INT. J. RADIAT. BIOL., 1984, VOL. 46, NO. 5, 479–506

An assessment of the radiological impact of the Windscale reactor fire, October 1957†

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(*Received 9 February 1984; revision received 28 June 1984; accepted 10 July 1984*)

On the 10 and 11 October 1957 a fire in the No 1 Pile at the Windscale establishment in Cumbria led to an uncontrolled release of activity to the atmosphere. The resultant cloud subsequently dispersed and radionuclides could be detected over England, Wales and parts of northern Europe. The extensive environmental measurements which were made during and after the release enabled a fairly accurate estimate to be made of the radiation doses to the most exposed individuals in the local population. Until recently, no estimates of the population dose resulting from the release had been published. This paper describes assessments which have been made by the NRPB of the population or collective dose from the release and of the possible associated health impact.

In addition to the fission products that escaped, radionuclides were released from materials undergoing irradiation in the pile at the time of the fire. The assessment has included the results of a review of previously unpublished data which established the quantity of these nuclides released and considers their impact on both individual and population doses.

The collective effective dose equivalent commitment from the release is estimated to have been $2{\cdot}0\times10^3$ man Sv. The route of exposure which contributed the most to the collective dose was the inhalation pathway. Iodine-131 was the most important radionuclide, contributing nearly all of the collective dose to the thyroid and a large part of the collective effective dose. Polonium-210 and caesium-137 also made significant contributions; that from caesium-137 came in the longer term via external irradiation from ground deposits and the ingestion of contaminated foodstuffs.

The methodology used in the study has been validated to a certain degree by comparing the predicted levels of individual thyroid activity and those measured directly in the weeks following the accident in London, Leeds and Cumbria.

1. Introduction

The accident at the Windscale No 1 Pile in October 1957 resulted in radioactive materials being released into the atmosphere which were subsequently dispersed and deposited over England and Wales and over parts of northern Europe. The most important of the released radionuclides was identified as ^{131}I, which was one of the elements which were preferentially released due to their volatility. Radionuclides of iodine are readily transferred to man via his consumption of milk from cows grazing on contaminated pasture. Iodine once taken into the body is concentrated in the

† Editor's Note: The substance of this paper was previously published in reports of the National Radiological Protection Board [NRPB-R135 (1982) and NRPB-R135 addendum (1983)] and aroused great interest and discussion. In view of the importance of this study, a condensed version of these reports is now published in the *IJRB* in order to reach an international scientific audience.

thyroid gland; the doses to this organ were the highest of those received due to the release.

The prompt imposition of a ban on milk supplies by the authorities had the effect of reducing intakes by the local population of radioiodine via the pasture–cow–milk pathway. The radiation doses to the thyroids of the local population were typically 5 to 20 mSv for adults and 10 to 60 mSv for children (Dunster *et al.* 1958). Without the milk ban it was anticipated that adult thyroid dose levels would have reached 70 mSv and for children thyroid doses could have been up to 360 mSv. The highest child thyroid dose inferred from measurements of thyroid activity was 160 mSv and this may have been due to the milk ban not being completely effective. The dose estimates and the results of environmental measurements made during and shortly after the release were published in Government reports and other papers in the years following the accident (Dunster *et al.* 1958, Atomic Energy Office 1957, Loutit *et al.* 1960, Baverstock and Vennart 1976). In those studies the radiological impact of the release was expressed mainly in terms of the radiation doses to individuals living in the vicinity of the Windscale establishment, although there were a few reports of dose estimates made for individuals living in other parts of England (Burch 1959, Maycock and Vennart 1958). While it is still true that the introduction of countermeasures following a nuclear accident will be based on the reduction of individual risk, it is recognized that the overall population or collective dose is of interest in assessing the radiological impact of accidental releases. The collective thyroid dose and the collective dose to other body organs as a result of the Windscale fire have been estimated recently by Clarke (1980) and by Taylor (1981). The method used by both authors involves extrapolating from the few estimates made of dose to individuals in the United Kingdom shortly after the incident to obtain an estimate of collective doses. The approach necessarily produces an approximate result.

In recent studies carried out at the NRPB (Crick and Linsley 1982, 1983) the collective dose is assessed more comprehensively by using several additional sets of data produced at the time of the incident. These give concentrations of radionuclides in environmental materials such as air, milk, grass and as a surface deposit at various places in the UK and the rest of Europe. These have been used to construct matrices describing the geographic distribution of activity in environmental materials resulting from the release. The matrices have been used together with simple environmental transfer models and data on spatial distributions of population, milk and other agricultural production to estimate collective doses arising from the contamination within various distance bands from the release point. The activity distribution matrices also allow dose estimates to be made for individuals at particular locations; the comparison of these estimates with dose estimates based on direct measurements on individuals made at the time of the incident provides an independent check on the reliability of the matrices.

The results are expressed both in terms of the collective thyroid dose equivalent commitment ($S_{\mathrm{T}}^{c'}$), which provides an expression of the collective risk from thyroid irradiation, and in terms of the collective effective dose equivalent commitment ($S_{\mathrm{eff}}^{c'}$), which expresses the overall risk of fatal cancer in all body organs and hereditary effects in the first two generations. The quantity effective dose equivalent has been defined by the International Commission on Radiological Protection (ICRP) for protection purposes and it provides a convenient means of comparing exposures which result in different distributions of dose equivalent in the body, such as those which occurred due to the release of the variety of different radionuclides in the Windscale Fire.

Most of the radionuclides released in the fire were fission products which escaped from overheated fuel elements but in addition, activity was released from cartridges which were undergoing irradiation in the pile at the time of the accident. The Windscale piles were being used mainly for the military production of plutonium but were also being used as an irradiation facility. The most significant releases from the cartridges were of the nuclides polonium-210 and tritium, which are produced from the irradiation of bismuth and lithium respectively. The radiological impact of these and of other nuclides not mentioned in the official reports (Atomic Energy Office 1957, Loutit *et al.* 1960) was assessed for the first time by Crick and Linsley (1983), drawing on previously unpublished data. The results of the two Board reports on the subject have been combined and incorporated into this paper.

2. General description of the accident

The fire at Windscale No 1 Pile in October 1957 is described in the report of the Committee of Inquiry set up immediately after the accident (Atomic Energy Office 1957). It occurred during a routine release of the Wigner energy which had become stored in the graphite moderator as a result of the normal operation of the pile. The immediate cause of the accident was the application too soon and at too rapid a rate of a second nuclear heating to release this stored energy. This created a failure in one or two channels of fuel, whose contents then oxidized slowly, eventually leading to the fire, and the overheating of some 150 channels by the evening of Thursday, 10 October. After initial unsuccessful attempts to put out the fire, it was finally extinguished at about 0900 hours on the morning of Friday, 11 October, by flooding the pile with large volumes of water.

Estimates of the amount of fission products released during the accident have been made by Loutit *et al.* (1960), based mainly on measurements of the activity in environmental materials around Windscale directly after the incident, and by Clarke (1974) using a computer code to model the fission product inventory of the reactor. In addition to the fission products released, a number of other radioactive isotopes escaped from sealed cartridges undergoing irradiation in the pile at the time of the fire. In particular polonium-210 and tritium produced from the irradiation of bismuth and lithium were released (Crick and Linsley 1983). Although a large quantity of tritium was released it proved to be a negligible radiological hazard compared with the other significant radionuclides. The various estimated quantities of radionuclides released in the fire and the values used in this assessment are given in table 1. For a discussion of the estimation of source terms for release the reports by Crick and Linsley (1983) and Chamberlain (1981) should be consulted.

Measurements made at the time of the release showed that the emission was mostly confined to the period from noon on 10 October to noon on 11 October with probable peaks in the discharge rates at around midnight of the 10th and 0900 hours of the 11th. The release of the radionuclides into the atmosphere from the 120-metre stack and their subsequent dispersion over England and Wales, and Europe, is discussed by Crabtree (1959); the pattern of deposition of ^{131}I is discussed by Chamberlain (1959).

The meteorological conditions varied during the release and produced a complex dispersion pattern (Crabtree 1959). From noon on 10 October the winds at Windscale were light and variable, with a south-westerly tendency. As the accident

Table 1. Estimates of quantities of radionuclides released.

Nuclide	Clarke (1974) ($\times 10^{12}$ Bq)	Loutit *et al.* (1960) ($\times 10^{12}$ Bq)	Crick and Linsley (1983) ($\times 10^{12}$ Bq)	Ratios used in this study relative $^{131}I = 1{\cdot}0$
^{85}Kr	$5{\cdot}9 \times 10^{1}$			$9{\cdot}8 \times 10^{-2}$
^{89}Sr	$5{\cdot}1 \times 10^{0}$	$3{\cdot}0 \times 10^{0}$		$4{\cdot}1 \times 10^{-3}$
^{90}Sr	$2{\cdot}2 \times 10^{-1}$	$7{\cdot}4 \times 10^{-2}$		$1{\cdot}0 \times 10^{-4}$
^{90}Y	$2{\cdot}2 \times 10^{-1}$			$1{\cdot}0 \times 10^{-4}$
^{91}Sr	$3{\cdot}7 \times 10^{-2}$			$6{\cdot}2 \times 10^{-5}$
^{91}Y	$6{\cdot}4 \times 10^{0}$			$1{\cdot}1 \times 10^{-2}$
^{93}Y	$5{\cdot}9 \times 10^{-2}$			$9{\cdot}8 \times 10^{-5}$
^{95}Zr	$7{\cdot}5 \times 10^{0}$			$1{\cdot}3 \times 10^{-2}$
^{95}Nb	$7{\cdot}5 \times 10^{0}$			$1{\cdot}3 \times 10^{-2}$
^{97}Zr	$3{\cdot}6 \times 10^{-1}$			$6{\cdot}0 \times 10^{-4}$
^{99}Mo	$3{\cdot}6 \times 10^{1}$			$6{\cdot}0 \times 10^{-2}$
^{103}Ru	$4{\cdot}0 \times 10^{1}$			$6{\cdot}7 \times 10^{-2}$
^{105}Rh	$5{\cdot}2 \times 10^{-1}$			$8{\cdot}7 \times 10^{-4}$
^{106}Ru	$5{\cdot}9 \times 10^{0}$	$3{\cdot}0 \times 10^{0}$		$4{\cdot}1 \times 10^{-3}$
^{106}Rh	$5{\cdot}9 \times 10^{0}$			$4{\cdot}1 \times 10^{-3}$
^{111}Ag	$5{\cdot}2 \times 10^{-1}$			$8{\cdot}7 \times 10^{-4}$
^{115}Cd	$1{\cdot}6 \times 10^{0}$			$2{\cdot}7 \times 10^{-3}$
^{123}Sn	$2{\cdot}4 \times 10^{-1}$			$4{\cdot}0 \times 10^{-4}$
^{125}Sn	$2{\cdot}5 \times 10^{-1}$			$4{\cdot}2 \times 10^{-4}$
^{127}Sb	$3{\cdot}3 \times 10^{-2}$			$5{\cdot}6 \times 10^{-5}$
^{129m}Te	$2{\cdot}5 \times 10^{1}$			$4{\cdot}2 \times 10^{-2}$
^{129}Te	$2{\cdot}5 \times 10^{1}$			$4{\cdot}2 \times 10^{-2}$
^{131m}Xe	$6{\cdot}5 \times 10^{1}$			$1{\cdot}1 \times 10^{-1}$
^{131}I	$6{\cdot}0 \times 10^{2}$	$7{\cdot}4 \times 10^{2}$		$1{\cdot}0 \times 10^{0}$
^{132}Te	$6{\cdot}0 \times 10^{2}$	$4{\cdot}4 \times 10^{2}$		$5{\cdot}9 \times 10^{-1}$
^{133}Xe	$1{\cdot}2 \times 10^{4}$			$2{\cdot}1 \times 10^{1}$
^{134}Cs	$1{\cdot}2 \times 10^{0}$			$2{\cdot}0 \times 10^{-3}$
^{135}Xe	$3{\cdot}5 \times 10^{1}$			$5{\cdot}9 \times 10^{-2}$
^{136}Cs	$1{\cdot}5 \times 10^{0}$			$2{\cdot}5 \times 10^{-3}$
^{137}Cs	$4{\cdot}6 \times 10^{1}$	$2{\cdot}2 \times 10^{1}$		$3{\cdot}0 \times 10^{-2}$
^{140}Ba	$6{\cdot}4 \times 10^{0}$			$1{\cdot}1 \times 10^{-2}$
^{140}La	$6{\cdot}4 \times 10^{0}$			$1{\cdot}1 \times 10^{-2}$
^{141}Ce	$7{\cdot}1 \times 10^{0}$			$1{\cdot}2 \times 10^{-2}$
^{143}Ce	$1{\cdot}6 \times 10^{0}$			$2{\cdot}6 \times 10^{-3}$
^{144}Ce	$4{\cdot}0 \times 10^{0}$	$3{\cdot}0 \times 10^{0}$		$4{\cdot}1 \times 10^{-3}$
^{147}Nd	$2{\cdot}3 \times 10^{0}$			$3{\cdot}8 \times 10^{-3}$
^{147}Pm	$2{\cdot}3 \times 10^{0}$			$3{\cdot}8 \times 10^{-3}$
^{149}Pm	$5{\cdot}9 \times 10^{-1}$			$9{\cdot}9 \times 10^{-4}$
^{151}Pm	$1{\cdot}0 \times 10^{-1}$			$1{\cdot}7 \times 10^{-4}$
^{153}Sm	$7{\cdot}8 \times 10^{-2}$			$1{\cdot}3 \times 10^{-4}$
^{156}Eu	$2{\cdot}6 \times 10^{-1}$			$4{\cdot}3 \times 10^{-4}$
^{210}Po			$8{\cdot}8 \times 10^{0}$	
^{239}Pu			$1{\cdot}6 \times 10^{-3}$	
^{238}U			$6{\cdot}0 \times 10^{-5}$	
^{235}U			$2{\cdot}0 \times 10^{-6}$	
^{3}H			$5{\cdot}0 \times 10^{3}$	

proceeded a cold front moved south-easterly across the country, and the winds freshened and veered in a northerly direction. During the morning of 11 October they backed to the north-west. Hence some material released early in the incident

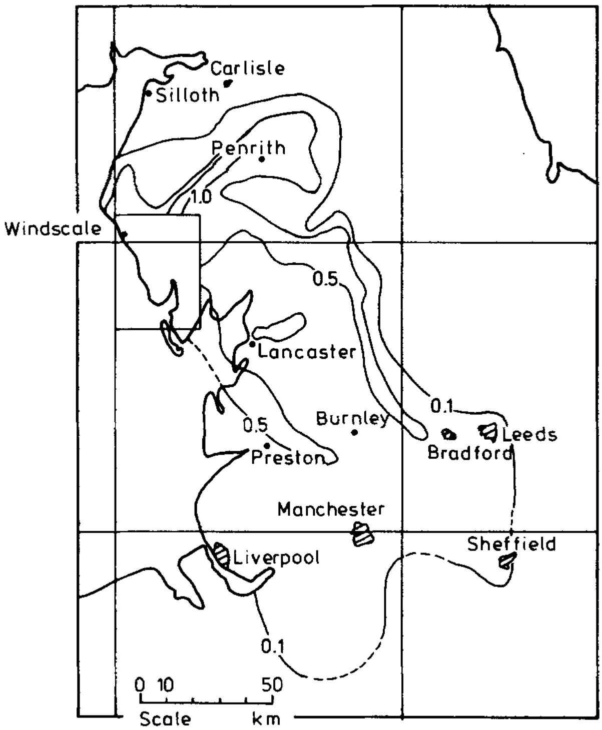

Figure 1. Deposition of ^{131}I in NW England, μCi m^{-2} (Chamberlain 1959).

was carried north-east beyond Penrith in Cumbria. Material discharged at a later stage was carried south-easterly over Cumbria and Lancashire. The pattern of ^{131}I deposition in northern England, as reported by Chamberlain (1959), figure 1, correlates well with this description of meteorological conditions. The path of the cloud was followed at the time across the country and into Europe and Scandinavia by means of air sampling (Crabtree 1959); in recent years its path has been calculated by the use of trajectory analysis (ApSimon *et al.* 1977).

The most important nuclide, in terms of the potential hazard to health in the local population, was correctly identified in the early stages of the incident as being ^{131}I. The group in the population which was most at risk was identified as young children drinking milk produced locally to Windscale (young children have a milk intake rate comparable to that of adults and receive a higher committed dose per unit ^{131}I activity ingested). After consultations between medical and health physics experts, restrictions were imposed on the distribution of milk which contained more than 3700 Bq l^{-1} (0·1 μCi/l) of ^{131}I (Dunster *et al.* 1958). These restrictions were introduced in the period 11–13 October and the final area restricted was 520 km^2, covering a rectangular strip of coastline about 16 km wide, from 10 km north of Windscale southwards to the Barrow peninsula. The resumption of milk distribution was allowed when samples contained less than 3700 Bq l^{-1} (0·1 μCi/l) and the activity was falling with a half-life of not more than 8 days. This was achieved within 25 days for most of the region, although in the most contaminated area, close to Windscale, milk distribution was not resumed until 44 days after the accident, during which time the levels of other possible contaminants in the milk had been assessed and found to be always less radiologically significant than ^{131}I (Dunster *et al.* 1958).

Other items of diet, including eggs, vegetables, meat and water were examined in the most contaminated regions, but it was decided that there was no appreciable health hazard from these foodstuffs and hence that there was no need to implement bans on them (Dunster *et al.* 1958).

3. Procedure for collective dose evaluation

3.1. *Quantities and concepts*

The levels of dose equivalent in the population as a result of the Windscale fire were well below those at which early effects from radiation would be expected and consideration may be limited to the incidence of stochastic health effects (principally fatal and non-fatal cancers, and hereditary effects). In these circumstances the collective dose in an exposed population provides a measure of the overall radiological impact of the release. Its use implies the assumption that the relationship between the probability of occurrence of stochastic effects and dose equivalent is linear, without thresholds and therefore that the number of stochastic effects in the exposed population can be considered proportional to the sum of the individual dose equivalents in the population, i.e., the collective dose equivalent commitment.

The two radiological quantities which have been evaluated in this assessment are the collective thyroid dose equivalent commitment, S^{c}_{T} and the collective effective dose equivalent commitment, S^{c}_{eff}. The former quantity may be used to assess the risk of the incidence of thyroid cancer. It is evaluated in this assessment because the thyroids in the exposed population are known to have been preferentially irradiated due to the high proportion of radioiodine present in the release (table 1). The second quantity, S^{c}_{eff}, provides a means of expressing the overall risk of fatal cancer in all body organs and hereditary effects in the first two generations within a single quantity. It is the integral over time and over the whole population of the effective dose equivalent rate ($\dot{H}_{eff}$). The 'effective dose equivalent' is a weighted quantity; the weighting is on the basis of the relative risk associated with the irradiation of body organs as compared with that of the whole body.

It is defined by ICRP (1977) as

$$H_{eff}=\sum_{T} W_T H_T$$

where W_T is a weighting factor representing the proportion of the stochastic risk resulting from tissue (T) to the total risk when the whole body is irradiated uniformly and H_T is the dose equivalent in tissue (T).

The values of W_T recommended by ICRP (1977) are shown below:

Tissue	W_T
Gonads	0·25
Breast	0·15
Red bone marrow	0·12
Lung	0·12
Thyroid	0·03
Bone surfaces	0·03
Remainder†	0·30

† A value of $W_T=0{\cdot}06$ is applicable to each of the five organs or tissues of the remainder receiving the highest dose equivalents.

The effective dose equivalent is used in this study since a number of radionuclides were released other than isotopes of iodine which give rise to the irradiation of a variety of organs and tissues in the body. There are, however, deficiencies associated with the use of S^{c}_{eff} as a measure of health detriment and these have been fully discussed elsewhere (Clarke and Smith 1980). Of particular note in the present context is the absence of an allowance within S^{c}_{eff} for those non-fatal cancers which arise following thyroid irradiation.

The method adopted in this study for the evaluation of S^{c}_{eff} (and S^{c}_{T}) has been described more fully in another publication (NRPB/CEA 1979). The collective effective dose equivalent commitment (S^{c}_{eff}) may be conveniently expressed as the sum of contributions from external and internal irradiation

$$S^{c}_{eff} = \int_0^\infty \dot{S}_{eff,ext}(t)\,dt + H^{u}_{50,eff} \int_0^\infty \dot{I}^{c}\,dt \tag{1}$$

where

$\dot{S}_{eff,ext}$ is the collective dose equivalent rate from external radiation

$H^{u}_{50,eff}$ is the committed effective dose equivalent per unit intake (or the time integral of the effective dose equivalent rate per unit intake over a 50-year period following intake)

$\dot{I}^{c}$ is the collective intake rate by inhalation or ingestion of a nuclide by the population, and is a quantity which can be readily evaluated using environmental models.

The main pathways by which members of the public were exposed after the Windscale release were:

(i) inhalation of radioactive materials in the plume;
(ii) ingestion of contaminated milk, drinking water and other foodstuffs;
(iii) external irradiation from ground deposits;
(iv) external irradiation from the radioactive cloud.

The evaluation of the collective dose via each of these pathways requires a knowledge of the manner in which the plume of radioactive material was dispersed over the UK and the rest of Europe and of the resulting spatial distribution of deposited activity. In addition, it is necessary to know the spatial distributions of the population and of agricultural production with respect to the discharge point.

The spatial distributions of the population and of agricultural production around the Windscale site are continuously varying functions of distance, d, and angle, θ, relative to the discharge point. These variations may be approximated in the manner indicated in figure 2. The area around the discharge point is divided into a number of annular segments and the population and agricultural production in each is determined from national and European statistics as described in a later section.

For external irradiation the contribution to collective effective dose equivalent commitment due to a nuclide, j, may be assessed as follows:

$$S^{c}_{eff,ext}(j) = \sum_{dm,\theta n} N(dm,\theta n) \int_0^\infty \dot{H}_{eff,ext}(dm,\theta n,j,t)\,dt \tag{2}$$

where

$N(dm,\theta n)$ is the population in the annular segment $(dm,\theta n)$.

$\dot{H}_{eff,ext}$ $(dm,\theta n,j,t)$ is the mean effective dose equivalent rate from external radiation in segment $(dm,\theta n)$ from the nuclide, j.

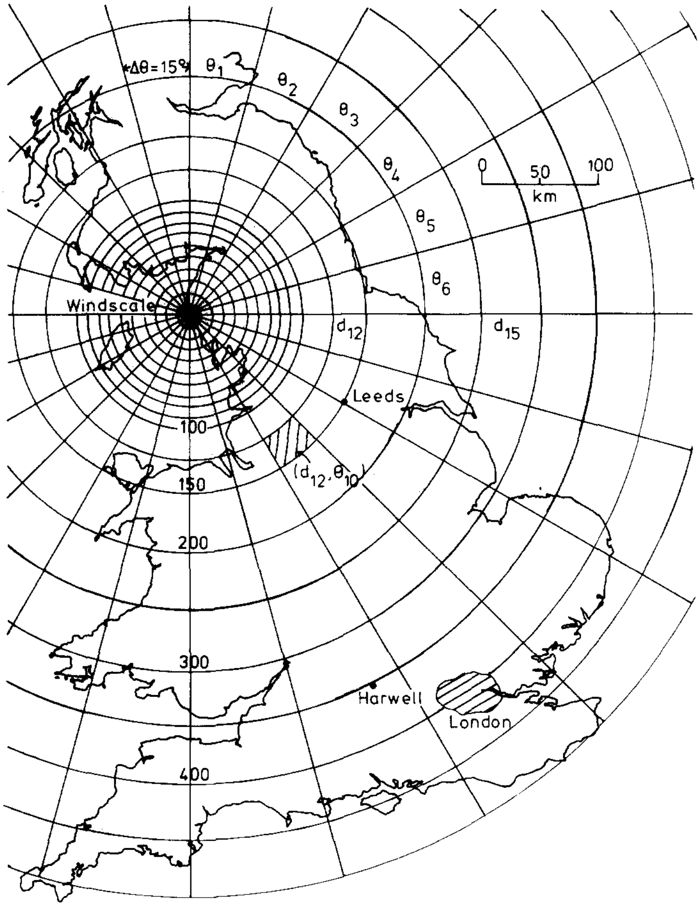

Figure 2. The radial coordinate grid adopted for representation of the spatial distribution of environmental materials and their degree of contamination following the Windscale accident 1957.

The contribution to collective dose equivalent commitment from inhalation of nuclide, *j*, may be expressed as:

$$S^{c}_{\mathrm{eff,inh}}(j)=H^{u}_{50,\mathrm{eff,inh}}(j)I\sum_{dm,\theta n}N(dm,\theta n)\int_{0}^{\infty}\chi(dm,\theta n,j,t)\,dt \tag{3}$$

where

I is the average breathing rate for members of the public
$N(dm,\theta n)$ is the population in segment $(dm,\theta n)$
$\chi(dm,\theta n,j,t)$ is the concentration in air of nuclide j in segment $(dm,\theta n)$ at time t

The contribution to collective effective dose equivalent commitment from the ingestion of food contaminated with nuclide *j*, may be expressed as:

$$S^{c}_{\mathrm{eff,ing}}(j)=H^{u}_{50,\mathrm{eff,ing}}\cdot F_1(j,g)\cdot F_2(g)\cdot\sum_{dm,\theta n}\left\{P(dm,\theta n,g)\int_{0}^{\infty}C(dm,\theta n,j,g,t)\,dt\right\} \tag{4}$$

where

$F_1(j,g)$	is a factor to account for the fractional decay of the nuclide, j, in foodstuff, g, in the time between production and consumption
$F_2(g)$	is the fraction of the activity present in the part of the food product, g, which is consumed by man (i.e., after processing or preparation for the table)
$P(dm,\theta n,g)$	is the production rate of foodstuff, g, in the segment $(dm,\theta n)$
$C(dm,\theta n,j,g,t)$	is the concentration of the nuclide, j, in the foodstuff, g, in the segment $(dm,\theta n)$ at time t.

The collective effective dose equivalent commitment, S^c_{eff}, from all pathways and from all nuclides, j, in the release is then

$$S^c_{\text{eff}}=\sum_j \{S^c_{\text{eff,ext}}(j)+S^c_{\text{eff,inh}}(j)+S^c_{\text{eff,ing}}(j)\} \tag{5}$$

The collective thyroid dose equivalent commitment, S^c_T, has been calculated using equations similar in form to those presented above but neglecting the contribution to the thyroid dose from external γ-radiation.

In the following sections, the methods and the data used to evaluate the parameters in the preceding equations are described.

3.2. *Evaluation of the spatial distribution of activity*

The measurements of radionuclides in air, milk, and vegetation made after the release and reported in the literature (Loutit *et al.* 1960, Chamberlain 1959, Booker 1958, Stewart and Crooks 1958, Stewart *et al.* 1961), have been used to form matrices describing the distribution of environmental concentrations over England, Wales and Northern Europe. No one set of measurements is sufficiently complete to allow a matrix to be assembled and it has been necessary to use relationships between different types of environmental measurements, together with some extrapolation, in order to build up complete spatial distributions. The procedures adopted and the relationships used for this purpose are fully described by Crick and Linsley (1982, 1983). Matrices have been assembled for the integrated concentrations of nuclides in air, milk and other foodstuffs and for ground deposition density.

3.3. *Population and agricultural production distribution*

The spatial distribution of population and of agricultural production around the Windscale site must be known in order to evaluate the collective dose. Grids of UK population and UK agricultural production distributions are available respectively on 1×1 km and 5×5 km squares of the National Grid (Hallam *et al.* 1980, Simmonds and Linsley 1980). These data have been converted to the radial distribution format shown in figure 2 for evaluation of the quantities $N(dm,\theta n)$ and $P(dm,\theta n,g)$ in equations (2)–(4).

The spatial distribution of population and agricultural production in the rest of Europe is also needed. Grids of population and foodstuff production distributions are available (NRPB/CEA 1979) for Europe and have been converted into the form required.

3.4. *Other quantities needed in the collective dose calculation*

The committed effective dose equivalent per unit intake, $H^{u}_{50,\mathrm{eff}}$, and the committed thyroid dose equivalent per unit intake, $H^{u}_{50,\mathrm{T}}$, which are required for the evaluation of $S^{c}_{\mathrm{eff,inh}}$ and $S^{c}_{\mathrm{eff,ing}}$ (equations (3) and (4)) have been taken from ICRP Publication 30 (1979). Both values relate to adults; for the reasons noted above, separate consideration has to be given to children in the exposed population. A method to take account of the age distribution in the population is described by Crick and Linsley (1982, Appendix A) and has been employed here to calculate the age-corrected collective thyroid dose, $S^{c'}_{\mathrm{T}}$ and collective effective dose, $S^{c'}_{\mathrm{eff}}$. It takes account of the different intake rates and committed doses per unit intake in three age groups represented by a 1-year-old infant, a 10-year-old child and an adult, and weights the estimated collective dose according to their proportions in the population of England and Wales in 1958. For inhalation, the dose is calculated assuming the materials to be in the form of 1-μm AMAD particles.

In evaluating the collective dose due to the intake of radionuclides in milk, account has to be taken of the delay between production and consumption. This is an especially important factor for short-lived radionuclides such as ^{131}I. In 1957–58 about 70 per cent of the milk produced in England, Scotland and Wales was consumed as fresh milk (Federation of UK Milk Marketing Boards 1958), with a mean delay of 2 days between production and consumption (Haywood 1983). The remaining 30 per cent was used for butter and cheese production, with a mean delay of 3 months. The factors $F_1(j, g)$ and $F_2(g)$ in equation (4), as applied to milk, may therefore be expressed as

$$F_1(j, \mathrm{M})F_2(\mathrm{M}) = 0{\cdot}7 \exp\left\{\frac{(-2 \times 0{\cdot}693)}{t_{j1/2}}\right\} + 0{\cdot}3 \exp\left\{\frac{(-90 \times 0{\cdot}693)}{t_{j1/2}}\right\}$$

where $t_{j1/2}$ is the radioactive half-life in days of the radionuclide j.

For green vegetables, the mean delay between production and consumption is taken to be 7 days, and therefore

$$F_1(j, v) = \exp\left\{\frac{(-7 \times 0{\cdot}693)}{t_{j1/2}}\right\}$$

Only a part of the activity in harvested green vegetables is ingested by man because of losses which occur during food preparation. It is assumed that the fractional loss is 80 per cent (Simmonds and Linsley 1982); thus, the factor $F_2(g)$ in equation (4) for green vegetables is

$$F_2(V) = 0{\cdot}2$$

The external dose per unit deposit of γ-emitting nuclides is evaluated using the model described in Crick and Linsley (1982). Account is taken in this model of attenuation due to the migration of the nuclide down the soil profile and due to surface roughness. A factor of 0·5 is introduced to take account of the shielding provided by being indoors for a large part of each day.

4. Calculation of the collective dose equivalent commitment to the thyroid, S^{c}_{T}

The pathways by which radionuclides can give rise to irradiation of members of the public can be represented schematically as in figure 3. The dose to the thyroids of the population exposed to the Windscale release was dominated by the contributions

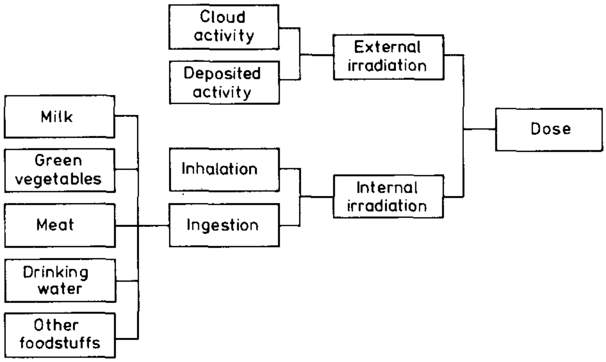

Figure 3. Pathways by which radionuclides can irradiate members of the public.

of the inhalation and ingestion pathways; thyroid exposure due to external irradiation from the plume and from ground deposits may be shown to be negligible by comparison. The collective dose equivalent commitment to the thyroid (S^c_T) is calculated using equations (3) and (4) for the inhalation, milk and green-vegetable pathways. S^c_T has been estimated for the milk pathway, taking account of the collective dose saved by the imposition of a ban on the consumption of milk supplies from the coastal strip, as described earlier. The collective dose which would have resulted without the imposition of a ban has also been calculated.

Dunster *et al.* (1958) reported that the concentrations of ^{131}I in reservoirs and streams close to Windscale were in the range 3·7 to 37 Bq l^{-1} in the first 10 days after the accident. No measurements appear to have been reported for the following months. However, in normal circumstances the time delays between deposition on lake and river catchments and consumption are of the order of weeks and months (although there are exceptions) and when this is considered, together with the relatively short radioactive half-life of ^{131}I, it seems most unlikely that the drinking water pathway could have contributed significantly to collective dose. It has not been considered further in this assessment.

Current NRPB models (Simmonds and Crick 1982) predict a ratio between the integrated concentration of ^{131}I in meat to the integrated concentration of ^{131}I in milk for a single deposit on pasture as being 0·21 Bq d kg^{-1}/Bq d l^{-1}. Applying a mean delay time for milk of 2 days (Haywood 1983) and for meat of 7 days (NRPB/CEA 1979) between milking and slaughter respectively, and the consumption of the foodstuff, and assuming average adult intake rates for milk and meat of 150 and 25 kg per year (Harrison and Simmonds 1980) respectively, the ratio of the total ^{131}I intake by meat and by milk is approximately 0·025. An estimate of the collective thyroid dose from meat is obtained by scaling the milk contribution to collective dose accordingly; it is 2·5 per cent of that due to milk.

The collective doses from the consumption of ^{131}I in grain and root crops are negligible. For grain, this is because there is a mean delay of about 1 year (Haywood 1983) between harvest and consumption in which time the ^{131}I would have almost totally decayed. For root crops the main mode by which the edible parts become contaminated with ^{131}I is likely to be due to translocation from the foliar parts of the plant. However, for most root crops there is a substantial delay, on the average, between harvest and consumption (4 months for potatoes) (Haywood 1983) and the collective dose due to ^{131}I in this pathway is again likely to be insignificant.

Tellurium-132 (^{132}Te) ($t_{1/2}=78$ h) which decays to ^{132}I ($t_{1/2}=2{\cdot}4$ h) also contributes to the collective thyroid dose, S^{c}_{T}, via the inhalation pathway. The collective thyroid dose due to this nuclide via the ingestion pathway can be shown to be small in comparison with that due to ^{131}I.

The contribution of other nuclides present in the release to the collective thyroid dose has been neglected, since they are not concentrated in the thyroid gland and most of them were present in the release at much lower activity concentrations than ^{131}I.

The estimated collective thyroid dose equivalent commitments ($S^{c'}_{T}$), corrected for age at intake, are given in table 2 for the Cumbrian area, the UK and the remainder of Europe. The collective dose estimate for the Cumbrian area is probably an overestimate, since the contribution to collective dose from milk relates to the milk produced in Cumbria rather than the milk consumed. However, since there is no significant export of milk from the UK as a whole, the UK collective dose estimate is considered to be more realistic.

Table 2. Collective dose equivalent commitment to the thyroid ($S^{c'}_{T}$) corrected for the age distribution of the population (man Sv).

Pathway	Cumbria (0–50 km)	UK	Total inc. continent
Inhalation	$4{\cdot}9\times10^{2}$	$5{\cdot}4\times10^{3}$	$5{\cdot}7\times10^{3}$
Ingestion			
milk	$2{\cdot}6\times10^{3}$	$1{\cdot}7\times10^{4}$	$1{\cdot}8\times10^{4}$
other foods	$9{\cdot}3\times10^{1}$	$2{\cdot}1\times10^{3}$	$2{\cdot}1\times10^{3}$
Totals	$3{\cdot}2\times10^{3}$	$2{\cdot}5\times10^{4}$	$2{\cdot}6\times10^{4}$

Notes

(1) The milk ban is estimated to have saved $3{\cdot}5\times10^{3}$ man Sv of the $S^{c'}_{T}$ for the Cumbria region.
(2) Other foods include green vegetables and meat.
(3) The figures for ingestion show the collective doses arising from the consumption of contaminated foodstuffs produced in each area, and not necessarily to the population within that area.

5. Correlation between predicted and measured individual thyroid doses in London, Leeds and Cumbria from ^{131}I

In the period after the Windscale fire, measurements were made of the ^{131}I activity in the thyroids of children and adults in London, Leeds and Cumbria. These measurements provide a further source of information which can be used to examine the reliability of the database described in previous sections.

The procedure described earlier for estimating collective dose does not require a knowledge of the origins of foodstuffs consumed by the population; it is necessary only to assume that all or an appropriate fraction of food produced in the area under consideration is consumed. In order to make predictions of dose to individuals in particular locations, however, the source of the contaminated foodstuff, in this case predominantly milk, must be known so that the level of activity in the ingested material can be determined. This type of information is available for the milk supplies to London in 1957; for the other locations and for other foodstuffs, however, assumptions have had to be made about the source of supply.

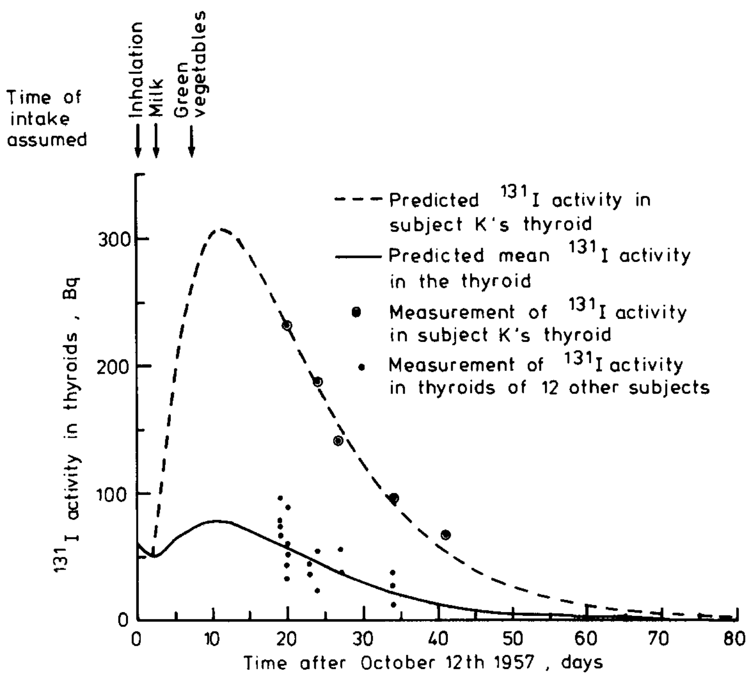

Figure 4. Comparison between predicted and measured ^{131}I activity in the thyroids of London residents as a function of time after the passing of the plume.

5.1. *London*

Maycock and Vennart (1958) published measurements of the ^{131}I activity concentration in the thyroids of some thirteen adults, resident in the Greater London area. The measurements were made in the weeks following the accident; the earliest were made on 31 October. The data are reproduced in figure 4. The points fitted by the upper curve represent the measurements where the activity in one person's thyroid (subject K) was followed as a function of time after the accident. This person was reported to have had a high milk intake rate, of at least 1·1 litres per day. Maycock and Vennart fitted an equation to these data using a simple model which enabled them to estimate a dose of 1·3 mSv to K's thyroid. On the basis of the measurements made on the other subjects they predicted a probable thyroid dose of $400 \pm 80\,\mu$Sv to an average adult individual living in London. Their model has several shortcomings; it allows only for intake from drinking milk and it does not account for any delay between the production and consumption of the contaminated milk. In addition, they assumed that the activity concentrations of ^{131}I in milk decayed with an effective half-life of 7 days. From Booker's measurements, it is known that a shorter half-life was observed (5 days).

The integrated concentration of ^{131}I in air, $\tilde{\chi}$(I), was measured at Harrow Middlesex (Loutit *et al.* 1960, Crabtree 1959), and was found to be 15·7 Bq d m^{-3}. Assuming an inhalation rate for adults of 23 m^3 d^{-1} (Harrison and Simmonds 1980) and a committed dose equivalent to the thyroid per unit activity inhaled, $H^{u}_{50,\mathrm{T,inh}}$, of $2{\cdot}9 \times 10^{-7}$ Sv Bq^{-1} (ICRP 1979), the average thyroid dose equivalent to people living in London from inhalation, $\bar{H}_{\mathrm{T}}(\mathrm{I, inh})$ is estimated to have been $100\,\mu$Sv.

The volumes of milk supplied to Greater London from various counties in England and Wales in June 1956 are known (Milk Marketing Board 1981, Crick and

Linsley 1982). This information, taken together with estimates of the mean integrated concentration of ^{131}I in milk, $\tilde{C}(\mathrm{I, M})$, for each county from the matrix described earlier, permits the derivation of an estimate of the average integrated concentration of ^{131}I, $\tilde{C}_{\mathrm{L}}(\mathrm{I, M})$, in milk consumed in London. The dose equivalent to the thyroid of the average adult milk consumer in London, $H_{\mathrm{T}}(\mathrm{I, M})$, as a result of the Windscale fire is thus

$$H_{\mathrm{T}}(\mathrm{I, M}) = \tilde{C}_{\mathrm{L}}(\mathrm{I, M}) \times I(\mathrm{M}) \times H^{\mathrm{u}}_{50,\mathrm{T,ing}} \times F_1(\mathrm{I, M})$$

where

$I(\mathrm{M})$ is the per caput milk intake rate of adults = 150 l per year (Harrison and Simmonds 1980)

$H^{\mathrm{u}}_{50,\mathrm{T,ing}}$ is the adult thyroid committed dose equivalent per unit ^{131}I ingested ($4{\cdot}8 \times 10^{-7}$ Sv Bq^{-1}) (ICRP 1979)

$F_1(\mathrm{I, M})$ is a factor to account for the decay of ^{131}I between production and consumption of the contaminated milk ($F_1(\mathrm{I, M}) = 0{\cdot}84$)

$\tilde{C}_{\mathrm{L}}(\mathrm{I, M}) = 1180$ Bq d l^{-1}

Substituting these values in the equation gives $\bar{H}_{\mathrm{T}}(\mathrm{I, M}) = 180\,\mu$Sv.

For the green-vegetables pathway it is assumed that vegetable supplies in London are derived from the whole of England and Wales and in proportion to their production. The integrated ^{131}I activity in UK green vegetables, $\tilde{C}(\mathrm{I, V})$, is estimated to be ~ 2 Bq year kg^{-1} assuming a 7-day delay between cropping and consumption. Assuming that the per caput adult intake rate of fresh green vegetables was 40 kg per year (Harrison and Simmonds 1980), the average thyroid dose equivalent, $\bar{H}_{\mathrm{T}}(\mathrm{I, V})$, from ingestion of ^{131}I in green vegetables is 40 μSv.

From these three intake routes, the total thyroid dose equivalent, $\bar{H}_{\mathrm{T}}$, to an average adult in London is

$$\bar{H}_{\mathrm{T}}(\mathrm{I}) = \bar{H}_{\mathrm{T}}(\mathrm{I, M}) + \bar{H}_{\mathrm{T}}(\mathrm{I, inh}) + \bar{H}_{\mathrm{T}}(\mathrm{I, V})$$

The value estimated in this way for $\bar{H}_{\mathrm{T}}$ is 320 μSv.

The time distribution of the ^{131}I activity in the thyroid can be calculated from these estimates using a suitable model. For the inhalation pathway it is assumed that a single intake occurred on 12 October. There would then have been a delay of roughly 2 days between this intake and the intake of contaminated milk, because of the time delay in distribution, and roughly 7 days' delay before the consumption of contaminated green vegetables.

Using NRPB models (Simmonds and Crick 1982), the time-distribution of activity in milk and green vegetables consistent with the thyroid dose estimates can be predicted. The lower curve in figure 4 is the predicted time distribution of thyroid activity for the average London adult as a result of the contributions of the inhalation and milk and green vegetables ingestion pathways; it is considered to be in good agreement with the measurements, bearing in mind the uncertainties, particularly those in the estimates of contamination levels in milk and green vegetables.

The upper curve in figure 4 is a fit to the measurements made on subject K, by varying his milk intake, but keeping the inhalation and green vegetable intake fixed. It is found that K would have had to consume an equivalent of 2·4 l of milk per day at the estimated average London milk contamination. From the preceding discussion it seems equally possible that K consumed milk of higher ^{131}I concentration or alternatively that his metabolism for iodine was significantly different from the average. The spread of measured values around the lower curve supports these suggestions.

5.2. *Leeds*

Measurements of the activity of ^{131}I in the thyroids of some nine people resident in the Leeds area at the time of the accident were reported by Burch (1959) For two subjects (A and B), the time-variation of the activity was followed into mid-November 1957. These data are represented by the plots in figure 5. By integrating the activity under the curves, Burch estimated the average thyroid dose equivalents for these two adult Leeds residents to be 1·0 mSv. He used a thyroid mass of 30 g in his calculation rather than 20 g, as recommended by ICRP for Reference Man (1975). When modified for the lower thyroid mass the dose is 1·5 mSv. The time-dependence of thyroid activity at short times after the accident could not be deduced directly from the measurements.

The peak activity of ^{131}I in milk in Leeds as a result of the Windscale fire has been estimated from measurements in milk to be between 440 and 810 $Bq\,l^{-1}$ (Baverstock and Vennart 1976). Applying the models described by Crick and Linsley (1982), this corresponds to integrated ^{131}I concentrations in milk, $\tilde{C}(I, M)$, of 3590 and 6590 $Bq\,d\,l^{-1}$ respectively. In the four annular segments of the $\tilde{C}(I, M)$ matrix about Leeds the values of $\tilde{C}(I, M)$ in $Bq\,d\,l^{-1}$ are as follows:

	125–150 km	150–200 km
sector 8	7040	1480
sector 9	3700	2370

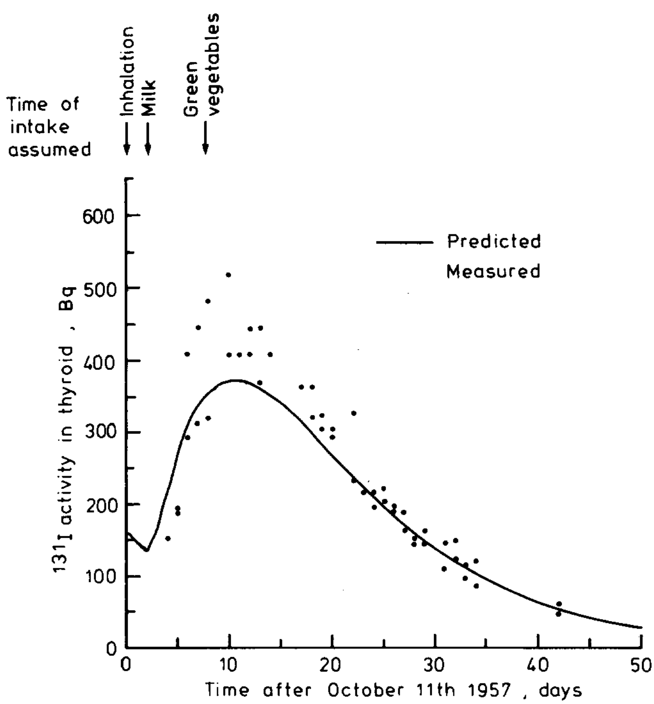

Figure 5. Comparison between predicted and measured ^{131}I activity in the thyroids of Leeds residents as a function of time after the passing of the plume.

Assuming that the people of Leeds derive their milk from the 125–150 km band and the 150–170 km band of sectors 8 and 9 (i.e., four annular segments equal in area about Leeds), then the calculated mean value of $\tilde{C}(\mathrm{I,M})$ for these areas is $4300\,\mathrm{Bq\,d\,l^{-1}}$. This is within the range of values obtained from milk measurements.

The two people in the measurement study were reported to consume an average of about 1·2 pints of milk per day (Burch 1959) (250 l per year). The dose equivalent to their thyroids from drinking milk with an integrated activity concentration of $4300\,\mathrm{Bq\,d\,l^{-1}}$ is estimated to be 1·1 mSv, taking into account a delay of 2 days between production and consumption.

The integrated concentration in air, $\tilde{\chi}(\mathrm{I})$, which would give rise to a $\tilde{C}(\mathrm{I,M})$ value of $4300\,\mathrm{Bq\,d\,l^{-1}}$ in milk is $41\,\mathrm{Bq\,d\,m^{-3}}$ (Crick and Linsley 1982). This results in a thyroid dose equivalent of 0·27 mSv from inhalation.

The dose from consumption of green vegetables in estimated using the same assumption as for London, giving a thyroid dose equivalent of the order of 0·04 mSv. The total from these three pathways, $\bar{H}_\mathrm{T}$, is 1·4 mSv, close to the 1·5 mSv estimated from the direct measurements of Burch. The time variation of the activity in the two subjects' thyroids can be estimated using a similar model to that described in § 5.1. The predicted curve presented in figure 5 gives a good fit to the measured thyroid activities.

5.3. *Cumbria*

Measurements of the ^{131}I content of thyroids in the Windscale area during the time when milk was banned were reported by Dunster *et al.* (1958). Clarke (1974) has shown that there is evidence that, in most cases,the thyroid doses can be mainly attributed to inhalation of ^{131}I, and not to contaminated milk being imbibed in error. The mean adult thyroid dose equivalent at various distances from the site may also be estimated by using the matrix of time-integrated concentration of ^{131}I in air, $\tilde{\chi}(\mathrm{I})$. The results from this calculation are presented along with Clarke's (1974) predictions and Dunster's measurements in table 3.

The agreement between the results is good and encourages confidence in the models used in deriving inhalation doses from measurements of ^{131}I in milk. The

Table 3. Comparison between measured and predicted thyroid doses to individuals living in the Windscale area.

Distance from Windscale (km)	Thyroid dose from inhalation (This study) (mSv)	Distance from Windscale (km)	Thyroid dose from inhalation (Clarke 1974) (mSv)	Measured thyroid dose (Dunster 1957) (mSv)
		3	18	5
0–10	18	6	21	14
		7	18	14
		9	16	18
10–20	13	18	9	14
20–30	5·5	—	—	—
		31	5	4
30–40	3·1	37	2	5
		38	2	3

results calculated here do not take account of any additional dose due to milk consumption after the ban was lifted. The individual thyroid dose equivalents could have been 5 mSv higher as a consequence. However, Dunster's measurements of ^{131}I concentrations in the thyroids of the local population were made before the milk ban was lifted and hence would not be expected to include this contribution.

Overall, the comparisons of measured and predicted thyroid ^{131}I contents for people in London, Leeds and Cumbria encourage confidence in the models and data base employed in the collective dose assessment.

6. Calculation of the collective effective dose equivalent commitment, $S^{c'}_{eff}$

The collective effective dose equivalent commitment, $S^{c'}_{eff}$, corrected for age at intake, to populations within various distance bands from the Windscale site has been assessed, using the methodology outlined in § 3; the results are presented in table 4. The nuclides which proved to be of significance for the inhalation pathway were ^{210}Po, ^{131}I, ^{132}Te, ^{137}Cs, ^{103}Ru, ^{144}Ce, ^{91}Y and ^{129m}Te. The nuclides of importance for the ingestion and external irradiation (ground deposits) pathways were ^{131}I, ^{132}Te and ^{137}Cs.

In assessing the contribution to S^{c}_{eff} from food-chain contamination, account has to be taken of the transfer of long-lived radionuclides from soil into foodstuffs. Those considered were milk, meat and liver from grazing animals, green vegetables, grain and root crops.

Consideration has been given to the contribution of the collective dose to the workers at Windscale, during the accident, to the total S^{c}_{eff}. In the attempts to clear the damaged channels some of the workers at the Windscale reactors were exposed to high external dose rates and to significant air concentrations of radionuclides. Protective measures were taken to control the exposure of the workers, including the wearing of respirators and the monitoring of external radiation. Measurements of ^{131}I in the thyroids of 96 workers in the plant showed that the largest doses to this

Table 4. The collective effective dose equivalent commitment $S^{c'}_{eff}$ (man Sv).

Pathway	Cumbria (0–50 km)	UK	Total including continental Europe
Inhalation	$3{\cdot}5 \times 10^1$	$9{\cdot}0 \times 10^2$	$9{\cdot}8 \times 10^2$
Ingestion			
Milk	$8{\cdot}8 \times 10^1$	$5{\cdot}7 \times 10^2$	$5{\cdot}9 \times 10^2$
Other foods	$1{\cdot}2 \times 10^1$	$1{\cdot}7 \times 10^2$	$1{\cdot}9 \times 10^2$
External			
Ground deposit	$1{\cdot}2 \times 10^1$	$1{\cdot}9 \times 10^2$	$2{\cdot}1 \times 10^2$
Cloud γ	$4{\cdot}9 \times 10^0$	$5{\cdot}4 \times 10^1$	$5{\cdot}7 \times 10^1$
Totals	$1{\cdot}5 \times 10^2$	$1{\cdot}9 \times 10^3$	$2{\cdot}0 \times 10^3$

Notes

(1) The figures for ingestion show the collective doses arising from the consumption of contaminated foodstuffs produced in each area, but not necessarily to the population within that area.

(2) $S^{c'}_{eff}$ is the collective effective dose equivalent commitment corrected, where necessary, for the age distribution of the population.

(3) The milk ban is estimated to have saved 108 man Sv of the $S^{c'}_{eff}$ for the Cumbria region.

organ were 95 and 21 mSv, with an average of 4 mSv, due to inhalation of ^{131}I (Loutit *et al.* 1960). The external radiation doses of 14 workers were in excess of the maximum permissible quarterly dose of 30 mSv which existed at the time, the highest dose being 47 mSv (Loutit *et al.* 1960). The contribution of the workers' doses to the total collective dose was nevertheless negligibly small (less than 1 man Sv to the thyroid and less than 1 man Sv effective dose).

The cooling water used to extinguish the fire in the reactor was ultimately discharged to sea. On the basis of an approximate estimate of the quantities discharged (Chamberlain 1981), an assessment of the contribution to S^{c}_{eff} from the marine exposure pathways has been made using the model described by Clark and Camplin (1979). The contribution from this source to S^{c}_{eff} is estimated to be less than 5 man Sv.

7. Discussion of the results

The results of the calculations of the age-corrected collective dose equivalent commitment to the thyroid ($S^{c'}_{\mathrm{T}}$) and of the age-corrected collective effective dose equivalent commitment ($S^{c'}_{\mathrm{eff}}$) following the Windscale release of 1957 are given in tables 2 and 4, respectively.

7.1. *Collective dose equivalent commitment to the thyroid*

The total collective dose equivalent commitment to the thyroid, $S^{c'}_{\mathrm{T}}$, corrected for the age distribution of the population was estimated to be $2{\cdot}6 \times 10^4$ man Sv (37 per cent higher than if an adult population was assumed). Of this, 70 per cent is contributed by the milk pathway, 22 per cent by inhalation of activity in the plume, and 8 per cent by other foodstuffs. Of the $2{\cdot}6 \times 10^4$ man Sv it is estimated that 95 per cent was delivered in the UK and approximately 12 per cent of the total dose would have arisen from within 50 km of the Windscale site. However, since milk and other foodstuffs are not necessarily ingested where they are produced, this figure does not imply that the local population received that dose.

The most important nuclide contributing to the collective thyroid dose equivalent was ^{131}I. It was responsible for almost the entire dose from the milk pathway. The only other nuclide to make a noticeable contribution to the collective thyroid dose was ^{132}Te via the inhalation pathway; its decay-chain daughter, ^{132}I, is concentrated in the human thyroid gland. Both ^{131}I and ^{132}Te have relatively short radioactive half-lives (8·02 d and 78 h respectively) and thus almost all of the dose would have been received within a few weeks of the accident.

It is interesting to note that the inhalation pathway is predicted to have been relatively more important than assumed by Baverstock and Vennart (1976). This is mainly because of the comparatively lower ground deposit to milk transfer of ^{131}I observed by Booker (1958) and used in this assessment, and because of the inclusion of ^{210}Po in this study.

Recently Taylor (1981) has estimated the collective thyroid dose to an adult population resulting from the Windscale fire by extrapolating the few measurements on individuals in the UK to obtain the population dose. His method, though approximate, gives results which are in reasonable agreement with the corresponding adult S^{c}_{T} of this assessment. Only the collective thyroid doses in the 0–50 km zone are appreciably different and this is not unexpected since the collective dose contribution from milk contamination in this assessment refers to milk produced, but not necessarily consumed, in the area.

7.2. *Collective effective dose equivalent commitment*

The collective effective dose equivalent commitment, corrected for the age distribution of the population, $S_{\mathrm{eff}}^{c'}$, has been estimated to be $2 \cdot 0 \times 10^3$ man Sv. Of this the inhalation pathway is the single largest contributor of collective dose (50 per cent). The milk ingestion pathway accounts for nearly 30 per cent and the remaining 20 per cent is shared between other ingestion pathways and the external irradiation pathways.

The most important nuclides contributing to collective effective dose are ^{131}I (37 per cent), ^{210}Po (36 per cent) and ^{137}Cs (15 per cent). Other less important nuclides are ^{144}Ce, ^{129m}Te, ^{106}Ru, ^{103}Ru, ^{132}Te and ^{91}Y.

The use of effective dose equivalent provides a convenient means of expressing the overall risk from the irradiation of different body organs and tissues by a single quantity but it does result in a loss of information when used on its own. For example, an effective dose equivalent of 1 mSv could arise from 33 mSv to the thyroid gland or from 8·3 mSv to the lung or as a result of a combination of other organ irradiations. For this reason the nature of the most important irradiations which contribute to $S_{\mathrm{eff}}^{c'}$ are discussed below.

The contribution of ^{131}I to $S_{\mathrm{eff}}^{c'}$ is $7 \cdot 4 \times 10^2$ man Sv and arises almost entirely from the exposure of the thyroid gland as a result of milk ingestion and inhalation (table 2). ^{210}Po contributes almost as much to $S_{\mathrm{eff}}^{c'}$ as ^{131}I ($7 \cdot 1 \times 10^2$ man Sv) but unlike iodine, polonium is not concentrated in one particular organ after being metabolized but is distributed fairly uniformly throughout all organs and tissues in the body with elevated concentrations being found in the spleen, kidneys and liver (ICRP 1979). However, the assessment has shown the ^{210}Po contribution to $S_{\mathrm{eff}}^{c'}$ comes mostly via inhalation (90 per cent) and so the lungs too could be one of the more highly exposed parts of the body. The predicted distribution of dose in body organs and tissues following inhalation of ^{210}Po according to the ICRP metabolic models is dependent on the form of the polonium on intake. If it is inhaled as a particulate in the oxide, hydroxide or nitrate forms it is predicted to behave as a class W compound which is characterized by a fairly long retention half-time in the lung (10–110 days). Other polonium compounds are more soluble and are retained for much shorter periods in the lung; their behaviour is described by class D compounds, in the ICRP model.

The limited information on the form of ^{210}Po in the environment as a result of the Windscale fire suggests that it was present as particles of size around 1 μm AMAD or less. Crouch and Swainbank (1958) found bismuth oxide and lead oxide present on the pile filters in aggregates of mean diameter 1 μm. Since polonium is known to behave not unlike lead and bismuth (Bagnall 1957) it seems reasonable to assume that it was released in the same form. This is supported by the observation that the ratio of polonium to bismuth is about the same on the pile filter as it would have been in the bismuth undergoing irradiation in the pile (Benson *et al.* 1983). In the environment, the deposition velocity calculated for ^{210}Po ($\sim 6 \times 10^{-4}$ m s^{-1}) is not inconsistent with a particle size of around 1 μm. Although the behaviour of polonium in the oxide form would, according to the ICRP model, be represented by a class W compound which is characterized by fairly long retention times in the lung, human experiments with submicron particles of lead oxide have shown rapid clearance from the lungs, with half-times of a day or less (ICRP 1980). If this behaviour were exhibited by the small particles of polonium oxide, which seems quite likely, it would be considered as a class D compound. There is, thus, some uncertainty about the behaviour of the polonium in the body following inhalation, and while the resultant effective dose equivalent is the same whether the intake was of a class W or a class D material the distribution of doses in body organs and tissues is different for the two cases. Thus the estimated collective effective dose equivalent commitment ($S^{c'}_{eff}$) due to the inhalation of ^{210}Po, $7{\cdot}1 \times 10^2$ man Sv, could result from collective organ dose equivalent commitments of $7{\cdot}1 \times 10^3$ man Sv to spleen, $4{\cdot}2 \times 10^3$ to kidneys and $7{\cdot}1 \times 10^2$ to liver if the aerosol behaved as a class D compound, or $4{\cdot}2 \times 10^3$ man Sv to lungs, $2{\cdot}1 \times 10^3$ to spleen and $1{\cdot}3 \times 10^3$ to kidneys if the aerosol behaved as a class W compound.

The doses arising from the releases of ^{137}Cs are mainly due to external irradiation from ground deposits and from the intake of caesium in foodstuffs. In both cases the resulting dose distribution in the body is fairly uniform and the contribution to $S^{c'}_{eff}$ from ^{137}Cs (3×10^2 man Sv) may be regarded as a uniform whole-body dose.

Taylor (1981) did not estimate S^{c}_{eff} but he evaluated the collective whole-body dose equivalent from external irradiation. This may be compared with the estimates of the contribution to collective effective dose from external irradiation from this study. Again, the results are of the same order (Crick and Linsley 1982).

8. Health effects in the exposed population

The main risks to health from radiation exposure as a result of the releases from the 1957 Windscale Fire are associated with the possible induction of cancer in the thyroid glands of those exposed. A small proportion of the cancers induced by radiation lead to death but the majority can be treated successfully and are termed non-fatal. Their appearance after irradiation is not immediate but occurs over a few decades. The risks of cancer induction therefore may be best expressed in terms of a time-integrated risk. The risks of cancer induction in a normal population will vary with sex and with age tending to be higher in children and females. The extensive literature on the subject of the risks of late effects from exposure to ionizing radiations has been reviewed by UNSCEAR (1977), Clarke and Smith (1980) and more recently by Pochin (1983, 1984). The risk coefficients which can be obtained from these sources have considerable uncertainty associated with them and care has to be exercised in their use. They are mainly obtained from observations of health effects at high levels of dose and their application to the lower dose ranges, which are mostly of concern in radiological protection, is based on extrapolation.

UNSCEAR imply that the total risk of thyroid cancer incidence is likely to be in the range 1 to 3×10^{-2} Sv^{-1} and the risk of fatality in the range 5 to 15×10^{-4} Sv^{-1} for exposure to low-l.e.t. radiation. Pochin (1984) and Kelly and Hemming (1984) have discussed the applicability of these thyroid cancer incidence risk factors to an average population exposed to low-l.e.t. radiation at low doses and dose rates. They suggest that lower risk factors may be appropriate since most of the data on thyroid cancer incidence were obtained at high doses and dose rates and were largely based on the external irradiation of children who may have higher induction rates than adults. Further, there is some evidence that the risk from internal radiation of the thyroid from iodine radionuclides is less than that from external irradiation. In view of these considerations they suggest that 3×10^{-3} Sv^{-1} may be more appropriate as a thyroid cancer incidence risk factor for application to an average population exposed to low doses and dose rates. In this study we have used the values recommended by Clarke and Smith and used by NRPB in recent accident consequence assessments (Pochin 1983), namely, 1×10^{-2} Sv^{-1} for the total risk of thyroid cancer incidence in a population and 5×10^{-4} Sv^{-1} for the risk of fatal thyroid cancer. These are the lower values in the range recommended by UNSCEAR but for the reasons given above may be considered to represent an upper estimate of the thyroid cancer risks in the situation being considered where an average population was exposed to internal radiation due to iodine-131 at generally low doses and dose rates.

The collective thyroid dose to the UK population when corrected for the population age distribution is estimated to be $2{\cdot}5 \times 10^4$ man Sv. The majority of this dose was delivered within the first few months after the release but the predicted health effects in the population would be distributed in time over a few tens of years. Use of the risk coefficients given above, gives an upper estimate of the total number of expected thyroid cancers of 250 (13 of which would be fatal). If the mean life expectancy of the population is taken to be 40 years, and the radiation-induced thyroid cancers are assumed to be manifested uniformly over the period (which is an oversimplification) the annual incidence rate would be 6·5. It is again emphasised that the use of the risk coefficients for regimes of low dose and dose rate must be regarded as giving only an approximate upper estimate to the incidence of health effects in the population.

The thyroids of members of the UK population are also subject to continuous irradiation from natural background radiation sources, for example, cosmic rays, terrestrial radiation, and irradiation from naturally-occurring materials in the diet. To provide perspective the same risk coefficients may be used to obtain an upper estimate of the contribution of the natural thyroid cancer incidence in the population due to natural background radiation. The average annual thyroid dose equivalent from natural sources is about 0·9 mSv; this corresponds to an annual induction of 360 thyroid cancers per year (with 18 expected fatalities) in a population of size comparable to that of England and Wales.

The incidence rate of newly diagnosed thyroid cancer in England and Wales may be obtained from the statistics published by the Office of Population Censuses and Surveys (OPCS) (1979–1983). However, in using these statistics certain facts have to be borne in mind; firstly, that thyroid cancer is not one disease but comprises several different histological types, only some of which are known to be capable of being radiation induced (in the OPCS statistics annual rates are reported simply as thyroid cancers with no distinction between types); secondly the thyroid cancer registration statistics are known to be unreliable largely because of difficulties in the comprehensive diagnosis of thyroid cancer. Clinical diagnosis has been shown to produce fewer thyroid cancers than would be revealed by histological examination although many of those revealed by histological examination would not be considered clinically significant (Alderson 1980, Munro 1980). The histological examination of thyroid sections itself presents problems and very different interpretations of the same thyroid sections have been made by different pathologists (Ron and Modan 1982). Despite these reservations concerning the adequacy of the cancer registration data, they represent the only published comprehensive statistics on the subject and they are used here to obtain a further perspective on the rates predicted above. In the period 1968–79 the reported incidence of thyroid cancers in England and Wales has been in the range 600–800 cases per year (OPCS 1979–1983) although from the foregoing discussion the actual number may have been higher.

Even if the risks of radiation-induced cancer at the generally low doses from the Windscale Fire release were at the levels assumed above, the annual predicted excess would not be detectable against the fluctuations in the reported incidence rate. In

South-West Cumbria, where the individual thyroid doses due to the release were highest, the registered thyroid cancer incidence rates have not shown an excess over national rates in the period 1969–78 (Tiplady 1983). While these statistics do not provide conclusive evidence of the absence of an effect due to the release, they at least indicate that the risk rates due to thyroid irradiation are not greatly in excess of those assumed.

The expected incidence of health effects other than thyroid cancer in the exposed population is comparatively small since the radiation dose from nuclides other than those of iodine is not delivered entirely to a single organ or tissue but is fairly uniformly spread in the body. An upper estimate of the total number of fatal cancers plus hereditary effects in the first two generations may be obtained by using the collective effective dose equivalent commitment, $S^{c'}_{eff}$, together with a risk coefficient of $1{\cdot}65 \times 10^{-2}\,Sv^{-1}$ (ICRP 1977). This method implies a total of 33 health effects (cancer deaths plus hereditary effects in the first two succeeding generations); 13 of these are the thyroid cancer fatalities discussed previously. The same uncertainties, referred to earlier, concerning the risk coefficient values apply to this estimate, and it therefore is regarded as an upper estimate of radiation-induced health effects.

Again, for perspective it may be noted that the collective effective dose equivalent to the UK population from the accident, estimated to be $1{\cdot}9 \times 10^3$ man Sv, and mostly delivered at very low individual dose levels, is a small fraction of that received annually from natural background radiation (1×10^5 man Sv). On the same basis of estimation, this latter dose equivalent would cause $1{\cdot}65 \times 10^3$ serious health effects every year.

9. Estimates of individual doses

Measurements made soon after the release on people living close to the Windscale site established the range of individual thyroid doses due mainly to the release of iodine isotopes (Atomic Energy Office 1957, Loutit *et al.* 1960). Doses due to external radiation were also assessed from environmental dose rate measurements (Atomic Energy Office 1957, Loutit *et al.* 1960). Clarke (1974) has assessed individual organ doses from the inhalation of a spectrum of nuclides released, and also from external irradiation due to deposited nuclides and from nuclides in the airborne cloud. However, ^{210}Po was not included in that study. In this section, estimates are made of the committed effective dose equivalents to the individuals in the population likely to be the most highly exposed as a result of the release. In addition, an estimate is made of how the collective dose was distributed over the exposed population in terms of the proportion of the dose delivered in particular ranges of individual dose.

9.1. *Maximum individual doses*

The maximum reported deposition density of ^{131}I was $960\,kBq\,m^{-2}$ (Chamberlain 1959) at Seascale (approximately 3 km downwind at a bearing of about 160°). Assuming that the peak in ^{210}Po integrated air concentration occurred at the same point as for ^{131}I, the maximum individual dose due to the inhalation of ^{210}Po may be estimated. The relevant integrated ^{131}I concentration in air, based on $v_d = 3 \times 10^{-3}\,m\,s^{-1}$, is $320\,MBq\,s\,m^{-3}$. This value may be compared with the results of a calculation using an atmospheric dispersion model (Clarke 1979) in which, for an assumed release of 1 PBq of ^{131}I over 1 h the integrated air concentration at a distance of 3 km downwind on-axis is predicted to be approximately

1000 MBq s m^{-3}. Given the variations in meteorological conditions and wind direction, and the complex time pattern of the release, the agreement between the theoretical model and the calculation from gross measurements is considered reasonable. Assuming a $^{210}Po/^{131}I$ ratio of 8×10^{-3} in air as measured on the Calder Hall environmental air filters (Chamberlain 1981), the peak integrated ^{210}Po concentration in air is estimated to be 2·6 MBq s m^{-3}. Using this concentration, the maximum committed effective dose equivalent to adults from the inhalation of ^{210}Po is estimated to be 2 mSv.

In table 5, estimates are given of the dose to which an individual at that location might have been exposed from all nuclides and pathways as a result of the release. It is assumed that the fission products in the release are present in the atmosphere in the ratios to ^{131}I given in table 1. The exposures of individual members of the public as a result of intake by ingestion of milk, assumed to be produced from cows grazing pasture in the zone of maximum deposition, and by inhalation, have been calculated for adults, children (10 years) and infants (1 year) with average and extreme milk intakes (Harrison and Simmonds 1980, Greenhalgh 1983). The introduction of restrictions on the distribution of milk supplies in the area had the effect of reducing the exposure of those most at risk (infants). An estimate is therefore included in table 5 of the residual doses to members of the public assuming that the milk ban was introduced at the prescribed ^{131}I concentration (3700 Bq l^{-1}).

On the basis of the results of the calculations presented in table 5 it can be seen that the introduction of the milk supply restrictions reduced the effective doses to the most potentially highly exposed infants by a factor of about five, and to other age groups by lesser factors. It is clear that the potential ingestion of milk by infants would have represented the greatest individual risk to health and its withdrawal was the most effective procedure available for individual dose reduction. The risks to the most exposed individuals, assuming that the milk ban was completely effective, were of the same order as those implied by the ICRP annual dose equivalent limit of 5 mSv, which is applied in controlling doses to members of the public from routine releases to the environment (ICRP 1977). The residual doses can also be placed in perspective by comparing them with exposure to natural background radiation, taken to be responsible for an average annual effective dose equivalent of 2 mSv to

Table 5. Estimates of the individual time integrated effective dose equivalent corresponding to the area of maximum deposition density of ^{131}I (mSv).

	Age at time of accident					
	Adult		Child		Infant	
Milk consumption	extreme	average	extreme	average	extreme	average
No milk ban	8·2	5·7	18	11	36	22
With milk ban	4·2	4·0	6·8	6·4	7·1	6·2

Notes

(1) The maximum measured thyroid dose equivalent to a child was 160 mSv; the corresponding effective dose equivalent is 4·8 mSv. Adding in the contributions from other nuclides and pathways the maximum effective dose equivalent could have been about 9 mSv.

(2) For adults (20 years), children (10 years) and infants (1 year) the effective dose equivalent is integrated to age 70 years.

individuals in the UK (NRPB 1981). This comparison shows that the risks associated with the maximum dose estimates in table 5 may be equated with the risks which would be associated with exposure to natural background radiation over a period of 3–4 years.

9.2. *Individual dose distribution in the exposed population*

The procedure which has been used to estimate collective dose allows individual doses to be estimated accurately for the inhalation and external exposure pathways, but it does not provide a direct indication of how the collective dose is distributed into individual dose ranges for the ingestion pathway. To obtain an accurate estimate of this distribution, it would be necessary to have information on food supply distribution patterns and this is not readily available in the UK. An approximate estimate of the contribution to individual doses from ingestion has been made by assuming that the food produced in each sector of the activity distribution grids is consumed at an average UK intake rate (I_g) for each food

$$I_g = \frac{P_g}{N}$$

where

I_g is the representative average intake rate of a food, g (kg per year).
P_g is the UK production rate of foodstuff, g (kg per year).
N is the UK population.

Individual dose estimates for each segment and age-group are obtained by summing the inhalation, external irradiation and ingestion contributions to individual dose. The collective dose associated with each segment is then allocated to a particular band of individual dose in mSv, i.e., $<10^{-3}$, 10^{-3}–10^{-2}, 10^{-2}–10^{-1}, 10^{-1}–1, >1. The results of the calculations are presented in table 6. It is recognized that this procedure does not give the true individual dose distribution because of the treatment of ingestion dose, but since the inhalation pathway is responsible for the largest contribution to collective dose the associated error does not significantly affect the nature of the results. The results in table 6 are expressed in terms of the estimated fraction of the population of England and Wales exposed within each dose-band. Some perspective on the doses within each of the chosen bands of individual

Table 6. The distribution of collective dose within individual dose bands.

Range of representative individual effective dose equivalents (mSv)	Corresponding period of exposure to natural background	Collective effective dose equivalent commitment (man Sv)	Percentage of the population of England/Wales within each dose band
$<10^{-3}$	<4 hours	2.7×10^{-1}	6.6
10^{-3}–10^{-2}	4 hours–2 days	2.2×10^{1}	8.8
10^{-2}–10^{-1}	2 days–18 days	1.3×10^{3}	79.7
10^{-1}–1	18 days–6 months	4.6×10^{2}	4.9
>1	>6 months	3.7×10^{1}	0.05

Note: The average annual natural background effective dose equivalent in the UK is taken to be 2 mSv (NRPB 1981).

dose is provided by calculating the time in which a person would receive a dose of the same approximate magnitude from natural background radiation (taken to be 2 mSv annual effective dose equivalent (NRPB 1981)).

It may be noted that on the basis of the results of the calculations presented in table 6, about 80 per cent of the population of England and Wales exposed as a result of the Windscale fire received effective doses equal to those received from between 2 and 18 days of average exposure to natural background radiation in the UK. Less than 5 per cent of the population received doses greater than this and only 0·05 per cent (approx. 20 000 people) received doses corresponding to more than 6 months exposure to natural background. The doses to the most exposed individuals have been discussed in § 9·1.

10. Accuracy of the results

The assessment indicates that the contributions of the milk ingestion and inhalation pathways dominate the collective thyroid dose equivalent commitment and that together with the dose due to external irradiation from ground deposits, they are the main contributors to the collective effective dose equivalent commitment. The calculations of collective dose via these pathways rely on both the accuracy of the predicted spatial distribution of contamination and on the reliability of the transfer models used to relate environmental measurements to dose.

The values of environmental activity given in the matrices described in § 3.2 fall into three categories; those values, out to a distance of about 200 km from Windscale, which are based in the main on direct measurements of the ^{131}I concentration in milk; those which are modelled from measurements made in other environmental media; and those which are estimates made by considering the trajectory of the plume and interpolating between the nearest measurements. Of the $1{\cdot}2 \times 10^4$ man Sv total adult collective thyroid dose from milk (table 2), approximately 75 per cent comes from the region out to 200 km, where the estimates of integrated milk contamination are most reliable. Only about 12 per cent is based on values which are estimates from interpolation. An error of 2 times in these estimates would change the collective thyroid dose from milk by only about 10 per cent. In general, the sum of the contributions from all the segments is more accurate than the collective dose from an individual segment. Similar considerations apply to the matrix of ^{210}Po integrated air concentrations in table 3; most of the collective effective dose due to ^{210}Po comes from regions where direct measurements were available.

The main errors likely to be incurred in any collective dose calculations are systematic errors. They may be associated with factors which are applied equally to every segment in the grid, irrespective of its location. The most important parameters are the dosimetric ones, which directly determine the collective dose. Of lesser importance are the parameters which affect parts of the calculations but not the whole; they include deposition velocities, dose reduction factors for external irradiation, the ratio of nuclides released from the stack, and factors used in modelling the transfer from grass to milk. All of these parameters affect parts of the calculation but not the entire estimate. Sensitivity analyses have been performed on the collective dose calculations to investigate the importance of these parameters. For example, it can be shown that increasing the deposition velocity of ^{131}I by a factor of three reduces the collective thyroid dose by less than 5 per cent, whereas reducing the deposition velocity by a factor of three increases the estimate by about 50 per cent.

Taking into account the possible ranges of all the parameters in the assessment that might be varied, as well as the possible uncertainties in the spatial distribution of contamination, the total collective doses are considered to be accurate to within a factor of two or three.

11. Conclusions

(1) A methodology has been described and used for estimating the age-corrected collective thyroid dose equivalent commitment, $S_T^{c'}$, and the age-corrected collective effective dose equivalent commitment, $S_{eff}^{c'}$, following the release on 10 October 1957 from the No. 1 Pile at Windscale. It involved the establishment of matrices describing the spatial distribution of environmental contamination and the use of transfer models for dose estimation. The values calculated for $S_T^{c'}$ and $S_{eff}^{c'}$ are $2{\cdot}6\times10^4$ and $2{\cdot}0\times10^3$ man Sv, respectively.

(2) The pathway which contributed the most to the collective thyroid dose was the ingestion of contaminated milk. It is estimated that the banning of milk in the Windscale area, which was introduced to limit the thyroid doses of individuals most at risk in the population (see conclusion 4, below) saved approximately $3{\cdot}5\times10^3$ man Sv of the age-corrected collective thyroid dose equivalent commitment, $S_T^{c'}$, and 108 man Sv of the age-corrected collective effective dose equivalent commitment, $S_{eff}^{c'}$.

(3) ^{131}I was the most important radionuclide, contributing nearly all of the collective dose to the thyroid and a large part of the collective effective dose via the ingestion and inhalation pathways. The ^{210}Po in the release also made a significant contribution to the collective effective dose via the inhalation pathway. In the longer term following the release, the contribution of the long-lived ^{137}Cs to the collective effective dose via external dose from ground deposits and the ingestion of contaminated foodstuffs became significant.

(4) The most exposed group in the population were young children drinking milk produced in the northern counties, the most important contaminant of which was ^{131}I. The withdrawal of milk supplies reduced their risks by a factor of five. The maximum individual thyroid dose estimated from measurements was 160 mSv to a child in the Windscale area.

(5) The methodology used in the study has been validated to a degree by comparing the predicted levels of individual thyroid dose and those measured directly in the weeks following the accident in London, Leeds and Cumbria.

References

ALDERSON, M. R., 1980, Epidemiology. *Thyroid Cancer*, edited by W. Duncan (Springer-Verlag).

APSIMON, H. M., EARNSHAW, D., GODDARD, A. J. H., and WRIGLEY, J., 1977, *Trajectory analysis with particular reference to the 1957 Windscale release.* (London: Imperial College of Science and Technology, Nuclear Power Section).

ATOMIC ENERGY OFFICE, 1957, *Accident at Windscale No. 1 pile on 10th October, 1957*. Cmnd 302 (London: HMSO).

BAGNALL, K. W., 1957, *Chemistry of the Rare Radioelements* (London: Butterworths).

BAVERSTOCK, K. F., and VENNART, J., 1976, Emergency reference levels for reactor accidents: A re-examination of the Windscale reactor accident. *Hlth Phys.*, **30**, 339–344.

BENSON, J., BOLTON, F. M., RILEY, C. J., and ROSS, A. E., (declassified 1983). *The examination of a contaminated filter from No. 1 pile at Windscale*. FWP/8.

BOOKER, D. V., 1958, *Physical measurements of activity in samples from Windscale*. AERE-HP/R2607 (Harwell: UKAEA).

BURCH, P. R. J., 1959, Measurements at Leeds following the Windscale reactor accident. Iodine-131 in human thyroids and iodine-131 and caesium-137 in milk. *Nature*, **183,** 515–517.

CHAMBERLAIN, A. C., 1959, Deposition of I-131 in Northern England in October, 1957. *Q. Jl R. met. Soc.*, **85,** 350–361.

CHAMBERLAIN, A. C., 1981, declassified 1983, *Emission of fission products and other activities during the accident to Windscale Pile No. 1 in October 1957*. AERE-M3194 (Harwell: UKAEA).

CLARK, M. J., and CAMPLIN, W., 1979, *A model to calculate exposure from radioactive discharges into the coastal waters of Northern Europe*. NRPB-R109 (London: HMSO).

CLARKE, R. H., 1974, An analysis of the 1957 Windscale accident using the WEERIE code. *Ann. nucl. Sci. Eng.*, **1,** 73.

CLARKE, R. H., 1979, (Chairman of the Working Group), *A model for short and medium range dispersion of radionuclides released to the atmosphere*. NRPB-R91 (London: HMSO).

CLARKE, R. H., 1980, A re-examination of the 1957 Windscale reactor incident. *Proceedings 5th Annual Meeting Health Physics Society, July 1980*, Paper P/203. *Hlth Phys.*, **39,** 1056 (Abstract only).

CLARKE, R. H., and SMITH, H., 1980, *Calculation of the incidence of stochastic health effects in irradiated populations*. NRPB-R102 (London: HMSO).

CRABTREE, J., 1959, The travel and diffusion of the radioactive material emitted during the Windscale accident. *Q. Jl R. met. Soc.*, **85,** 362–370.

CRICK, M. J., and LINSLEY, G. S., 1982, *An assessment of the radiological impact of the Windscale Reactor Fire, October 1957*. NRPB-R135 (London: HMSO); 1983, *An assessment of the radiological impact of the Windscale Reactor Fire, October 1957*. NRPB-R135 Addendum (London: HMSO).

CROUCH, E. A. C., and SWAINBANK, I. G., 1958, declassified 1982, *Radiochemical and physical examination of the debris from the Windscale accident*. AERE-C/R2589 (Harwell: UKAEA).

DUNSTER, H. J., HOWELLS, H., and TEMPLETON, W. L., 1958, District surveys following the Windscale incident, October 1957. *Proceedings 2nd International Conference on Peaceful Uses of Atomic Energy, Geneva, 1958*, **18,** 296.

FEDERATION OF UK MILK MARKETING BOARDS, 1958, *Dairy Facts and Figures*.

GREENHALGH, R., 1983, *Integrated dose equivalents incurred by children and adults after unit intake of radioisotopes of iodine*. NRPB-M89 (Chilton: NRPB).

HALLAM, J., JONES, J. A., and HEMMING, C. R., 1980, *The establishment of population data grids for use in radiological protection*. NRPB-M65 (Harwell: NRPB).

HARRISON, N. T., and SIMMONDS, J. R., 1980, *Dosimetric quantities and basic data for the evaluation of generalised derived limits*. NRPB-DL3 (Harwell: NRPB).

HAYWOOD, S. M., 1983, *A review of data on the time delay between harvesting or collection of food products and consumption*. NRPB-M83 (Chilton: NRPB).

ICRP, 1975, *Report on the Task Group on Reference Man*. ICRP Publication 23 (Oxford: Pergamon Press).

ICRP, 1977, *Recommendations of the International Commission on Radiological Protection*. ICRP Publication 26. *Ann. ICRP*, **1** (3) (Oxford-Pergamon Press).

ICRP, 1979, *Limits for intakes of radionuclides by workers*. ICRP Publication 30, Part 1. *Ann. ICRP*, **2** (3/4) (Oxford: Pergamon Press).

ICRP, 1980, *Limits for intakes of radionuclides by workers*. ICRP Publication 30, Part 2. *Ann. ICRP*, **4,** (3/4) (Oxford: Pergamon Press).

KELLY, G. N., and HEMMING, C. R., 1984, *The radiological consequences of degraded core accidents for the Sizewell PWR: the influence of adopting increased risk coefficients for exposures at high doses*. NRPB-M108 (Chilton: NRPB).

LOUTIT, J. F., MARLEY, W. G., and RUSSELL, R. S., 1960, Appendix H to *The hazards to man of nuclear and allied radiations*. Second report to the MRC. Cmnd 1225 (London: HMSO), pp. 129–139.

MAYCOCK, G., and VENNART, J., 1958, Iodine-131 in human thyroids following the Windscale reactor accident. *Nature*, **182,** 1545–1547.

MILK MARKETING BOARD, 1981 (private communication).

MUNRO, D. S., 1980, Dysplasia and neoplasia. *Recent Results in Cancer Research, Thyroid Cancer*, edited by W. Duncan (Springer-Verlag).

NRPB, 1981, *Living with radiation*. Chilton, National Radiological Protection Board (London: HMSO).

NRPB/CEA, 1979, *Methodology for evaluating the radiological consequences of radioactive effluents released in normal conditions*. Joint report by the National Radiological Protection Board and the Commissariat a l'Energie Atomique. Doc. No. V/3865/79 (Luxembourg: CEC).

Office of Population Censuses and Surveys, 1971–1983, *The Registrar General's Statistical Review of England and Wales for the three years 1968–70 (Supplement on Cancer), and Cancer Statistics Registrations 1971–79*, Series MB1 No. 1 to No. 11 (OPCS).

POCHIN, E., *Proof of Evidence for the Sizewell B Inquiry. The Biological Bases of the Assumptions made by NRPB in the Calculation of Health Effects*, Chilton, NRPB/P/2(Rev) (1983) and NRPB/P/2(Rev) Add 1 (1984).

RON, E., and MODAN, B., 1982, Thyroid, *Cancer Epidemiology and Prevention*, edited by D. Scholtenfeld and J. F. Fraumeni (W. B. Saunders Company).

SIMMONDS, J. R., and CRICK, M. J., 1982, *Transfer parameters for use in terrestrial foodchain models*. NRPB-M63 (Chilton: NRPB).

SIMMONDS, J. R., and LINSLEY, G. S., 1980, *A methodology for the evaluation of the collective dose from radioactivity in the terrestrial food chains*. NRPB-R97 (London: HMSO).

SIMMONDS, J. R., and LINSLEY, G. S., 1982, Parameters for modelling the interception and retention of deposits from atmosphere by grain and leafy vegetables. *Hlth Phys.*, **43,** 679–691.

STEWART, N. G., and CROOKS, R. N., 1958, Long-range travel of the radioactive cloud from the accident at Windscale. *Nature*, **182,** 627–628.

STEWART, N. G., CROOKS, R. N., and FISHER, E. M. R., 1961, declassified 1962, *Measurements of the radioactivity of the cloud from the accident at Windscale: Data submitted to the I G Y*. AERE-M857 (Harwell: UKAEA).

TAYLOR, P., 1981, *The Windscale fire, October 1957; Report for the Union of concerned Scientists, Cambridge, Mass, USA*. RR-7 (Oxford: Political Ecology Research Group).

TIPLADY, P., 1983, *Cancer Registrations by Health District of Cumbria, 1969–78*, private communication—East Cumbria Health Authority, Department of Community Medicine, Carlisle.

UNSCEAR, 1977, *Sources and Effects of Ionising Radiation*, Report of the United Nations Scientific Committee on the Effects of Atomic Radiation to the General Assembly, with annexes. (New York: UN).