4.3E-08 | 1.2E-09 | 6.3E-06 | 6.3E-06 |
| Sr-89 | 2.0E-07 | 1.5E-08 | 0.0 | 2.1E-07 |
| Sr-90+Y-90 | 2.4E-06 | 3.0E-07 | 0.0 | 2.7E-06 |
| Y-90 | 2.1E-07 | 2.8E-09 | 0.0 | 2.1E-07 |
| Tc-99m | 1.7E-09 | 3.8E-11 | 5.8E-07 | 5.8E-07 |
| Mo-99+Tc-99m | 4.9E-08 | 1.9E-09 | 1.2E-06 | 1.2E-06 |
| Ru-103+Rh-103m | 5.8E-08 | 5.7E-09 | 2.2E-06 | 2.2E-06 |
| In-111 | 2.3E-08 | 4.4E-10 | 1.8E-06 | 1.8E-06 |
| In-113m | 2.2E-09 | 3.8E-11 | 1.1E-06 | 1.1E-06 |
| I-123 | 1.7E-08 | 1.4E-10 | 7.6E-07 | 7.8E-07 |
| I-125 | 1.2E-06 | 9.7E-09 | 1.9E-07 | 1.4E-06 |
| I-131 | 1.7E-06 | 1.4E-08 | 1.7E-06 | 3.4E-06 |
| Ba-137m | 1.0E-06 | 7.4E-08 | 2.5E-06 | 3.5E-06 |
| Tl-201 | 7.5E-09 | 8.4E-11 | 4.1E-07 | 4.1E-07 |
| U-238+ | 1.9E-04 | 2.7E-04 | 1.4E-05 | 4.7E-04 |
| Th-232+ | 8.7E-05 | 3.2E-04 | 8.1E-06 | 4.2E-04 |
| Any alpha (Ra-226) | 2.2E-05 | 1.8E-05 | 3.4E-08 | 4.0E-05 |

Note. The above dose factors are normalised to a nominal site effluent flow of 10,000 m3 per month.

**Table D3 Sewer maintenance workers; dose per unit input data**

| Name of sewage plant | Total annual dose to worker, µSv per year | | |
|---|---|---|---|
| | Sewage plant worker | Sewer maintenance worker | Dominant radio-nuclide |
| **Public STP:** | | | |
| Basildon | 1.1 | 0.20 | Tc-99m |
| Bedford | 0.82 | 0.18 | Tc-99m |
| Boston | 3.8 | 0.25 | Tc-99m |
| Broadholme | 0.51 | 0.14 | Tc-99m |
| Bury St. Edmunds | 3.0 | 0.27 | Tc-99m |
| Camwick | 4.0 | 1.2 | I-131 |
| Chelmsford | 0.57 | 0.19 | Tc-99m |
| Cliff Quay | 4.3 | 1.0 | Tc-99m |
| Corby | <0.01 | <0.01 | H-3 |
| Cotton Valley | 0.08 | 0.04 | Tc-99m |
| Flag Fen | 0.72 | 0.31 | Tc-99m |
| Grantham | 2.4 | 0.21 | Tc-99m |
| Great Billing | 1.5 | 0.71 | I-131 |
| Great Chesterford | 0.01 | <0.01 | P-32 |
| Haven | 2.2 | 0.43 | Tc-99m |
| Huntingdon | 3.5 | 0.24 | Tc-99m |
| Kentford | 7.1 | 0.01 | Tc-99m |
| Kings Lynn | 1.1 | 0.20 | Tc-99m |
| Melbourn | <0.01 | <0.01 | - |
| Milton | 13.0 | 4.0 | Other, I-131 |
| Newmarket | <0.01 | <0.01 | - |
| Papworth Everard | 65.0 | 0.19 | Tc-99m |
| Pyewipe (pump station) | n/a | 0.40 | Tc-99m |
| Sandy | <0.01 | <0.01 | - |
| Silsoe | <0.01 | <0.01 | - |
| Southend | 3.4 | 1.1 | I-131 |
| Uttons Drove | 0.01 | <0.01 | - |
| Whittlingham | 3.1 | 1.9 | Mo-99, 1-131 |
| **Private STP:** | | | |
| Agrevo | n/a | 0.01 | Other |
| Babraham Institute | n/a | <0.01 | - |
| Conoco | n/a | 0.13 | Na-24, Tc-99m |
| Cranfield | n/a | <0.01 | - |
| Huntingdon Life Sciences, Alconbury | n/a | 0.02 | Other |
| Huntingdon Life Sciences, Eye | n/a | <0.01 | - |
| Inst. Terrestrial Ecology | n/a | <0.01 | - |
| Lindsey Oil | n/a | 0.05 | Na-24, Br-82 |
| Unilever Research | n/a | <0.01 | - |
| Woodland Hospital | n/a | 0.02 | Tc-99m |

**Table D4 Sewage plant workers and sewer maintenance workers; total annual doses**