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An Assessment of the Radiological Impact of the Windscale Reactor Fire, October 1957

M.J. Crick and G.S. Linsley

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November 1982

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NRPB-R135

AN ASSESSMENT OF THE RADIOLOGICAL IMPACT OF THE WINDSCALE REACTOR FIRE OCTOBER 1957

M J Crick and G S Linsley

ABSTRACT

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 atmosphere. The resultant cloud was 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. An assessment of the associated collective dose has been performed; the results and the methods used for calculating this quantity are reported here.

The collective effective dose equivalent commitment from the release is estimated to have been 1.2×10^3 man Sv. The route of exposure which contributed the most to the collective dose was the ingestion of contaminated milk. Iodine-131 was the most important radionuclide, contributing nearly all of the collective dose to the thyroid and the largest part of the collective effective dose. In the longer term the contribution of caesium-137 to the collective effective dose via external irradiation from ground deposits and the ingestion of contaminated foodstuffs became significant.

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

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CONTENTS

		Page No.
1.	INTRODUCTION	1
2.	GENERAL DESCRIPTION OF THE ACCIDENT	2
3.	PROCEDURE FOR COLLECTIVE DOSE EVALUATION	3
	3.1 Quantities and concepts	3
	3.2 Evaluation of the spatial distribution of activity	6
	3.2.1 Derivation of values for the integrated concentration of ^{131}I in milk	6
	3.2.2 Matrices of ^{131}I distribution in environmental materials	8
	3.2.3 Matrices for the distribution of other nuclides in environmental materials	10
	3.3 Evaluation of other quantities needed in the collective dose calculation	11
	3.4 Evaluation of the population and agricultural production distributions	13
4.	CALCULATION OF THE COLLECTIVE DOSE EQUIVALENT COMMITMENT TO THE THYROID, S_T^c	13
5.	CORRELATION BETWEEN PREDICTED AND MEASURED INDIVIDUAL THYROID DOSES IN LONDON, LEEDS AND CUMBRIA FROM ^{131}I	15
	5.1 London	16
	5.2 Leeds	17
	5.3 Cumbria	18
6.	CALCULATION OF THE COLLECTIVE EFFECTIVE DOSE EQUIVALENT COMMITMENT, S_{eff}^c	19
7.	DISCUSSION OF THE RESULTS	20
	7.1 Collective dose equivalent commitment to the thyroid	20
	7.2 Collective effective dose equivalent commitment	22
8.	HEALTH EFFECTS IN THE EXPOSED POPULATION	22
9.	ACCURACY OF THE RESULTS	24
10.	CONCLUSIONS	25
11.	REFERENCES	26
List of Tables (see below)		29
List of Figures (see below)		36
APPENDIX A:	Factors to be applied to the collective dose estimates to account for the increased sensitivity of children to internal irradiation.	47

TABLES

1.	Estimates of radionuclides released.	29
2.	Values used for the matrix of integrated ^{131}I activity in milk.	30
3.	The origins of contaminated milk distributed to Greater London.	31
4.	Comparison between measured and predicted thyroid doses to individuals living in the Windscale area.	32

1004676

Page No.

5. Collective dose equivalent commitment to the thyroid (S_T^c). 33

5A. Collective dose equivalent commitment to the thyroid ($S_T^{c'}$) corrected for the age distribution of the population. 33

6. Collective effective dose equivalent commitment (S_{eff}^c). 34

6A. Collective effective dose equivalent commitment ($S_{eff}^{c'}$) corrected for the age distribution of the population. 34

7. Comparison between estimates of dose by this assessment and the assessment by Taylor. 35

FIGURES

1. Deposition of ^{131}I in N W England. 36

2. The radial co-ordinate grid adopted for the representation of the spatial distribution of environmental materials and their degree of contamination following the Windscale accident 1957. 37

3. The radial co-ordinate grid adopted for the representation of the spatial distribution of environmental materials and their degree of contamination for Europe. 38

4. Comparison of ^{131}I concentration in milk from a farm close to Windscale with predicted concentration using NRPB models. 39

5. Pathways by which radionuclides can irradiate members of the public. 40

6. 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. 41

7. 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. 42

8. Contribution to the collective thyroid dose equivalent commitment, S_T^c. 43

9. Contribution to the collective effective dose equivalent commitment, S_{eff}^c. 44

10. Estimates of mean adult thyroid dose equivalents in England and Wales resulting from the 1957 release. 45

11. Variation of the annual collective effective dose equivalent (S_{eff}^c) as a function of time after release. 46

1004677

As from 1 April 1978 NRPB adopted the International System of Units (SI). The relationship between the new SI units which are used in this report and the previous units are shown in the table below.

Quantity	New named unit and symbol	In other SI units	Old special unit and symbol	Conversion factor
Exposure	-	$C\ kg^{-1}$	röntgen (R)	$1\ C\ kg^{-1} \sim 3876\ R$
Absorbed dose	gray (Gy)	$J\ kg^{-1}$	rad (rad)	1 Gy = 100 rad
Dose equivalent	sievert (Sv)	$J\ kg^{-1}$	rem (rem)	1 Sv = 100 rem
Activity	becquerel (Bq)	s^{-1}	curie (Ci)	$1\ Bq \sim 2.7 \times 10^{-11}\ Ci$

1004678

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 major radionuclide in ground deposits from the plume was found to be ^{131}I, which was preferentially released due to its volatility. Radionuclides of iodine are readily transferred to the population via milk from cows grazing on contaminated pasture. Iodine once taken in by the body is concentrated in the thyroid gland which would have received the highest doses from 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 average radiation doses to the thyroids of the local population were typically 5 to 20 mSv for adults and 10 to 60 mSv for children[8]. Without the milk ban it was thought at the time 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 doses inferred from measured thyroid activity were 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[1,6,8,19]. 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 to individuals living in other parts of England[9,10]. 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 recognised 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[39] and by Taylor[28]. 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 this report 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. They have been used to construct matrices describing the geographic distribution of activity in environmental materials resulting from the release. These 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

1004679

various distance bands from the release point. The activity distribution matrices also allow dose estimates for individuals at particular locations to be made; 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.

2. GENERAL DESCRIPTION OF THE ACCIDENT

The fire at Windscale No 1 Pile in October 1957 is described fully in the report of the Committee of Inquiry set up immediately after the accident[1]. 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 oxidised 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[6], based mainly on measurements of the contamination in environmental materials around Windscale directly after the incident, and by Clarke[7] using a computer code to model the fission product inventory of the reactor. These estimates are reproduced in Table 1. 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[2]; the pattern of deposition of ^{131}I is discussed by Chamberlain[3].

The meteorological conditions varied during the release and produced a complex dispersion pattern[2]. From noon on 10 October the winds at Windscale were light and variable, with a south-westerly tendency. As the accident 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 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[3], 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[2]; in recent years its path has been calculated by the use of trajectory analysis[4].

1004680

The most important nuclide as far as health consequences to the population were concerned 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 high milk intake rate, as well as a high committed dose per unit activity ingested relative to adults). 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[8]. These restrictions were introduced in the period 11 - 13 October and the final area restricted was 520 square kilometres 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[8].

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[8].

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, ie, the collective dose equivalent commitment.

The two radiological quantities which have been evaluated in this assessment are the collective thyroid dose equivalent commitment, S_T^c and the collective effective dose equivalent commitment, S_{eff}^c. 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

1004681

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 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 used in this study as an indicator of the health detriment associated with the release, since a number of radionuclides were released other than isotopes of iodine. 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[31]. 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 $S_T{}^c$) has been described more fully in another publication[16]. The collective effective dose equivalent commitment (S^c_{eff}) which is the integral over all time of the collective effective dose equivalent rate ($\dot{S}^c_{eff}$) may be conveniently expressed as the sum of contributions from external and internal irradiation.

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

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 collective 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) ingestion of contaminated milk, drinking water and other foodstuffs;

(ii) inhalation of radioactive materials in the plume;

(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

1004682

angle, Θ, relative to the discharge point. These variations may be approximated in the manner indicated in Figures 2 and 3. 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:

$$S^c_{eff,ext}(j) = \sum_{dm,\Theta n} N(dm,\Theta n) \int_o^\infty \dot{H}_{eff,ext}(dm,\Theta n,j,t)dt \quad \text{..... (2)}$$

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.

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

$$S^c_{eff,inh}(j) = H^u_{50,eff,inh}(j)\ I \sum_{dm,\Theta n} N(dm,\Theta n) \int_o^\infty \chi(dm,\Theta n,j,t)dt \quad \text{... (3)}$$

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:

$$S^c_{eff,ing}(j) = H^u_{50,eff,ing} \cdot F_1(j,g) \cdot F_2(g) \cdot \sum_{dm,\Theta n} \{P(dm,\Theta n,g) \times \int_o^\infty C(dm,\Theta n,j,g,t)dt\} \quad \text{..... (4)}$$

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 (ie, 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

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

The collective thyroid dose equivalent commitment, S^c_T, has been calculated using

1004683

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 preceeding equations are described.

3.2 Evaluation of the spatial distribution of activity

Widespread surveys were made to determine the ^{131}I concentration in various environmental materials in the days following the accident. These are reported in the literature as follows:

Measurements	References	Area surveyed
1. Milk contamination	Booker[11]	Cumbria/northern England (some in mid & southern England & Wales)
2. Herbage contamination	Booker[11]	Cumbria (some in England and Wales)
3. Total ground deposition	Chamberlain[3]	Northern England
4. Integrated concentration in air	Stewart & Crooks[5]	England and Wales
" " "	Loutit et al[6]	Europe

A few measurements were made of the activities in the environment of other nuclides released[8].

For each site where a measurement was made, it is assumed that there is an implied value for the integral to infinity of the ^{131}I concentration in milk; from equation (4), this may be expressed as:

$$\tilde{C}(I,M) = \int_0^\infty C(I,M,t)dt$$

By applying appropriate environmental transfer models, the four types of measurement of ^{131}I can all be converted into the integrated ^{131}I concentration in milk. The results from different types of measurement can then be compared to establish the distribution of ^{131}I activity over the UK and the continent. This distribution is then used as the basis for estimating the spatial distribution of other significant nuclides in the release.

3.2.1 Derivation of values for the integrated concentration of ^{131}I in milk

(a) $\tilde{C}(I,M)$ from ^{131}I activity concentration measurements in milk

Booker[11] reported measurements of the ^{131}I concentration in milk at various sites in Northern England. He corrected the observed measurements for radioactive decay since 11 October, 1957, using the 5-day effective half-life with which they had been observed to decay. This 5-day half-life may be interpreted as being the combined effect of the radioactive half-life of ^{131}I of 8 days and the 14-day retention half-life of activity on pasture.

The integrated concentration, $\tilde{C}(I,M)$, of ^{131}I in milk has been estimated from these measurements with the aid of a time-dependent pasture-cow-milk model for ^{131}I[18,29]. It has been used to calculate the relationship between the

1004684

values given by Booker[11] for the concentration of ^{131}I in milk extrapolated to t=0, (see Figure 4) and the integral of the ^{131}I concentration $\tilde{C}(I,M)$. The ratio of these quantities is predicted by the model to be 5.3 d. Thus, the integral of the concentration of ^{131}I in milk may be obtained from Booker's results using the following relationship:

$\tilde{C}(I,M)$ = 5.3 d x concentration of ^{131}I in milk extrapolated to t=0 (Bq d l^{-1})

In using Booker's measurements decay-corrected to 11 October, no allowance has been made for the finite duration of the release, nor for the time taken for travel of the plume. However, as previously stated, the majority of the release was thought to have occurred in the period from noon on 10 October to noon on 11 October, with peaks at midnight and at 0900 hours. Decay-correcting to 0000 hours on the 11th therefore gives an average effect. Also since Booker's report of milk measurements is confined to Cumbria and parts of the surrounding counties, the time delay between the release from the stack and deposition on the ground was small, and it is not unreasonable for these purposes to assume that all deposition in this region occurred at midnight.

(b) $\tilde{C}(I,M)$ from measurements of activity on herbage

Booker[11] gives the ^{131}I activity on herbage at a few sites about the country, decay-corrected back to 10 October, 1957. He gives an empirical ratio between the activity on herbage (μCi m^{-2}) and activity in milk (μCi l^{-1}) extrapolated to t=0, as 11 l m^{-2}. The integrated ^{131}I concentration in milk, $\tilde{C}(I,M)$ is given by:

$\tilde{C}(I,M) = \frac{5.3}{11}$ x concentration of ^{131}I on herbage at t=0 (Bq d l^{-1})

(c) $\tilde{C}(I,M)$ from measurements of ground deposition

Chamberlain reported levels of the ^{131}I ground deposition over the north-west England region from which he estimated the contour lines on a map of the region which are shown in Figure 1. They were mostly obtained from a gamma-radiation survey using a sensitive detector in the period shortly after the release. The values are approximately corrected for radioactive decay between the time of release and the time of measurement. They can be correlated with Bookers' measurements[11] of the activity on herbage, and thereby related to $\tilde{C}(I,M)$ by the following relationship:

Concentration of ^{131}I on herbage at t=0 = 0.82 x ground deposit of ^{131}I (Bq d l^{-1})[11]

$$\therefore \quad \tilde{C}(I,M) = 0.40\ U(I)$$

where U(I) is the ground deposit density of ^{131}I in Bq m^{-2}.

The transfer factor from ground deposit to milk observed by Booker is less than that used in some models[19,29] by a factor of about four. There are various possible reasons for this difference concerned with the season of the year, the retention of the deposit on herbage, the fraction of stored feed or concentrates in cattle diet, etc. However, in this assessment the data of Booker were used.

1004685

(d) $\tilde{C}(I,M)$ from measurements of concentrations in air

Measurements of ^{131}I concentrations in air at various locations in England and Wales and in parts of Europe are another source of data by which $\tilde{C}(I,M)$, the integrated concentration of ^{131}I in milk, may be estimated. The measurements in air may be related to ground deposition by means of a ratio, known as the deposition velocity, v_d(m s^{-1}), defined as

$$v_d(I) = \frac{\text{total deposited activity per unit area (Bq m}^{-2})}{\text{time integral of the air concentration (Bq s m}^{-3})} = \frac{U(I)}{\tilde{\chi}(I)}$$

The deposition velocity for ^{131}I appears to have varied with distance from the Windscale site. In the northern counties Lancashire and Yorkshire, v_d was estimated to be in the range 3×10^{-3} to 5×10^{-3} m s^{-1}[3], whereas further away from Windscale, at Harwell in Oxfordshire, the values were around 1×10^{-3} m s^{-1}[3].

Chamberlain[3] has suggested that the variation in v_d for ^{131}I with distance from Windscale was because the radioiodine was emitted partly as a hot gas, which would have cooled rapidly to a vapour form, and partly in a form adsorbed on to sub-micron particles. The observed higher v_d values closer to the site would have been associated with the vapour form, which deposits more rapidly due to its higher molecular diffusivity. As the plume was progressively depleted of the iodine vapour, the deposit would have become relatively more enhanced in the particulate form with its associated lower deposition velocity. The effects of rainfall and the particular atmospheric conditions could theoretically also be great, but the available information is insufficient to say whether or not the differences in deposition velocities can be attributed to these factors.

Because the data are insufficient to enable the variation of $v_d(I)$ as a continuous function of distance to be assessed, a single value of $v_d(I) = 3 \times 10^{-3}$ m s^{-1} has been adopted as an average for the UK, and a value of $v_d(I) = 1 \times 10^{-3}$ m s^{-1} is used for the continent.

The expression for the integrated concentration of ^{131}I in milk, $\tilde{C}(I,M)$ may then be written:

$$\tilde{C}(I,M) = 0.40 \quad v_d(I) \quad \tilde{\chi}(I) \quad (\text{Bq d l}^{-1})$$

where $\tilde{\chi}(I)$ is the integrated concentration of ^{131}I in air.

3.2.2 Matrices of ^{131}I distribution in environmental materials

The procedures outlined in the previous section allow values for the integrated concentration of ^{131}I in milk, $\tilde{C}(I,M)$, to be obtained from four different sources. The data base is limited, however, and only allows a partial spatial distribution of activity levels in the UK to be established. It has therefore been necessary to estimate activity levels at some locations by means of extrapolation based on assumptions of the plume trajectory taken together with the nearest measurements made at the time.

1004686

The scheme of annular segments used in the calculations of collective dose is as described in Section 3.1 and is illustrated in Figures 2 and 3. The radial sectors in the scheme for the UK (Figure 2) are 15° wide and there are 20 distance bands extending out to 500 km from the Windscale site. The scheme for the continent (Figure 3) has sectors 30° wide with distance bands between 500 and 1600 km from Windscale. The matrices for $\tilde{C}(I,M)$ are reproduced for the UK and for the rest of Europe in Tables 2a and 2b respectively.

The matrices for $\tilde{C}(I,M)$ have been applied for the estimation of the spatial distribution of other environmental ^{131}I concentrations required in the collective dose evaluation. The integrated concentration of ^{131}I in air, $\tilde{\chi}(I)$, is required for the estimation of the collective dose via the inhalation pathway. Although this quantity was evaluated by direct measurement at some locations, for the majority it has to be based on milk measurements. The matrix of ^{131}I concentration in air is scaled from the matrix of integrated ^{131}I concentration in milk using the following relationship, derived in Section 3.2.1 (d)

$$\tilde{\chi}(I) = \frac{\tilde{C}(I,M)}{0.4\ v_d(I)} \qquad (\text{Bq d m}^{-3})$$

The total ground deposit of ^{131}I, U(I), is required for the estimation of the collective dose from external irradiation. Although this quantity was evaluated by direct measurement at some locations, at others it has had to be obtained by using the milk matrix. The deposition matrix is scaled from the milk matrix for ^{131}I using the relationship derived in Section 3.2.1(c):

$$U(I) = \frac{\tilde{C}(I,M)}{0.40} \qquad (\text{Bq m}^{-2})$$

The collective dose from the consumption of green vegetables following the contamination of agricultural land may be estimated using a matrix of integrated concentrations in each foodstuff of interest. The models described by Simmonds and Crick[29] are used to approximate the contamination on green vegetables following a single deposit. For ^{131}I, with its short radioactive half-life, the concentration in vegetables is dominated by the direct deposition from the plume on to the plant surface; the contribution from the process of root uptake from the contaminated soil is small in comparison. The model assumes that production is constant throughout the year with a mean period between cropping of the vegetables of 100 days. The process of direct deposition is modelled by assuming that 0.3 of the initial deposit is intercepted by the surfaces of the vegetables and that the half-life of activity on the vegetation is 14 days.

The integrated concentration of ^{131}I in green vegetables, $\tilde{C}(I,V)$ is required to evaluate the collective dose via this pathway (equation (4)) and using the models mentioned above is given by:

$$\tilde{C}(I,V) = 2.2\ U(I) = 5.5\ \tilde{C}(I,M) \qquad (\text{Bq d kg}^{-1})$$

1004687

3.2.3 Matrices for the distribution of other nuclides in environmental materials

Estimates of the quantities of individual radionuclides present in the release are given in Table 1. Few measurements were made of the environmental concentrations of nuclides other than ^{131}I and therefore the information assembled in Table 1 must be used with the environmental measurements of ^{131}I discussed previously. The values of the ratio of the quantities of the various nuclides in the release to that of ^{131}I assumed in this assessment are also shown in Table 1.

The concentrations of the other nuclides in environmental materials have been estimated from a knowledge of the nuclide/^{131}I release ratio together with the ^{131}I concentration matrices. Corrections are necessary, however, to take account of variations of the ratio in environmental materials due to differences in deposition velocity and radioactive half-lives of the other nuclides compared with radioiodine. Near Windscale it can be assumed that the ratios in air are similar to the estimates of the ratios of nuclide/^{131}I released[7].

Estimates of the $^{137}Cs/^{131}I$ release ratio have been made by several authors. Clarke[7] calculated a value of 0.076 using a computer code to predict fission product inventory with certain assumptions about reactor fuel burn-up. Chamberlain[27] has recently reviewed information that was previously unpublished and endorses the value of 0.03 estimated by both Beattie[32] and Loutit[6] as being as good an estimate as is possible. The value of 0.03 will be used in this report.

Measurements of ^{137}Cs concentrations in air made at various locations showed that the ratio of ^{137}Cs to ^{131}I changed markedly with distance from Windscale; it increased from 0.03 at Windscale to 0.11 at Harwell, Oxfordshire, to 0.20 in Germany and to 0.36 in Norway[5]. A mean of measurements made at ten sites in the UK, south of Lancaster, was 0.11 ± 0.02. The increase in the $^{137}Cs/^{131}I$ ratio may be associated with the short radioactive half-life of ^{131}I (8 days) as compared with ^{137}Cs (30.1 y) and the finite transit time of the plume, together with the more rapid depletion from the plume of iodine vapour as described earlier. Chamberlain[3] has suggested that the caesium released in the fire rapidly became associated with particles in the air and so was deposited at a slower rate compared with the iodine vapour throughout the duration of the plume travel.

The matrices of ^{137}Cs concentrations in air and ground deposits have been assembled by estimating the ^{137}Cs enhancement factor, f_r, as a function of distance, r, from Windscale and applying it to the ^{131}I matrices.

$$f_r = \frac{(^{137}Cs/^{131}I) \text{ concentrations in air at distance } r}{(^{137}Cs/^{131}I) \text{ concentrations in air at Windscale } (r=0)}$$

Thus at Windscale, $f_0 = 1$, and at Harwell ($r = 350$ km), $f_{350} = 3.7$. Inter-

1004688

polation between these points has been achieved by assuming that the plume travelled from Windscale towards the south, that the trajectory was straight and, in order to fit the observed variation of the $^{137}Cs/^{131}I$ ratio, that it can be represented by the relation $f_r = r^{0.223}$ for distances between r = 1 and 500 km. Using these assumptions a matrix of integrated concentration of ^{137}Cs in air has been assembled. The integrated concentration of ^{137}Cs in air in segment (dm,θn) is given by

$$\tilde{\chi}(Cs) = A_{Cs/I} \cdot f_{dm} \cdot \tilde{\chi}(I) \qquad (Bq\ s\ m^{-3})$$

where $A_{Cs/I}$ is the ratio of ^{137}Cs to ^{131}I in the release ($A_{Cs/I} = 0.03$)

$\tilde{\chi}(I)$ is the integrated concentration of ^{131}I in air in segment (dm,θn)

and f_{dm} is the mean of f_r for the distance band d_m.

For the rest of Europe a single value of 0.20 was assumed for the ratio of ^{137}Cs to ^{131}I in air[5].

Similarly, the matrix for ^{137}Cs ground deposition was obtained by applying the following relation to the matrix of integrated concentration of ^{131}I in air.

$$U(Cs) = A_{Cs/I} \cdot f_{dm} \cdot v_d(Cs) \cdot \tilde{\chi}(I) \qquad (Bq\ m^{-2})$$

where U(Cs) is the total ground deposit of ^{137}Cs

and $v_d(Cs)$ is the deposition velocity of ^{137}Cs, assumed to be 0.15 x $v_d(I)$ (4.5×10^{-4} m s^{-1}) as reported for both the UK and continent[5].

Matrices for other radiologically significant nuclides in the release were assembled by comparison with the ^{137}Cs matrices making the assumption that they deposited from the plume in a similar manner to ^{137}Cs[5], with the exception of ^{132}Te. This nuclide has a half-life of 78 h and its activity would therefore have fallen off much more quickly with distance than ^{137}Cs ($t_{\frac{1}{2}}$ = 30 y), behaving more like ^{131}I. Chamberlain[27] notes that the $^{132}Te/^{131}I$ ratios seemed reasonably constant across the country. The following expression is assumed:

$$\tilde{\chi}(Te) = A_{Te/I} \cdot \tilde{\chi}(I)$$

Matrices for the radiologically significant nuclides and pathways were evaluated using the models described in Simmonds and Crick[29]. These were adapted for the case of a single deposit of activity, and thus the matrix of deposition for a given nuclide is readily converted into a matrix of integrated food concentration.

3.3 The evaluation of other quantities needed in the collective dose calculation

The spatial distribution of the effective dose equivalent commitment from ground deposits, $S^c_{eff,ext}$ (equation (2)), has been evaluated by using the

1004689

matrices for ground deposition described in previous sections. For a radionuclide, j,

$$S_{eff,ext}(j) = 0.5 \times Q_j \times U(j)$$

where Q_j is the effective dose equivalent commitment per unit deposit of a radionuclide j. This quantity has been evaluated using the model described in (16), and takes account of attenuation due to migration of the nuclide down the soil profile and due to surface roughness.

0.5 is a factor to take account of shielding by buildings, and the average time spent outdoors[34].

U(j) is the total ground deposit of radionuclide j (Bq m^{-2}). Its spatial distribution is obtained from the matrices described earlier.

The most significant nuclides for this pathway are ^{137}Cs, ^{131}I and ^{132}Te. (For ^{131}I, $Q_I = 2.5 \times 10^{-10}$ Sv per Bq m^{-2}, for ^{132}Te, $Q_{Te} = 6.25 \times 10^{-10}$ Sv per Bq m^{-2} and for ^{137}Cs, $Q_{Cs} = 1.1 \times 10^{-7}$ Sv per Bq m^{-2})[16]

The committed effective dose equivalent per unit intake, $H^u_{50,eff}$, and the committed thyroid dose equivalent per unit intake, $H^u_{50,T}$, which are required for the evaluation of $S^c_{eff,inh}$ and $S^c_{eff,ing}$ (equations (3) and (4)) have been taken from ICRP Publication 30[25]. Both values relate to adults and separate consideration has to be given to children in the exposed population. Infants are particularly susceptible to ^{131}I contamination in milk because their milk intake rate is comparable with that of adults while their dose per unit intake by ingestion is significantly higher. Consideration is given to children in the population and the effects on radiological impact in Appendix A.

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% of the milk produced in England, Scotland and Wales was consumed as fresh milk[12] with a mean delay of 2 days between production and consumption[33]. The remaining 30% was used for butter and cheese production with a mean delay of 3 months[33]. The factors $F_1(j,g)$ and $F_2(g)$ in equation (4), as applied to milk, may therefore be expressed as

$$F_1(j,M)\ F_2(M) = 0.7 \exp\left(\frac{-2 \times 0.693}{t_{j\frac{1}{2}}}\right) + 0.3 \exp\left(\frac{-90 \times 0.693}{t_{j\frac{1}{2}}}\right)$$

where $t_{j\frac{1}{2}}$ is the radioactive half-life of the radionuclide j, in days.

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

$$F1(j,v) = \exp\left(\frac{-8 \times 0.693}{t_{j\frac{1}{2}}}\right)$$

Only a fraction of the activity in harvested green vegetables is ingested by man

1004690

because of losses which occur during food preparation. It is assumed that the fractional loss is 80%[17], thus, the factor $F_2(g)$ in equation (4) for green vegetables is

$$F_2(V) = 0.2$$

3.4 Evaluation of the 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 x 1 km and 5 x 5 km squares of the National Grid[35,21]. 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), (3) and (4).

The data contained in both of these arrays are of more recent origin than 1957, and consideration has to be given to the validity of using them for this assessment. The population data were obtained from the 1971 census. Comparisons of the distributions of populations by county in 1957 and 1971 indicate that scaling in relation to national totals in the two years concerned is unlikely to affect the dose calculation by more than 10%. Similarly for the milk production data scaling has been carried out on the basis of national production in 1957/58[12,13] compared with that in 1972. Examination of county data indicates that the fractional production by county has changed little in the intervening years. For green vegetables no scaling for the difference in production between 1957 and 1972 was applied. This approximation is unlikely to affect the collective dose estimates significantly.

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[16] and have been converted into the radial co-ordinate form required (Figure 3). It has been assumed that to a first approximation the population and foodstuff production in each grid square can be scaled by similar ratios as in the UK between 1957 and 1971.

4. CALCULATION OF THE COLLECTIVE DOSE EQUIVALENT COMMITMENT TO THE THYROID, S_T^c

The pathways by which radionuclides can give rise to irradiation of members of the public can be represented schematically as in Figure 5. The dose to the thyroids of the population exposed to the Windscale release was dominated by the contributions of the inhalation and ingestion pathways because of the predominance of radioiodine in the radioactive materials released. 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_T^c) is calculated using equations (3) and (4) for the inhalation, milk and green vegetable pathways. S_T^c has been estimated for the milk pathway taking account of the collective dose saved by the imposition of a

1004691

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.

The former quantity was estimated by modifying values in the integrated milk concentration matrix in the areas from where the distribution of milk was interrupted. The conditions for removal of the milk ban were that the ^{131}I activity should be less than 0.1 μCi l^{-1} (3700 Bq l^{-1})[8]. If milk was consumed immediately after restrictions were removed, the maximum integrated activity of ^{131}I which could have been ingested is

$$\int_0^\infty 3700 \exp\left(\frac{-0.693t}{5}\right) dt = 26700 \text{ Bq d } l^{-1}$$

assuming a 5-day effective half-life on pasture. The matrix of integrated ^{131}I activity in milk, $\tilde{C}(I,M)$, was modified so that the segments within the ban area[8] were ascribed the above value for $\tilde{C}(I,M)$ while those outside remained unchanged. This assumption allows no delay period between the levels reaching 0.1 μCi l^{-1} (3700 Bq l^{-1}) and the milk being redistributed but, equally, no allowance has been made for activity ingested before the ban could be bought into effect[19]. There is likely to be some counterbalancing between the two assumptions, but in any case neither of the assumptions is likely to have a significant effect on the estimates of collective dose.

The collective dose to the thyroid from ^{131}I in milk to European populations was estimated on the basis of the measurements reported by Loutit et al[6] for integrated concentrations of ^{131}I in air, $\tilde{\chi}(I)$. A deposition velocity, $v_d(I)$ of 1.0×10^{-3} m s^{-1} (Section 3.2(d)) was used to obtain the distribution of $\tilde{C}(I,M)$ in Europe. Only a few measurements of $\tilde{\chi}(I)$ were made in Europe and the estimate of collective dose from activity in this area is only approximate.

Dunster et al[8] reported that the concentrations of ^{131}I in reservoirs and streams close to Windscale were in the range 3.7 Bq l^{-1} 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[29] 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[33] and for meat of 7 days[16] between milking and slaughter respectively, and the consumption of the foodstuff, and assuming average adult intake rates for milk and meat of 150 kg y^{-1} and 25 kg y^{-1}[15] 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% 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[33] 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)[33] and the collective dose due to ^{131}I in this pathway is again likely to be insignificant. It has therefore been neglected. Other foodstuffs, which are considered to be potentially small contributors to collective dose have also been neglected in this assessment.

Tellurium-132 (^{132}Te) ($t_{\frac{1}{2}}$ = 78 h) which decays to ^{132}I ($t_{\frac{1}{2}}$ = 2.4 h) also contributes to the collective thyroid dose, S_T^c, via the inhalation pathway. The collective thyroid dose due to this nuclide via the ingestion pathway can be shown to be small in comparison to that due to ^{131}I and it has been neglected.

The contribution of other nuclides present in the release to the collective thyroid dose has been neglected as small 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_T^c) are given in Table 5 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.

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 data which can be used to examine the reliability of the data base described in previous sections.

The procedure described earlier (Section 3.1) 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

1004693

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.

5.1 London

Maycock and Vennart[10] 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 of which were made on 31 October. The data are reproduced in Figure 6. 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 this 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 ± 80 μSv to an average adult individual living in London. Their model has several shortcomings; it only allows 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[11], 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[2,6], and was found to be 15.7 Bq d m^{-3}. Assuming an inhalation rate for adults of 23 m^3 d^{-1}[15] and a committed dose equivalent to the thyroid per unit activity inhaled, $H^u_{50,T,inh}$, of 2.9 x 10^{-7} Sv Bq^{-1}[25], the average thyroid dose equivalent to people living in London from inhalation, $\bar{H}_T(I,inh)$ is estimated to have been 100 μSv.

The volumes of milk supplied to Greater London from various counties in England and Wales in June 1956 are given in Table 3[22]. This information, taken together with estimates of the mean integrated concentration of ^{131}I in milk, $\tilde{C}(I,M)$, for each county from the matrix described earlier enables an estimate of the average integrated concentration of ^{131}I, $\tilde{C}_L(I,M)$, in consumed milk in London to be derived. The dose equivalent to the thyroid of the average adult milk consumer in London $H_T(I,M)$ as a result of the Windscale fire is thus

$$H_T(I,M) = \tilde{C}_L(I,M) \times I(M) \times H^u_{50,T,ing} \times F_1(I,M)$$

where I(M) is the per caput milk intake rate of adults = 150 l y^{-1}[15]

$H^u_{50,T,ing}$ is the adult thyroid committed dose equivalent per unit ^{131}I ingested (4.8 x 10^{-7} Sv Bq^{-1})[25]

1004694

$F_1(I,M)$ is a factor to account for the decay of ^{131}I between production and consumption of the contaminated milk ($F_1(I,M) = 0.84$)

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

Substituting these values in the equation gives $\bar{H}_T(I,M) = 180$ μSv.

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 for their production. The integrated ^{131}I activity in UK green vegetables, $\tilde{C}(I,V)$, is estimated to be ~2 Bq y 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 y^{-1}[15], the average thyroid dose equivalent, $\bar{H}_T(I,V)$, from ingestion of ^{131}I in green vegetables is 40 μSv.

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

$$\bar{H}_T(I) = \bar{H}_T(I,M) + \bar{H}_T(I,inh) + \bar{H}_T(I,V)$$

The value estimated in this way for $\bar{H}_T$ 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 two 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[29] models, the time-distribution of activity in milk and green vegetables consistent with the thyroid dose estimates can be predicted (eg, Figure 4). The lower curve in Figure 6 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 in the estimate, particularly with regard to the estimate of contamination levels in milk and green vegetables.

The upper curve in Figure 6 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 litres per day of milk 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[9].

1004695

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 7. 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 recommended by ICRP for Standard Man[36]. 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}[19]. Applying the models described in Section 3.2.1, 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

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

The two people in the measurement study were reported to consume an average of about 1.2 pints of milk per day[9] (250 l y^{-1}). The dose equivalent to their thyroids from drinking milk with an integrated activity concentration of 4300 Bq d l^{-1} is estimated to be 1.1 mSv taking into account a delay of 2 days between production and consumption.

From the relationship in Section 3.2.2 the integrated concentration in air, $\tilde{\chi}(I)$, which would give rise to a $\tilde{C}(I,M)$ value of 4300 Bq d l^{-1} in milk is 41 Bq d m^{-3} using a deposition velocity, v_d of 3×10^{-3} m s^{-1}. This results in a thyroid dose equivalent of 0.27 mSv from inhalation.

The dose from consumption of green vegetables is 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, $\bar{H}_T$, 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 Section 5.1. The predicted curve presented in Figure 7 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[8]. Clarke[7] has

1004696

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, $\tilde{\chi}(I)$. The results from this calculation are presented along with Clarke's[7] predictions and Dunster's measurements in Table 4.

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 results calculated here do not take account of any additional dose due to milk 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 do not show this effect.

Overall, the comparisons of measured and predicted thyroid ^{131}I contents for people in London, Leeds and Cumbria encourage confidence in the models and database 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}, to populations within various distance bands from the Windscale site has been assessed using the methodology outlined in Section 3; the results are presented in Table 6. The nuclides which proved to be of significance in the inhalation pathway were ^{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.

As discussed in Section 3.2, with the exceptions of ^{131}I and ^{132}Te, the nuclides were assumed to be deposited from the plume at the same rate as ^{137}Cs. The distribution matrices for ^{137}Cs integrated air concentration, $\tilde{\chi}(Cs)$, and ground deposit, U(Cs), were scaled in proportion to the activities of the other nuclides present in the release, in order to obtain their distribution patterns. For the inhalation pathway, no corrections were made for radioactive decay as the shortest half-life of the nuclides considered (other than ^{131}I and ^{132}Te) was 34 d for ^{129m}Te and there would have been little decay in the time between release and intake.

In assessing the contribution to S^c_{eff} from foodchain 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.

The assessment of the contribution to S^c_{eff} due to direct irradiation from radioactive material in the cloud is based on the calculations of cloud-γ dose made by Clarke[7]. By examining the results of these calculations and comparing

1004697

them with values used in the matrix of integrated concentration of ^{131}I in air an empirical approximation can be made that 1 Bq d m^{-3} corresponds to 1 x 10^{-7} Sv. Assuming a factor of 0.5[34] to account for shielding by buildings from a cloud source and the mean time spent outdoors, the total cloud-γ collective dose equivalent is estimated to be about 50 man Sv. The approximate nature of this estimate is recognised but since the contribution is small compared with the total collective dose a more detailed assessment does not seem to be justified.

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 organ were 95 mSv and 21 mSv, with an average of 4 mSv, due to inhalation of ^{131}I[6]. 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[6]. 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[27], an assessment of the contribution to S^c_{eff} from the marine exposure pathways has been made[37]. The contribution from this source to S^c_{eff} is estimated to be less than 2 man Sv.

7. DISCUSSION OF THE RESULTS

The results of the calculations of the collective dose equivalent commitment to the thyroid (S^c_T) and of the collective effective dose equivalent commitment (S^c_{eff}) following the Windscale release of 1957 are given in Tables 5 and 6, respectively. The collective doses corrected for the age distribution of the exposed population are given in Tables 5A and 6A. The contributions by pathway, nuclide and region are indicated in Figures 8 and 9.

7.1 Collective dose equivalent commitment to the thyroid

The total collective dose equivalent commitment to the thyroid, S^c_T, was estimated to be 1.9 x 10^4 man Sv. The main contributions to the collective dose were from ingestion of milk (62%), inhalation of activity in the plume (29%) and ingestion of other foods (9%). These estimates were made assuming a population made up of adults only. When allowance is made for the age distribution of the population (Appendix A) the collective thyroid dose, $S^{c'}_T$ is 2.6 x 10^4 man Sv,

1006090

(that is 37% higher than for an adult population). Of this 70% is contributed by the milk pathway, 22% by inhalation of activity in the plume, and 8% by other foodstuffs. Of the 2.6 x 10^4 man Sv it is estimated that 95% was delivered in the the UK and approximately 12% 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 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[19]. This is mainly because of the comparatively lower ground deposit to milk transfer of ^{131}I observed by Booker[11] and used in this assessment.

It is estimated that the imposition of the ban on the milk distribution from the region around Windscale in the weeks following the accident saved 3.5 x 10^3 man Sv of the age-corrected collective dose to the thyroid, $S_T^{c'}$; that is, the collective dose arising from the Cumbrian area was approximately halved by the ban although the total collective dose was only reduced by 12%.

It is of interest to examine the distribution of individual thyroid dose equivalents in the exposed population as a function of distance from Windscale. However, since most of the dose is predicted to have arisen from the intake of milk which is not necessarily consumed in the area where it is produced (see Table 3), any estimate made in the absence of comprehensive data on UK milk distribution patterns in 1957 is necessarily approximate. In Figure 10 estimates are presented of the mean adult thyroid dose equivalents in England and Wales due to the inhalation and milk ingestion pathways. Milk is assumed to be derived from the sector in which the exposed person lives and since the sectors are chosen to be fairly large the errors associated with real milk distribution patterns are to some extent reduced. For Cumbria it is assumed that those people within the area in which milk was restricted obtained milk from other parts of the north-western region. It is clear from Figure 11 that the highest doses were received in the north-west of England: doses in the south and west of the country and in Wales were lower by more than an order of magnitude.

Recently Taylor[28] has estimated the collective thyroid dose 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 those of this assessment (Table 7). 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, assuming an adult population, S^c_{eff}, has been estimated to be 9.9×10^2 man Sv. The main contributions to this value were from ingestion of foodstuffs (47%), inhalation of activity from the plume (26%) and from external irradiation (27%) due to the cloud and deposited activity. Again, because roughly three-quarters of the dose is due to internal irradiation of organs, correction factors for children's relatively higher doses per unit intake have been applied (Appendix A), and the collective effective dose equivalent commitment is re-evaluated to be 1.2×10^3 man Sv, allowing for the age-distribution of the population. Of this the milk ingestion pathway is the single largest contributor of collective dose (48%), representing the contamination of milk by ^{131}I. Inhalation and external irradiation contribute equally to the $S^{c'}_{eff}$ (roughly 22% each), the remainder coming from the ingestion of other contaminated foodstuffs.

The most important nuclides contributing to collective effective dose are ^{131}I, ^{137}Cs and ^{106}Ru (Figure 9). Other less important nuclides are ^{144}Ce, ^{129m}Te, ^{103}Ru, ^{132}Te and ^{91}Y. Because ^{137}Cs has a relatively long half-life ($t_{\frac{1}{2}}$ = 30.1 years) the collective effective dose commitment was delivered over a considerable period after the accident. An estimation of the annual collective effective dose equivalent rate as a function of time has been made and is given in Figure 11. Thus approximately 82% of the collective effective dose equivalent commitment was delivered within the first year following the release and the remaining 18% over the next few decades.

Taylor[28] 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 in Table 7. Again, the results are of the same order.

8. HEALTH EFFECTS IN THE EXPOSED POPULATION

The rates of radiation induced effects in the thyroids of the most highly-exposed members of the public can be estimated from published data. The extensive literature on the subject of the risks of late effects from exposure to ionising radiations has been summarised by Clarke and Smith[31]. The risk coefficients which can be obtained from this source have considerable uncertainty

associated with them and care has therefore 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 radiation protection is based on extrapolation. The risk coefficients used in this report for the radiation types and levels of dose are considered to represent an upper limit of risk.

The health effects expected as a result of thyroid irradiation are cancers; a few of them lead to fatality but the majority, being capable of treatment, are termed non-fatal. Their appearance after irradiation is not immediate but occurs over a few decades. The risks of cancer induction may be therefore, best expressed in terms of a time-integrated risk. For a standardised population group of young adults which lives long enough for the risk to be expressed, the time-integrated risks of thyroid cancer incidence are 1×10^{-2} Sv^{-1}, of which 5% are assumed to cause fatality.

The lifetime risk to the most exposed individuals in the local Windscale population of developing a radiation-induced thyroid cancer may then be conservatively expressed using this coefficient as 1×10^{-3} (or 1 in 1,000). These risks are based on the highest measured child thyroid doses of around 100 mSv; the highest adult exposures were less by a factor of about five and the associated cancer risks are proportionately less. If it is assumed that the integrated risk of thyroid cancer were spread uniformly over the remaining lifetime of the exposed individuals (say 60 years) an appropriate estimate of the annual risk of radiation-induced cancer incidence may be made (2×10^{-5} y^{-1}).

The natural risks of thyroid cancer incidence in the population are relatively low compared with some other types of cancer and are variable depending upon age and sex. In the age range 15 - 25 the rates of newly-diagnosed thyroid cancer in 1968 in England and Wales were 2×10^{-6} y^{-1} and 8×10^{-6} y^{-1} for males and females, respectively[30]. These rates increase throughout life and for people over 75 the rates are, respectively, 3×10^{-4} y^{-1} and 7×10^{-5} y^{-1}.

The collective thyroid dose to the UK population when corrected for the population age distribution is estimated to be 2.5×10^{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. Using the previous risk coefficient derived for a group of young adults but recognising that in a real population the risk would not be fully expressed in the older exposed individuals in the population, the total number of expected thyroid cancers is 250 (13 of which would be fatal). If the mean life expectancy of the 'standard' population is 40 years, and the radiation-induced thyroid cancers are assumed to be manifested uniformly over the period (which would not be the case) the annual incidence rate would be 6.5. To obtain some perspective on these numbers they may be compared with the natural incidence

1004701

rate in England and Wales of newly-diagnosed thyroid cancer, which was 666 in 1968 (180 males and 486 females) and has tended to be fairly constant in recent years[30]. This comparison does not, however, reveal the geographic distribution which might be expected in the radiation-induced cancers nor the predicted thyroid cancer incidence within different age groups and their relationships with the geographic and age variations of natural thyroid cancer incidence. A more detailed study of these aspects is being undertaken at the Board and the results will be published in due course.

Since 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, it is possible to make an estimate of this contribution to the natural thyroid cancer incidence in the population by using the same risk coefficients. The average annual thyroid dose equivalent from natural sources is about 0.9 mSv; this corresponds to an annual incidence of 360 thyroid cancers per year (with 18 expected fatalities) in a population of size comparable to that of England and Wales. This prediction will be an overestimate, however, since the risk coefficient applies to a young adult population and not to one with a real age distribution.

Due to the predominance of radioiodine in the release, the expected incidence of health effects other than thyroid cancer in the exposed population is comparatively small. The total number of fatal cancers plus hereditary defects in the first two generations may be estimated by using the collective effective dose equivalent commitment, S^c_{eff}, together with a risk coefficient of 1.65×10^{-2} Sv^{-1} recommended by ICRP[26]. This method implies a total of 20 health effects (cancer deaths plus hereditary effects); 13 of the health effects are due to thyroid cancer fatalities as discussed previously. No account is taken in this estimate of fatalities due to skin cancer nor of hereditary defects beyond the second generation. The same uncertainties, referred to earlier, concerning the risk coefficient values apply to this estimate, and it is regarded as an upper estimate of radiation induced health effects.

9. 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 both on the accuracy of the predicted spatial distribution of contamination and on the reliability of the transfer models used to relate environmental measurements to dose.

1004702

The values of environmental activity given in the matrix of Table 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 1.2×10^4 man Sv total adult collective thyroid dose from milk (Table 5), approximately 75% comes from the region out to 200 km, where the estimates of integrated milk contamination are most reliable. Only about 12% is based on values which are estimates from interpolation. An error of 2 in these estimates would change the collective thyroid dose from milk by only about 10%. In general, the sum of the contributions from all the segments is more accurate than the collective dose from an individual segment.

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 calculation 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 can be performed on the collective dose calculations to investigate the importance of these parameters. For example, it can be shown that increasing the deposition velocity by a factor of three reduces the collective thyroid dose by less than 5%, whereas reducing the deposition velocity by a factor of three increases the estimate by about 50%.

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.

10. 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 2.6×10^4 man Sv and 1.2×10^3 man Sv, respectively.

1004703

2. The pathway which contributed the most to the collective 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 doses to individuals most at risk in the population, saved approximately 3.5 x 10^3 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 the largest part of the collective effective dose. 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 maximum individual thyroid dose measured was 160 mSv to a child in the Windscale area.

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

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1004704

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1004705

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1004706

Table 1

Estimates of radionuclides released

Nuclide	Clarke[7] ($\times 10^{12}$ Bq)	Loutit et al[6]	Ratios used in this study relative $^{131}I = 1.0$
^{85}Kr	5.9×10^{1}		9.8×10^{-2}
^{89}Sr	5.1×10^{0}	3.0×10^{0}	4.1×10^{-3}
^{90}Sr	2.2×10^{-1}	7.4×10^{-2}	1.0×10^{-4}
^{90}Y	2.2×10^{-1}		1.0×10^{-4}
^{91}Sr	3.7×10^{-2}		6.2×10^{-5}
^{91}Y	6.4×10^{0}		1.1×10^{-2}
^{93}Y	5.9×10^{-2}		9.8×10^{-5}
^{95}Zr	7.5×10^{0}		1.3×10^{-2}
^{95}Ni	7.5×10^{0}		1.3×10^{-2}
^{97}Zr	3.6×10^{-1}		6.0×10^{-4}
^{99}Mo	3.6×10^{1}		6.0×10^{-2}
^{103}Ru	4.0×10^{1}		6.7×10^{-2}
^{105}Rh	5.2×10^{-1}		8.7×10^{-4}
^{106}Ru	5.9×10^{0}	3.0×10^{0}	4.1×10^{-3}
^{106}Rh	5.9×10^{0}		4.1×10^{-3}
^{111}Ag	5.2×10^{-1}		8.7×10^{-4}
^{115}Cd	1.6×10^{0}		2.7×10^{-3}
^{123}Sn	2.4×10^{-1}		4.0×10^{-4}
^{125}Sn	2.5×10^{-1}		4.2×10^{-4}
^{127}Sb	3.3×10^{-2}		5.6×10^{-5}
^{129m}Te	2.5×10^{1}		4.2×10^{-2}
^{129}Te	2.5×10^{1}		4.2×10^{-2}
^{131m}Xe	6.5×10^{1}		1.1×10^{-1}
^{131}I	6.0×10^{2}	7.4×10^{2}	1.0×10^{0}
^{132}Te	6.0×10^{2}	4.4×10^{2}	5.9×10^{-1}
^{133}Xe	1.2×10^{4}		2.1×10^{1}
^{134}Cs	1.2×10^{0}		2.0×10^{-3}
^{135}Xe	3.5×10^{1}		5.9×10^{-2}
^{136}Cs	1.5×10^{0}		2.5×10^{-3}
^{137}Cs	4.6×10^{1}	2.2×10^{1}	3.0×10^{-2}
^{140}Ba	6.4×10^{0}		1.1×10^{-2}
^{140}La	6.4×10^{0}		1.1×10^{-2}
^{141}Ce	7.1×10^{0}		1.2×10^{-2}
^{143}Ce	1.6×10^{0}		2.6×10^{-3}
^{144}Ce	4.0×10^{0}	3.0×10^{0}	4.1×10^{-3}
^{147}Nd	2.3×10^{0}		3.8×10^{-3}
^{147}Pm	2.3×10^{0}		3.8×10^{-3}
^{149}Pm	5.9×10^{-1}		9.9×10^{-4}
^{151}Pm	1.0×10^{-1}		1.7×10^{-4}
^{153}Sm	7.8×10^{-2}		1.3×10^{-4}
^{156}Eu	2.6×10^{-1}		4.3×10^{-4}

1004707

Table 2

Values used for the matrix of integrated ^{131}I activity in milk $\tilde{C}(I,M,d_m,\theta_n)$

Table 2 a) $\tilde{C}(I,M,d_m\,\theta_n)$ for the UK (Bq d l^{-1})

Sector, θ_n	Distance bands, d_m (km) from Windscale																			
	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-125	125-150	150-200	200-250	250-300	300-350	350-400	400-450	450-500	500+
0°-15°	1.0×10^4	1.9×10^3	1.5×10^3	3.7×10^2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15°-30°	1.0×10^4	2.6×10^3	1.9×10^3	1.9×10^3	2.6×10^3	2.6×10^3	1.1×10^3	7.4×10^2	3.7×10^2	0	0	0	0	0	0	0	0	0	0	0
30°-45°	1.0×10^4	5.6×10^3	3.1×10^3	3.0×10^3	2.6×10^3	2.2×10^3	7.4×10^2	2.2×10^3	1.1×10^3	0	0	0	0	0	0	0	0	0	0	0
45°-60°	1.0×10^4	7.0×10^3	4.8×10^3	7.0×10^3	7.4×10^3	4.1×10^3	1.9×10^3	2.2×10^3	1.5×10^3	3.7×10^2	0	0	0	0	0	0	0	0	0	0
60°-75°	1.9×10^4	1.9×10^4	1.6×10^4	1.1×10^4	1.4×10^4	5.6×10^3	5.9×10^3	7.4×10^3	1.9×10^3	1.1×10^3	1.9×10^2	3.7×10^1	0	0	0	0	0	0	0	0
75°-90°	2.0×10^4	2.0×10^4	3.7×10^4	2.4×10^4	1.0×10^4	1.2×10^4	7.8×10^3	3.0×10^3	1.1×10^3	7.4×10^2	3.0×10^2	7.4×10^1	3.7×10^1	0	0	0	0	0	0	0
90°-105°	9.9×10^4	9.6×10^4	2.0×10^4	8.9×10^3	6.3×10^3	8.1×10^3	7.4×10^3	7.8×10^3	5.2×10^3	1.5×10^3	1.1×10^3	5.6×10^2	7.4×10^1	3.7×10^1	0	0	0	0	0	0
105°-120°	6.8×10^4	6.3×10^4	3.0×10^4	6.3×10^3	5.6×10^3	3.0×10^3	6.3×10^3	7.4×10^3	4.8×10^3	1.0×10^4	1.0×10^4	7.0×10^3	1.5×10^3	7.4×10^2	5.6×10^2	4.4×10^2	4.4×10^2	3.0×10^2	0	0
120°-135°	1.4×10^5	7.3×10^4	2.4×10^4	3.6×10^4	8.1×10^3	1.3×10^4	1.1×10^4	5.6×10^3	4.1×10^3	6.3×10^3	6.3×10^3	3.7×10^3	2.4×10^3	1.9×10^3	1.5×10^3	7.8×10^2	3.7×10^2	1.9×10^2	7.4×10^1	0
135°-150°	3.0×10^5	2.2×10^5	8.9×10^4	5.0×10^4	3.0×10^4	3.1×10^4	2.1×10^4	2.0×10^4	8.9×10^3	5.2×10^3	5.2×10^3	1.9×10^3	6.7×10^3	1.5×10^3	1.4×10^3	9.3×10^2	1.1×10^3	7.4×10^2	7.4×10^1	0
150°-165°	7.4×10^4	7.9×10^4	8.7×10^4	4.8×10^4	4.1×10^4	0	1.2×10^4	6.7×10^3	6.7×10^3	5.9×10^3	3.3×10^3	2.0×10^3	5.2×10^3	1.5×10^3	1.1×10^3	6.3×10^2	9.3×10^2	1.1×10^3	7.4×10^1	0
165°-180°	7.4×10^4	7.4×10^4	7.4×10^4	0	0	0	0	0	0	1.9×10^3	5.6×10^2	3.7×10^1	7.4×10^2	3.7×10^2	3.0×10^2	3.0×10^2	7.4×10^2	8.5×10^2	0	0
180°-195°	7.4×10^4	0	0	0	0	0	0	0	0	0	0	0	0	7.4×10^1	2.2×10^2	3.7×10^2	5.6×10^2	5.6×10^2	0	0
195°-210°	7.4×10^4	0	0	0	0	0	0	0	0	0	0	0	0	0	1.9×10^2	1.5×10^2	0	0	0	0
210°-225°	7.4×10^4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
225°-240°	7.4×10^4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
240°-255°	7.4×10^4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
255°-270°	7.4×10^4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
270°-285°	7.4×10^4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
285°-300°	7.4×10^4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
300°-315°	7.4×10^4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
315°-330°	9.9×10^4	5.9×10^3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
330°-345°	5.9×10^4	1.0×10^4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
345°-360°	1.9×10^4	4.8×10^3	2.2×10^3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 2 b) $\tilde{C}(I,M,d_m,\theta_m)$ for the rest of Europe (Bq d l^{-1})

Sector, θ_m	Distance bands (km)		
	500-700	700-1100	1100-10000
0°-30°	0	0	0
30°-60°	0	0	0
60°-90°	0	1.3×10^0	1.3×10^0
90°-120°	1.0×10^1	7.7×10^0	3.2×10^0
120°-150°	4.2×10^1	2.0×10^1	1.3×10^{-1}
150°-180°	6.4×10^{-1}	3.8×10^{-1}	0
180°-210°	3.8×10^{-1}	1.3×10^{-1}	0

1004708

Table 3

The origins of contaminated milk distributed to Greater London

Counties	Volume of milk (June 1956)[22] ($\times 10^3$ l d^{-1})	Mean milk contamination (Bq d l^{-1})	Total activity ($\times 10^6$ Bq)
Cumberland	141	3.6×10^3	5.1×10^2
Westmorland	205	7.5×10^3	1.5×10^3
Yorkshire (North Riding)	27	4.5×10^2	1.2×10^1
Derbyshire	27	3.5×10^3	9.5×10^1
Staffordshire	14	3.7×10^3	5.2×10^1
Cambridgeshire	50	7.8×10^2	3.9×10^1
Huntingdonshire	23	8.0×10^2	1.8×10^1
Norfolk	141	3.3×10^2	4.7×10^1
East Suffolk	141	3.3×10^2	4.7×10^1
Leicestershire	55	1.5×10^3	8.3×10^1
Gloucestershire	105	7.0×10^2	7.4×10^1
Monmouth	59	3.0×10^2	1.8×10^1
Worcestershire	23	1.3×10^3	3.0×10^1
Shropshire	173	2.0×10^3	3.5×10^2
Cardiganshire	18	1.5×10^2	2.7×10^0
Carmarthenshire	584	1.9×10^2	1.1×10^2
Radnorshire	23	3.7×10^2	8.5×10^0
Berkshire	73	9.3×10^2	6.8×10^1
Buckinghamshire	146	1.0×10^3	1.5×10^2
Hampshire	278	1.0×10^3	2.8×10^2
Oxfordshire	68	7.2×10^2	4.9×10^1
Isle of Wight	9	1.0×10^3	9.0×10^0
Dorset	41	9.0×10^2	3.7×10^1
Somerset	333	7.4×10^2	2.5×10^2
Wiltshire	296	8.5×10^2	2.5×10^2
Devonshire	109	6.0×10^2	6.5×10^1
Cornwall	219	1.9×10^2	4.2×10^1
Essex	109	8.0×10^2	8.7×10^1
Hertfordshire	100	1.6×10^3	1.6×10^2
Kent	41	4.0×10^2	1.6×10^1
Middlesex	18	1.0×10^3	1.8×10^1
Surrey	87	9.0×10^2	7.8×10^1
East Sussex	91	4.0×10^2	3.6×10^1
West Sussex	82	9.3×10^2	7.6×10^1
Totals	3909		4.6×10^3

Assuming milk distributed in Greater London is uniformly mixed, mean milk contamination $= \frac{4.6 \times 10^9}{3909 \times 10^3} = 1180$ Bq d l^{-1}

1004709

Table 4

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) (mSv)	Measured thyroid dose (Dunster) (mSv)
0 - 10	18	3	18	5
		6	21	14
		7	18	14
		9	16	18
10 - 20	13	18	9	14
20 - 30	5.5	-	-	-
30 - 40	3.1	31	5	4
		37	2	5
		38	2	3

1004710

Table 5

Collective dose equivalent commitment to the thyroid (S_T^c)

(man Sv)

Pathway \ Region	Cumbria (0 - 50 km)	UK	Total inc. continent
Inhalation	4.8×10^2	5.2×10^3	5.5×10^3
Ingestion			
milk	1.7×10^3	1.1×10^4	1.2×10^4
other foods	7.4×10^1	1.7×10^3	1.8×10^3
Totals	2.2×10^3	1.8×10^4	1.9×10^4

Table 5A

Collective dose equivalent commitment to the thyroid ($S_T^{c'}$)

corrected for the age distribution of the population (man Sv)

Pathway \ Region	Cumbria (0 - 50 km)	UK	Total inc. continent
Inhalation	4.9×10^2	5.4×10^3	5.7×10^3
Ingestion			
milk	2.6×10^3	1.7×10^4	1.8×10^4
other foods	9.3×10^1	2.1×10^3	2.1×10^3
Totals	3.2×10^3	2.5×10^4	2.6×10^4

Notes:

1. The milk ban is estimated to have saved 2.3×10^3 man Sv of the S_T^c for the Cumbria region. (3.5×10^3 man Sv of the $S_T^{c'}$)

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.

1004711

Table 6

Collective effective dose equivalent commitment (S^c_{eff})

(man Sv)

Pathway \ Region	Cumbria (0 - 50 km)	UK	Total inc. continent
Inhalation	1.8×10^1	2.4×10^2	2.6×10^2
Ingestion			
milk	5.4×10^1	3.5×10^2	3.6×10^2
other foods	8.7×10^0	1.0×10^2	1.1×10^2
External			
ground deposit	1.2×10^1	1.9×10^2	2.1×10^2
cloud γ	4.9×10^0	5.4×10^1	5.7×10^1
Totals	1.0×10^2	9.4×10^2	9.9×10^2

Table 6A

Collective effective dose equivalent commitment ($S^{c'}_{eff}$)

corrected for the age distribution of the population (man Sv)

Pathway \ Region	Cumbria (0 - 50 km)	UK	Total inc. continent
Inhalation	1.9×10^1	2.5×10^2	2.7×10^2
Ingestion			
milk	8.5×10^1	5.5×10^2	5.7×10^2
other foods	1.1×10^1	1.2×10^2	1.4×10^2
External			
ground deposit	1.2×10^1	1.9×10^2	2.1×10^2
cloud γ	4.9×10^0	5.4×10^1	5.7×10^1
Totals	1.3×10^2	1.2×10^3	1.2×10^3

Notes:

1. The milk ban is estimated to have saved 70 man Sv of the S^c_T for the Cumbria region. (108 man Sv of the $S^{c'}_T$)

2. 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.

1004712

Table 7

Comparison between estimates of dose by this assessment and the assessment by Taylor[28]

Region	Cumbria (0 - 50 km)		UK		Total, including continent	
Author	(a)	(b)	(a)	(b)	(a)	(b)
Collective thyroid dose, S_T^c (man Sv)	2.2×10^3	4×10^2	1.8×10^4	2.5×10^4	1.9×10^4	3.0×10^4
Age-corrected thyroid dose, $S_T^{c'}$ (man Sv)	3.2×10^3		2.5×10^4		2.6×10^4	
Collective whole body dose, $S^c_{whole\ body}$ (man Sv)	-	5.4×10^0	-	2.2×10^2	-	2.5×10^2
Collective effective dose from external irradiation, $S^c_{eff,ext}$	1.7×10^1	-	2.4×10^2	-	2.7×10^2	

Notes:

(a) Results of this assessment

(b) Results of Taylor[28]

1004713

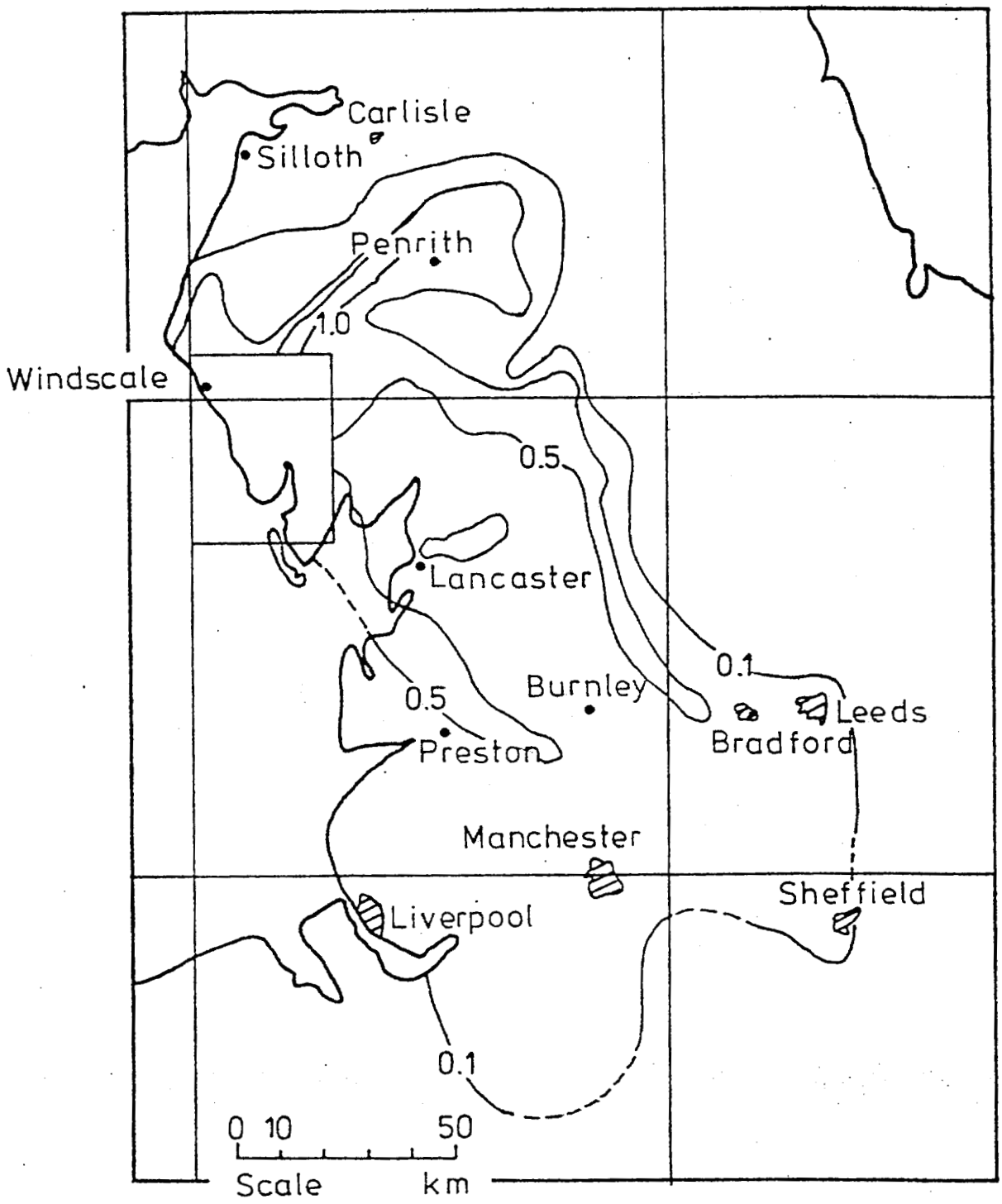

Figure 1 Deposition of ^{131}I in NW England $\mu Ci\ m^{-2}$ (Chamberlain (3))

1004714

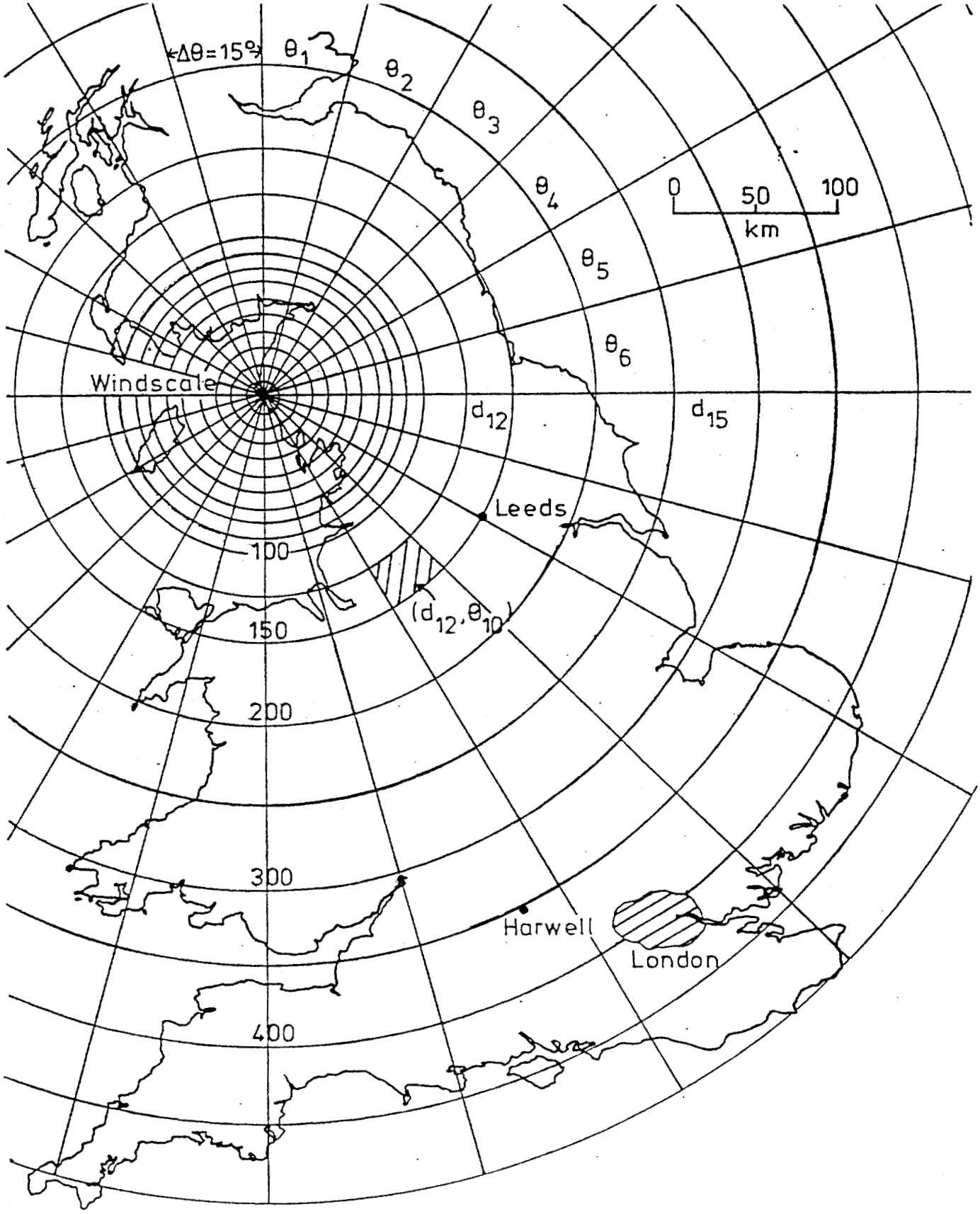

Figure 2 The radial co-ordinate grid adopted for representation of the spatial distribution of environmental materials and their degree of contamination following the Windscale accident 1957

1004715

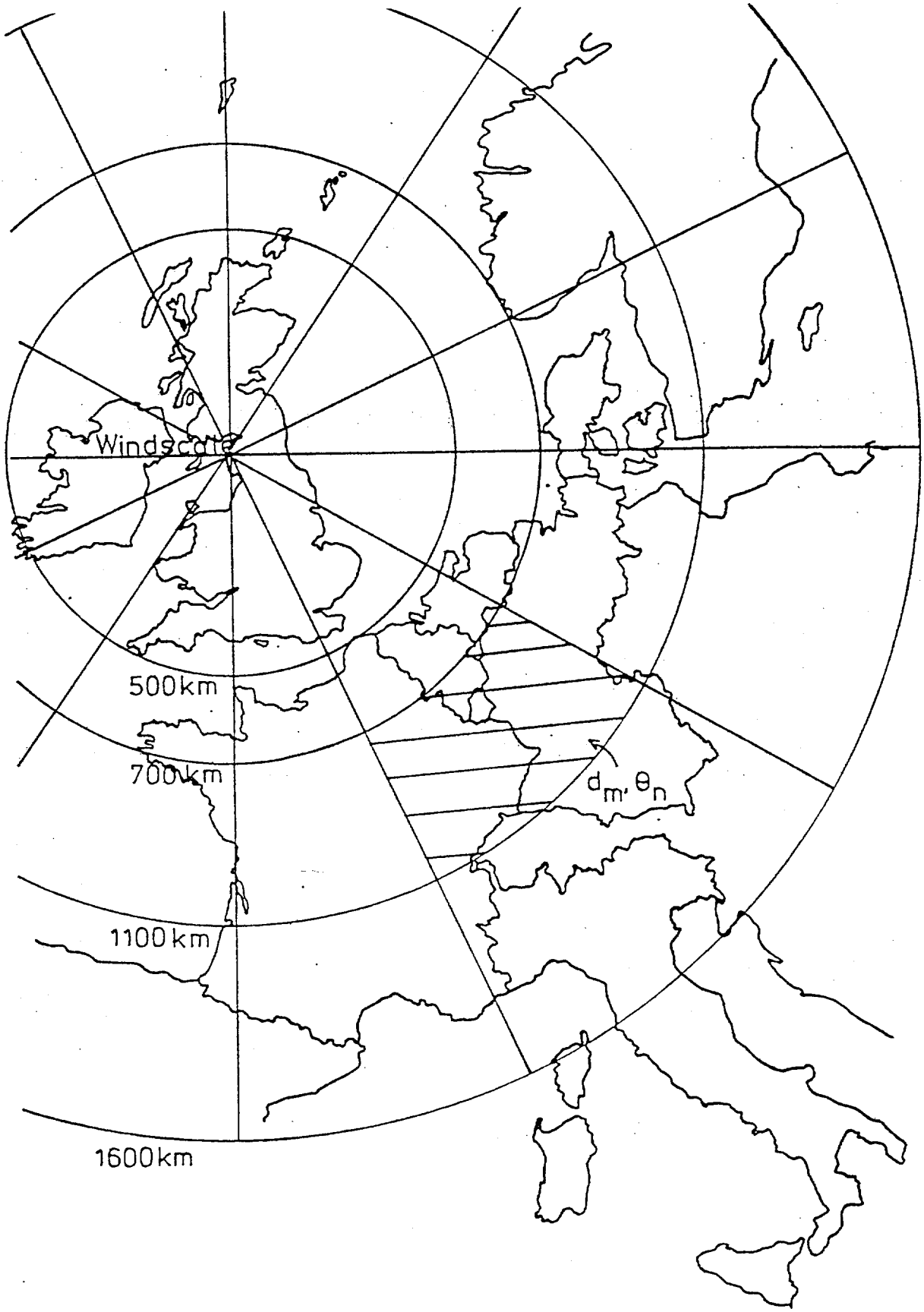

Figure 3 The radial co-ordinate grid adopted for the representation of the spatial distribution of environmental materials and their degree of contamination for Europe

1004716

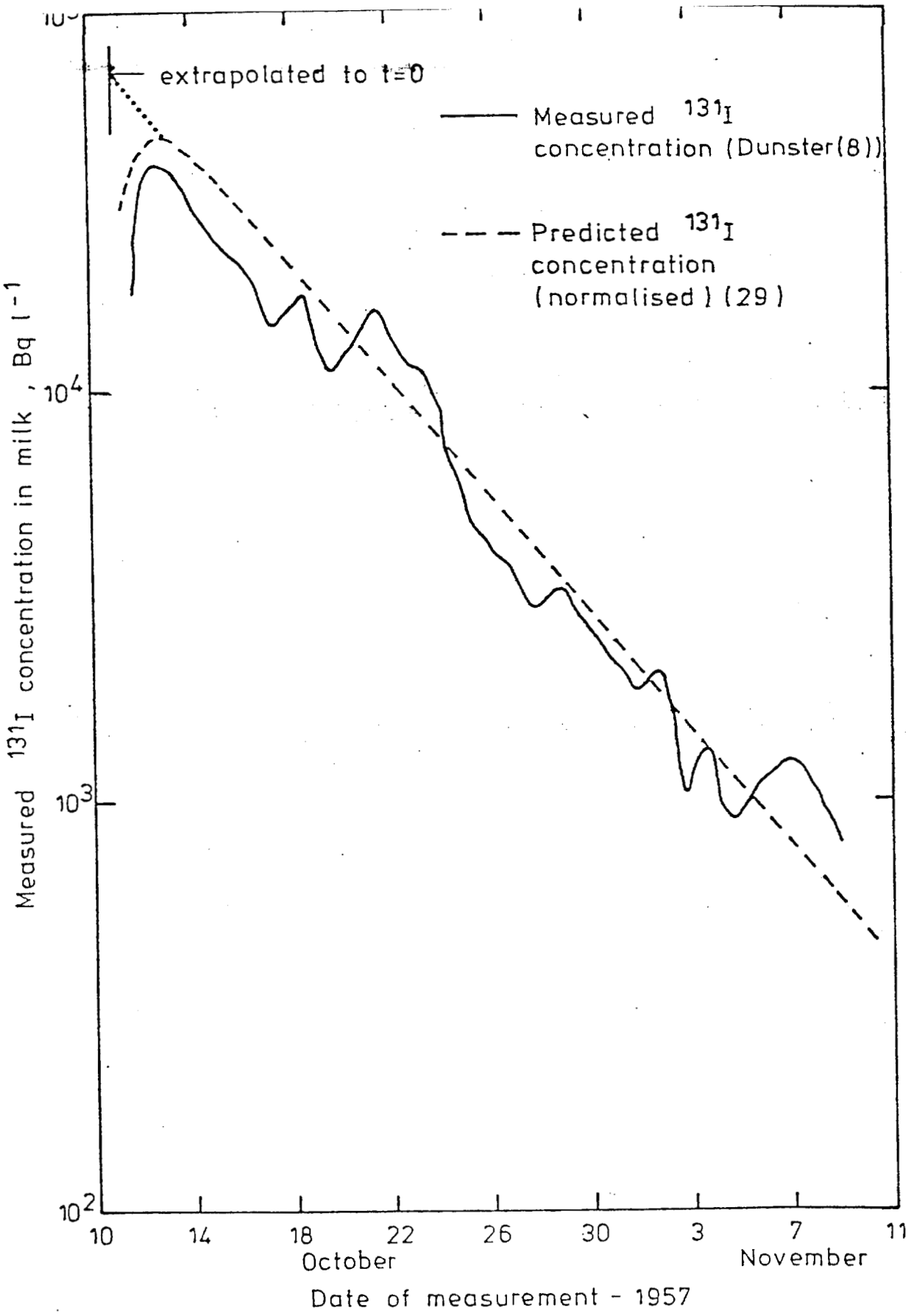

Figure 4 Comparison of ^{131}I concentration in milk from a farm close to Windscale with predicted concentration using NRPB models (29)

1004711

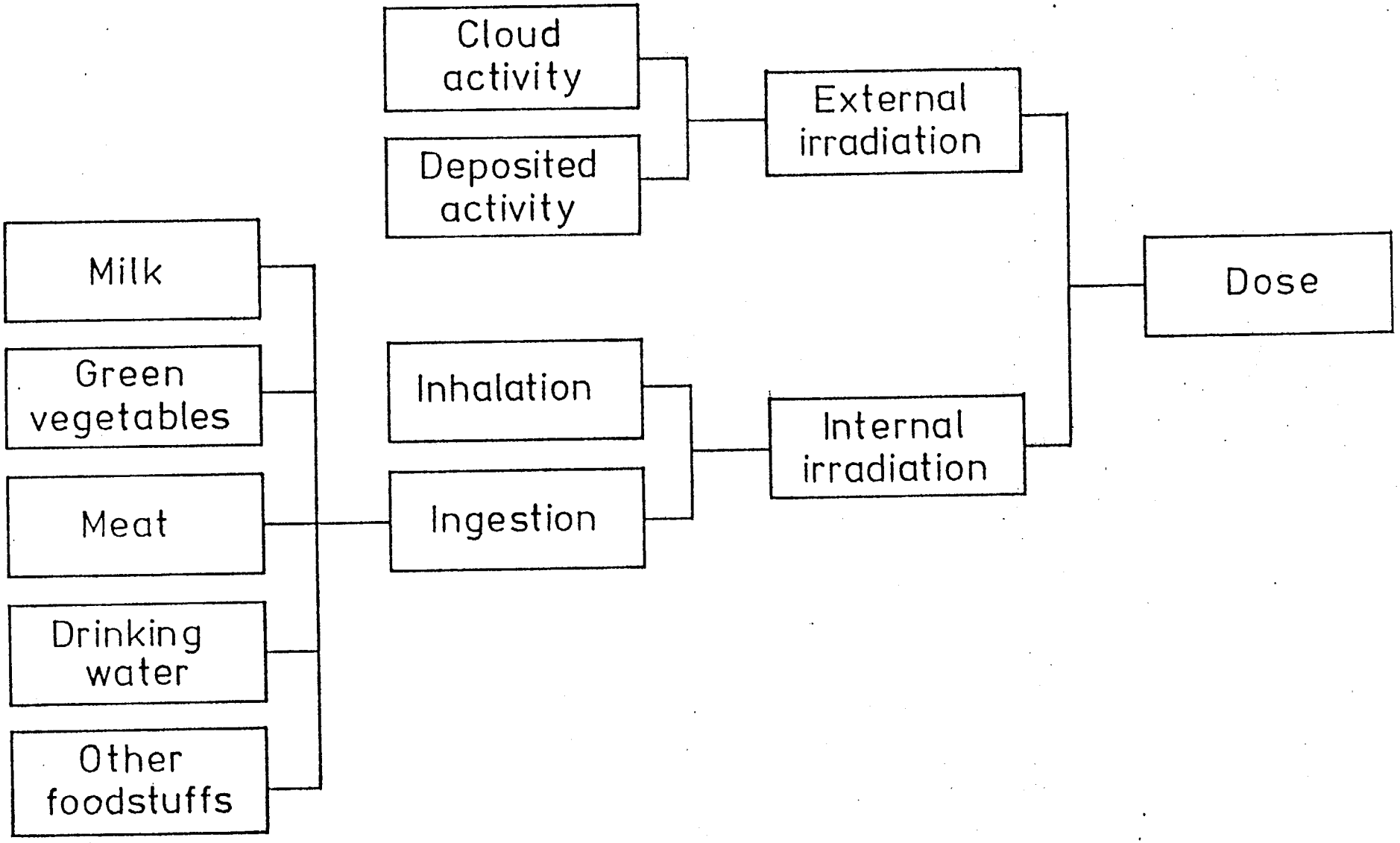

Figure 5 Pathways by which radionuclides can irradiate members of the public

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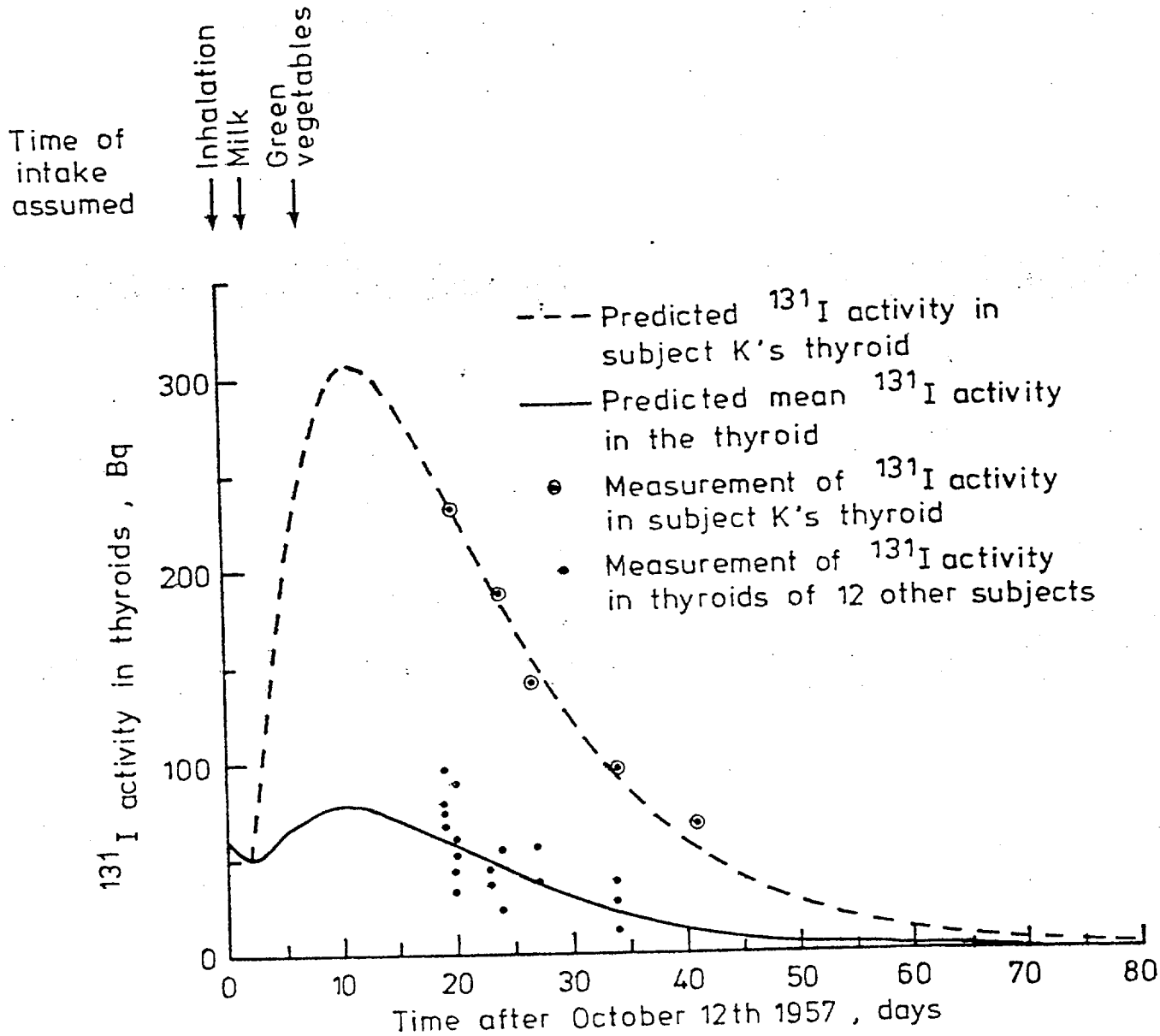


Figure 6 Comparison between predicted and measured ^{131}I activity in the thyroids of London residents as a function of time after the passing of the plume

1004719

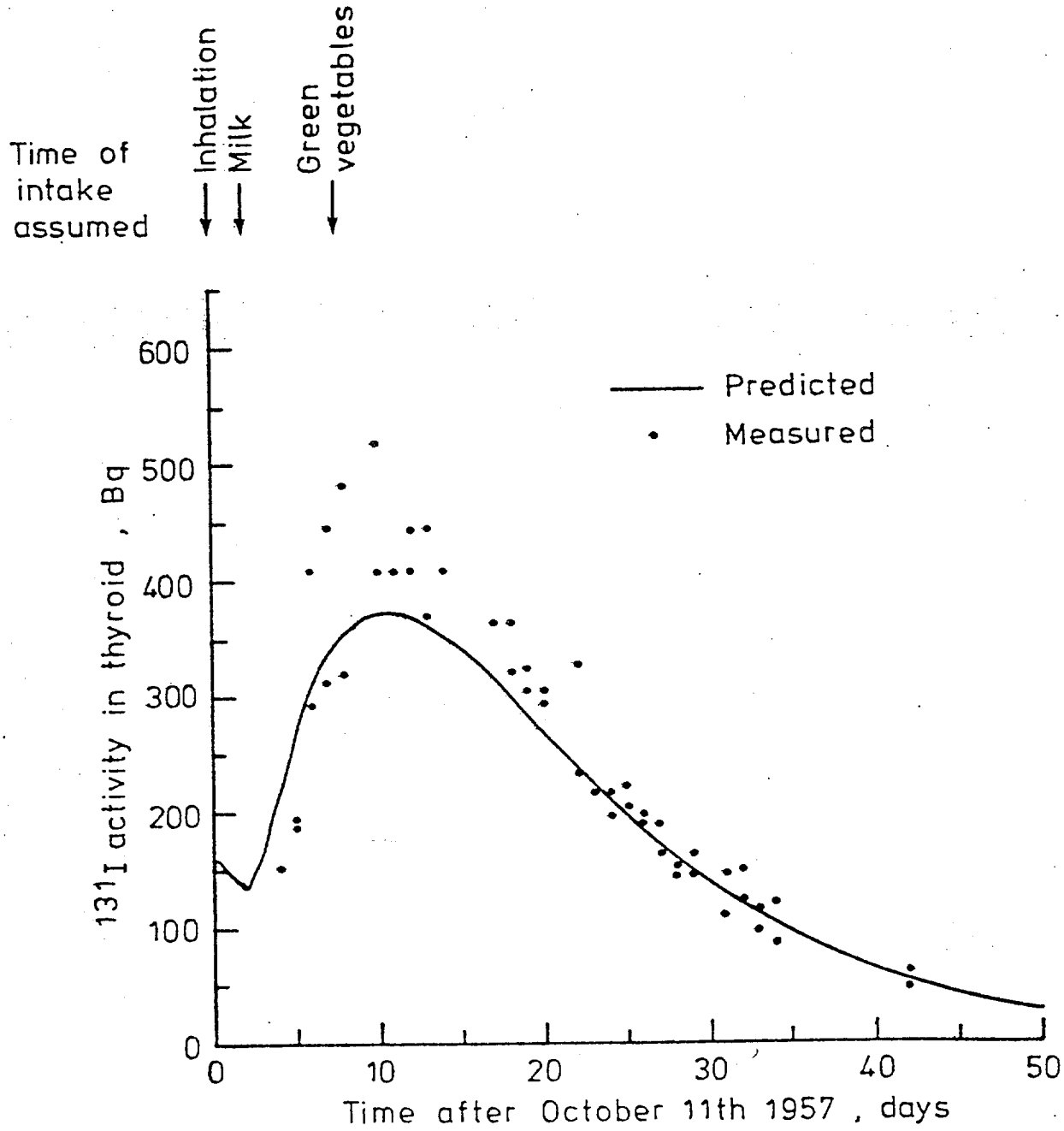
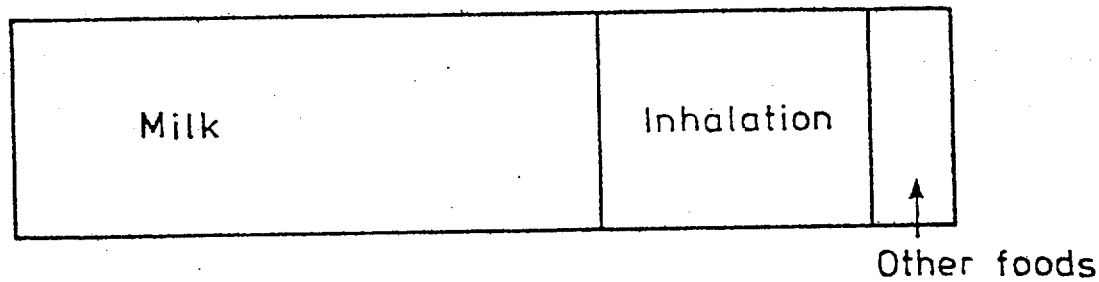
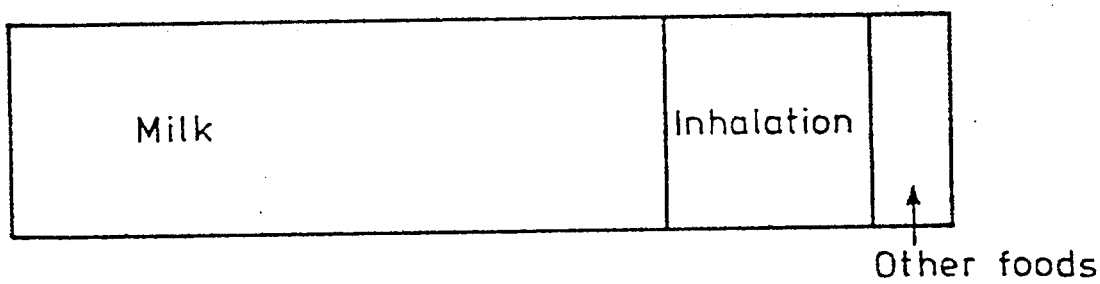


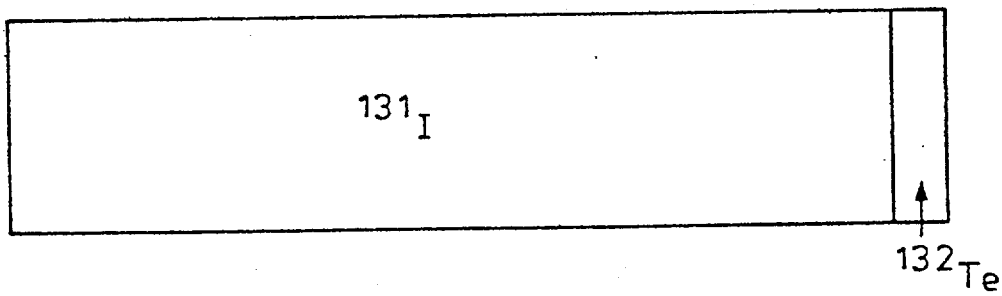
Figure 7 Comparison between predicted and measured ^{131}I activity in the thyroids of Leeds residents as a function of time after the passing of the plume



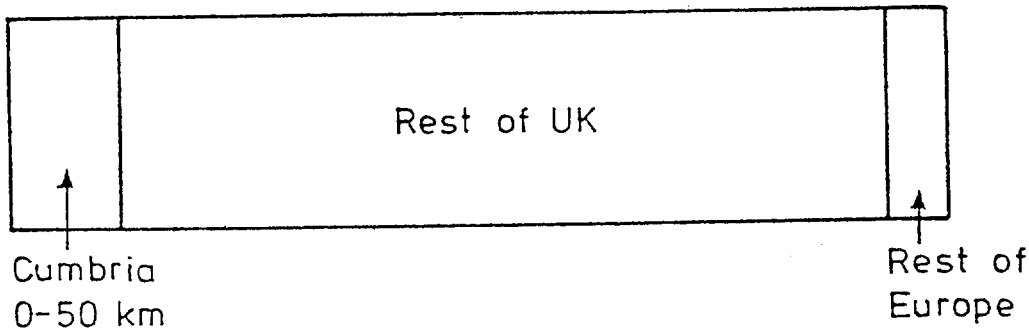
a) S_T^C by pathway



b) $S_T^{C'}$ by pathway



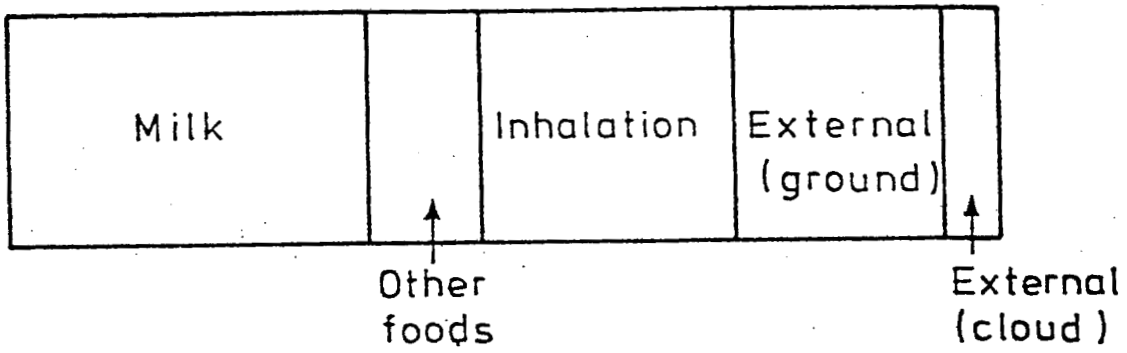
c) S_T^C by important nuclides



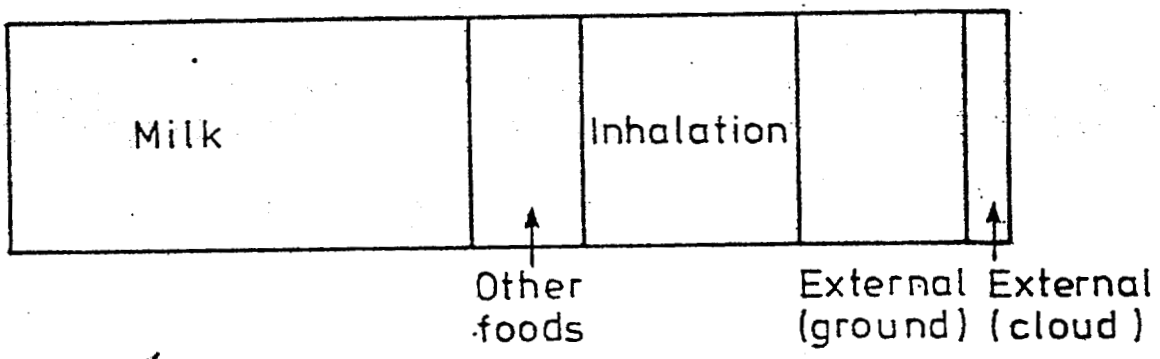
d) S_T^C by region

Figure 8 Contribution to the collective thyroid dose equivalent commitment, S_T^C

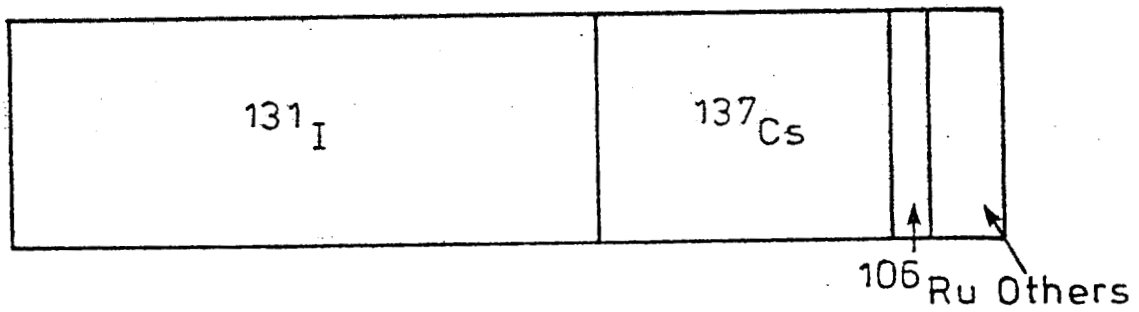
1004721



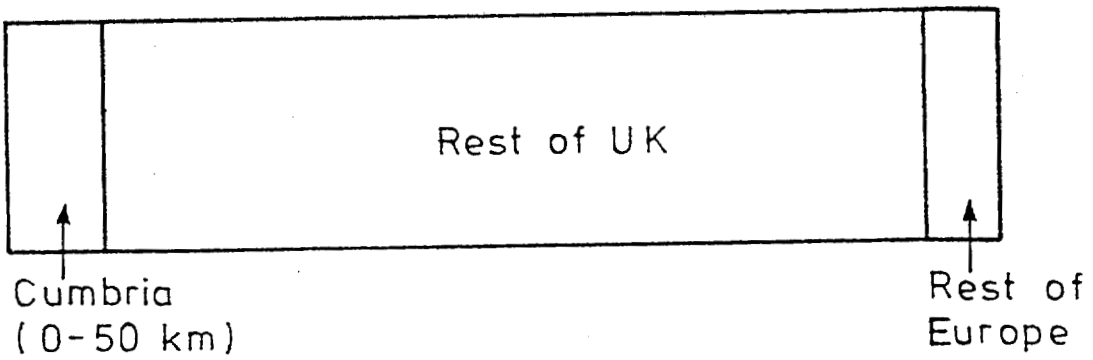
a) S^{c}_{eff} by pathway



b) $S^{c'}_{eff}$ by pathway



c) S^{c}_{eff} by major nuclide contribution



d) S^{c}_{eff} by regional contribution

Figure 9 Contribution to the collective effective dose equivalent commitment, S^{c}_{eff}

1004722

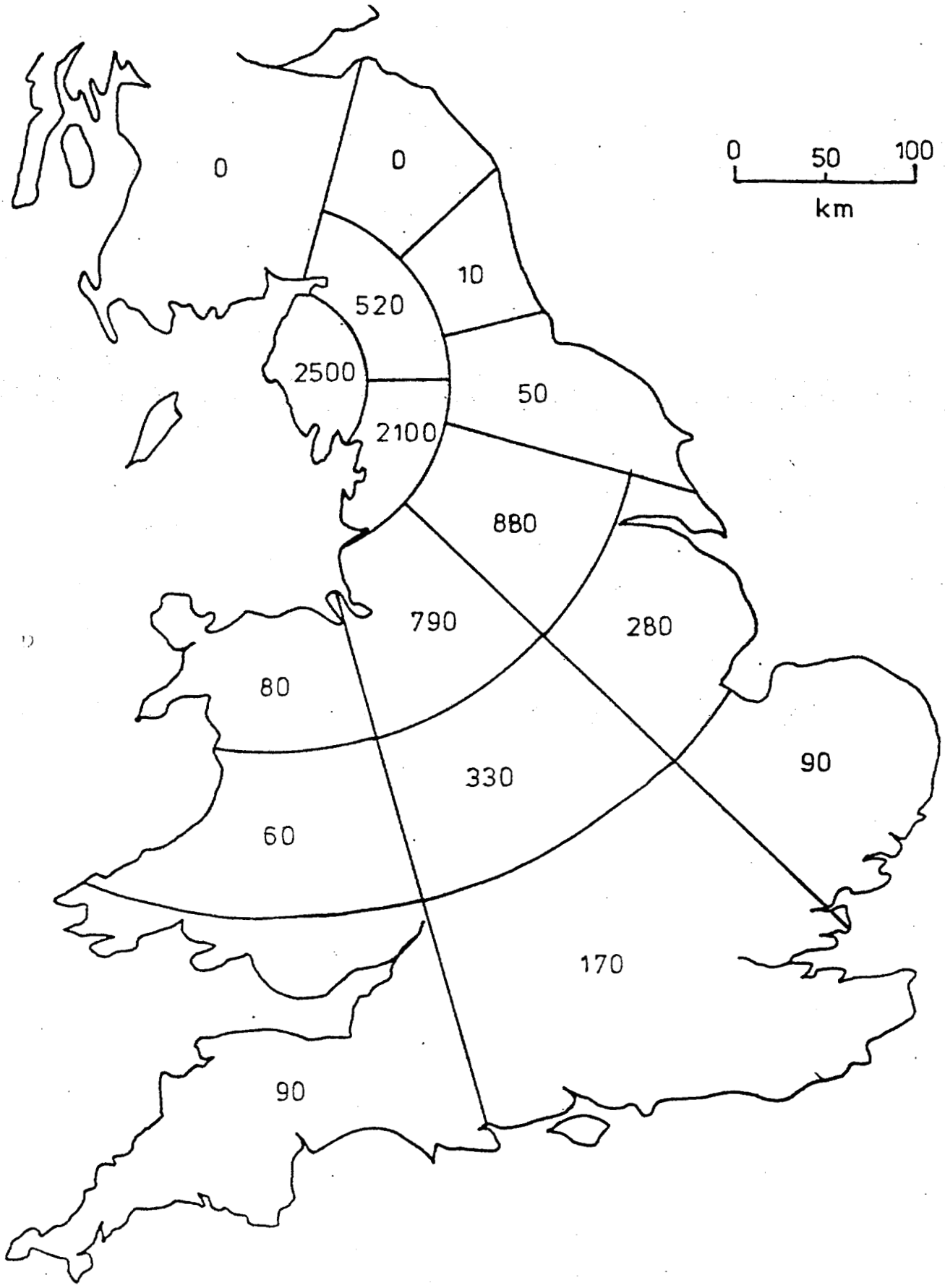


Figure 10 Estimates of mean adult thyroid dose equivalents in England and Wales resulting from the 1957 release (μSv)

1004723

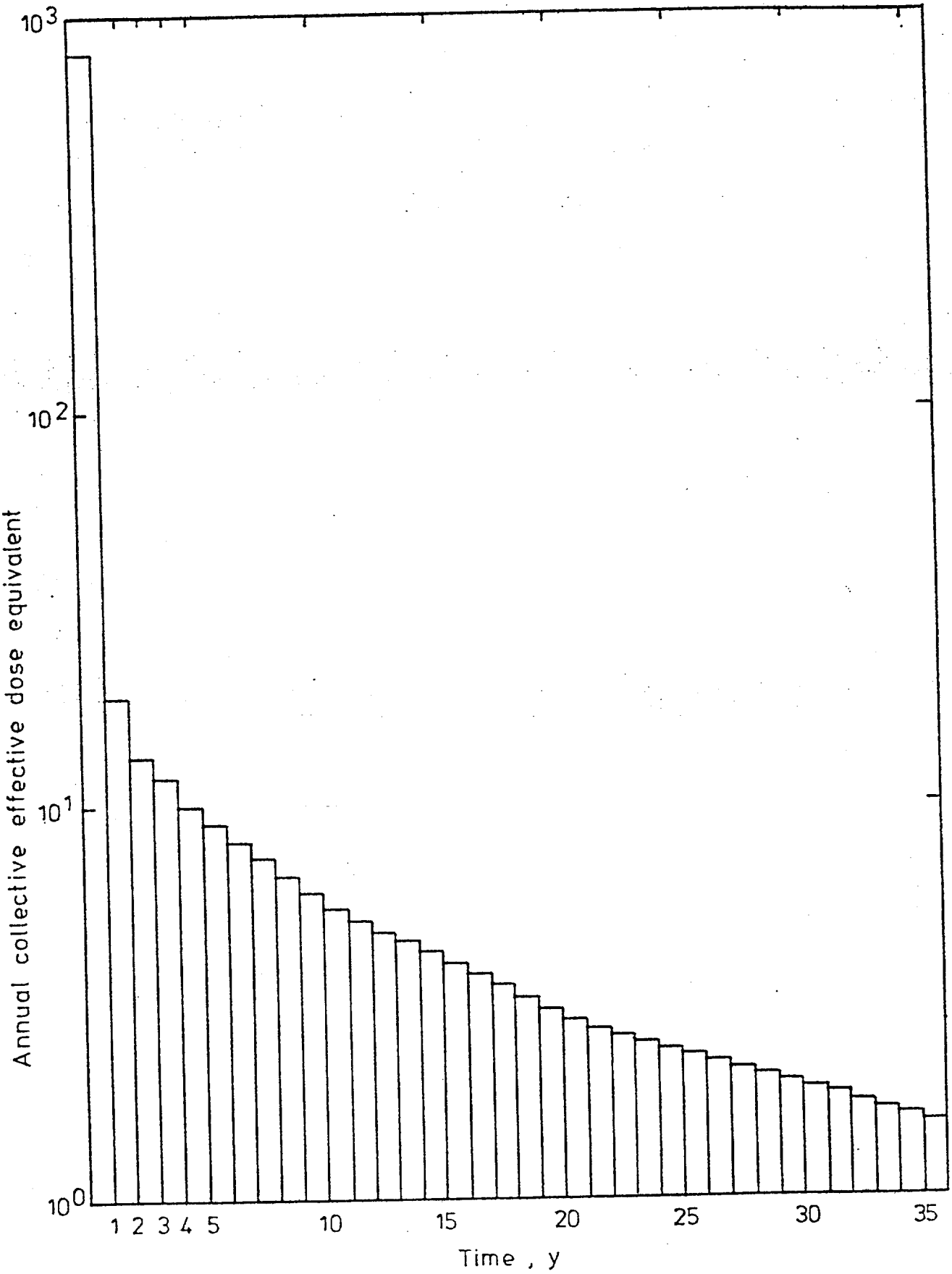


Figure 11 Variation of annual collective effective dose equivalent (S^c_{eff}) as a function of time after release

1004724

APPENDIX A

Factors to be applied to the collective dose estimates to correct for the increased sensitivity of children to internal irradiation

It has been shown that the pathway which contributed the most to the collective thyroid dose, S_T^c and collective effective dose, S_{eff}^c following the Windscale accident was the ingestion of contaminated milk. In calculating collective doses, adult consumption rates and committed doses per unit intake have been assumed implicitly. However, it is recognised that young children were particularly at risk following the release because of their relatively high milk consumption rate and committed dose per unit intake compared with adults. In this appendix, factors are derived for application to the previous estimates of collective dose, to take account of the age distribution of the population at the time of the accident.

CORRECTION FACTORS FOR INGESTION DOSES

The collective dose from ingestion of a nuclide, j, in a given foodstuff may be expressed, assuming a uniform adult population as:

$$S_{ing}^c(j) = A\, H_{50,ing}^u(j) \qquad \text{.... (A1)}$$

where A is the total activity in a given foodstuff that is available to be consumed by the entire population

and $H_{50,ing}^u(j)$ is the committed dose equivalent per unit intake of nuclide j for adults.

Consider now the exposed population being composed of three age-groups with n_i people in each: n_1 people in 1st group aged 0-5 years

n_2 people in 2nd group aged 5-15 years

n_3 people in 3rd group aged 15+ years.

For a given pathway let the respective mean intake rates be I_1, I_2 and I_3; and the mean committed dose equivalents per unit intake of nuclide, j, for each age group be $\bar{H}_1^u(j)$, $\bar{H}_2^u(j)$, $\bar{H}_3^u(j)$.

Of the total activity, A, in a given foodstuff, that is available to be consumed by the entire population, the fraction ingested by the ith group is $\frac{n_i I_i}{\sum_i n_i I_i}$, assuming a fixed age distribution over the entire country. Hence, the collective dose to that group may be written:

$$S_{i,ing}^c(j) = \bar{H}_i^u(j)\, A \frac{n_i I_i}{\sum_i n_i I_i} = \frac{n_i I_i}{\sum_i n_i I_i} \frac{\bar{H}_i^u(j)}{H_{50,ing}^u(j)} S_{ing}^c(j) \qquad \text{.... (A2)}$$

The collective dose corrected for the age distribution may then be written

$$S_{ing}^{c'}(j) = \sum_i S_{i,ing}^c(j) = \frac{S_{ing}^c(j)}{H_{50,ing}^u(j)} \frac{\sum_i n_i I_i \bar{H}_i^u(j)}{\sum_i n_i I_i} \qquad \text{.... (A3)}$$

1004725

CORRECTION FACTOR FOR INHALATION DOSES

The collective dose due to inhalation of a nuclide, j, assuming an adult population, may be expressed as

$$S^{c}_{inh}(j) = H^{u}_{50,inh}(j) \quad I_3 \; N \; \tilde{\chi}$$

where I_3 is the mean adult breathing rate

N is the total population $= n_1 + n_2 + n_3$

$\tilde{\chi}$ represents an appropriate mean integrated air concentration.

The collective dose to a particular age-group may be expressed as

$$S^{c}_{i,inh}(j) = \bar{H}^{u}_{i,inh}(j) \; I_i \; n_i \; \tilde{\chi}.$$

Thus, the age-corrected collective dose due to inhalation may be written as

$$S^{c'}_{inh}(j) = \sum_i S^{c}_{i,inh}(j) = \frac{\sum_i \bar{H}^{u}_{i,inh}(j) I_i \; n_i}{N} \; \frac{S^{c}_{inh}(j)}{I_3 \; H^{u}_{50,inh}(j)} \qquad \text{.... (A4)}$$

CALCULATION OF THE CORRECTION FACTORS

In order to evaluate Equations (A3) and (A4) the quantities n_i, I_i and $\bar{H}^{u}_{i}(j)$ have to be determined. In the calculations it was assumed that the mean intake rates, I_i, and the mean committed doses per unit intake for a nuclide, j, $\bar{H}^{u}_{i}(j)$ for the age-group 0 - 5-year olds and for 5 - 15-year olds can be represented by the respective parameters for a 1-year old infant and a 10-year old child[15,38]. It is also assumed that any regional variation in the age distribution of the population can be ignored, and the mean age distribution of England and Wales in 1958 has been assumed to apply uniformly across the country[24].

The expressions in equations (A3) and (A4) have been evaluated, and the correction factors to allow for the increased sensitivity of children to internal irradiation are given below for the most important pathways and nuclides.

	Age correction factors			
Pathway	Thyroid ($S^{c'}_{T}/S^{c}_{T}$)	Effective ($S^{c'}_{eff}/S^{c}_{eff}$)		
	^{131}I	^{131}I	^{137}Cs	^{106}Ru
Milk	1.54	1.57	1.46	-
Green vegetable	1.25	1.26	1.22	-
Inhalation	0.97	1.02	1.02	1.05

1004726

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