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ABSTRACT

Measurements of fallout levels in Australia up to 1971 are reviewed and used to estimate Australian average individual dose commitments. An alternative set of numbers is given based on the most recent figures for global average dose commitments provided by the United Nations Scientific Committee on the Effects of Atomic Radiation. The two sets of numbers show reasonable agreement; the larger are adopted for use in estimating adverse effects.

The contribution of the French and Chinese weapons tests relative to that from all tests is derived by inspection and extrapolation where necessary of data on the injection of strontium-90 into the northern and southern hemispheres and its subsequent deposition as a function of time.

The risk data reviewed and summarised in the 1972 UNSCEAR and BEIR reports are used to derive estimates of adverse effects. It is concluded that the French and Chinese test series to the end of 1972 may be responsible over the next 20 years for up to 1.4 and 0.2 cases of cancer per year respectively in Australia. Of these cases, 0.25 per year would be leukaemia, 0.75 per year thyroid cancer and 0.6 per year all other forms. Available evidence on the mutagenic effects of radiation suggests that the total number of cases of severe genetic disease produced may be of the same order as the total number of cases of cancer, with the former spread over many generations whereas the latter are not.

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AUSTRALIA; BONE MARROW; BONE TISSUES; CARBON 14; CESIUM 137; GENETIC RADIATION EFFECTS; GONADS; HUMAN POPULATIONS; INTEGRAL DOSES; INTERNAL RADIATION; IODINE 131; IRON 55; KRYPTON 85;LEUKEMIA; LOCAL FALLOUT; NUCLEAR EXPLOSIONS; PLUTONIUM 239; PREVENTIVE MEDICINE; RADIATION HAZARDS; STRONTIUM 90; THYROID; TRITIUM

CONTENTS

1. INTRODUCTION

Exposure to radioactive material in the environment results in radiation dose to members of the public from:

(i) Exposure to radiation from material outside the body.

(ii) Exposure to radiation from material inside the body which has either been inhaled when airborne, or ingested after deposition on the earth's surface and incorporation into foodstuffs.

Exposure to external radiation gives rise to reasonably uniform dose throughout the body; ingested and inhaled material may become uniformly distributed or it may be selectively retained only in certain organs, depending on its metabolic properties.

The radioactive materials produced by nuclear tests which give rise to the most dose are:

(a) The long-lived fission products strontium-90 and caesium-137. Strontium-90 does not give rise to any significant external radiation exposure, but when ingested in milk and other foodstuffs is retained selectively in bone. Caesium-137 gives rise to both external radiation exposure when initially deposited on the ground, and internal exposure of the whole body when ingested in milk and other foodstuffs.

(b) The short-lived fission products (there are a large number of these) which are not taken up by foodstuffs to any significant extent (except for iodine-131 - see below) but which give rise to external radiation exposure when initially deposited on the ground.

(c) The activation products tritium and carbon-14 which both give rise to internal exposure of the whole body as a result of intake by the same routes as followed by naturally occurring tritium and carbon-14.

(d) The short-lived fission product iodine-131 which is ingested in cow's milk and selectively retained in the thyroid gland.

To compare adequately the doses from short-lived and long-lived materials it is necessary in the latter case to estimate not only the dose which has been received but also the dose that will be received in future years from residual long-lived activity in the environment. This estimate of the total dose including the likely future component is known as the 'dose commitment'. This term was introduced by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 1964) and has continued in use. In its most recent report UNSCEAR (1972) gives estimates of average dose commitments from all tests to the end of 1970 for the northern and southern hemispheres and for the north and south temperate zones (40° to 60° latitude). The figures are based on world wide measurements of environmental fallout levels, uptakes of fallout into foodstuffs and measurements of internal contamination in man. They may be used to provide estimates of Australian dose commitments (that is, the average values of dose commitments for the Australian population). This approach to the estimate of Australian dose commitments is used in this paper. Additionally, local measurements are reviewed as an alternative source of Australian dose commitment estimates.

The major adverse consequences of radiation exposure of public health concern are the induction of cancer and the production of genetic damage. Currently available information has recently been reviewed (UNSCEAR 1972, BEIR 1972) and these reviews are used as a basis for assessing the possible consequences of Australian exposure to the fallout from the French and Chinese weapons tests. The genetic consequences of radiation exposure are not as well quantified as the risks of increased cancer incidence.

2. MEASURED FALLOUT LEVELS IN AUSTRALIA

Measurements of weapons test fallout in Australia have been reported by the Atomic Weapons Tests Safety Committee (AWTSC 1972) and the significance of the results has been assessed by the National Radiation Advisory Committee (NRAC 1971). Measurement of strontium-90 contamination began in 1956. Figure 1 shows a number of quantities of interest for the estimation of dose commitments from strontium-90. Firstly, average levels in milk are shown for the period 1957 to 1970. Secondly, age weighted values of levels in bone are plotted as a function of time, rising from about 0.3 pCi(gCa)$^{-1}$ in 1956 to a peak value of 1.35 pCi(gCa)$^{-1}$ in 1966 and a figure of 1.0 pCi(gCa)$^{-1}$ in 1969. The peak level in bone occurs some eighteen months after the peak level in milk. Thirdly, the average annual deposition over the period 1959 to 1971 is shown (weighted by population distribution). The peak deposition rate occurred in 1964. The data in these curves have been taken from the AWTSC (1972) and NRAC (1971) reports directly, or from summaries in the UNSCEAR (1964, 1972) or the Health and Safety Laboratory (HASL 1964 -1972) series of reports. Figure 2 gives estimates of the total annual deposit of strontium-90 in the northern and southern hemispheres (UNSCEAR 1972). The very large peak in the northern hemisphere in 1963 is a result of large injections of fission product activity from 1962 tests, and the broader peak in 1964-1965 in the southern hemisphere is attributable to the same series delayed by the slower transfer of material from one hemisphere to the other compared with the rate of deposition to the earth's surface. Following the cessation of major atmospheric tests, deposition dropped steadily until 1968. From then on the French and Chinese tests in respectively the southern and northern hemispheres maintained a relatively constant rate of deposition.

Caesium-137 fallout measurements in Australia are shown in Figure 3. Annual deposition rates (population distribution averaged) over the period 1966-1971 change with time in much the same way as the strontium-90 deposition rates, with a minimum in 1968. The average ratio of caesium to strontium is 1.3. It may be inferred therefore that the pattern of deposition prior to 1966 was very similar to that for strontium-90, with a major peak in 1964, due to the 1961-1962 tests in the northern hemisphere. This is supported by the measurements of caesium-137 in milk and in people,which show peaks in 1964-1965 and 1965 respectively. The contribution to each of these quantities from the French and Chinese tests is shown by the increased levels after the minimum deposition in 1968.

Measurements of the rate of deposition of short-lived activity and of iodine-131 in milk have been made since the start of the French Pacific tests and interpreted in terms of dose by the National Radiation Advisory Council (NRAC 1971).

No measurements of tritium or carbon-14 are consistently made. However, as the global distribution of these long-lived materials is more uniform than that of the fission products discussed earlier, particularly for carbon-14 which contributes significantly more than does tritium, figures for dose commitment for the southern hemisphere generally (UNSCEAR 1972) can be used without adjustment for location.

3. ESTIMATES OF DOSE FROM LOCAL FALLOUT MEASUREMENTS

Strontium-90. As the concentrations of strontium-90 in the skeleton are significantly greater than those elsewhere in the human body, dose to bone is the parameter of greatest interest. UNSCEAR gives the following figures relating dose rate and strontium-90 concentration (UNSCEAR 1972):

Bone marrow 1.42 $\mathrm{mrad.y^{-1}}$ per $\mathrm{pCi(gCa)^{-1}}$

Endosteal cells	1.95 $mrad.y^{-1}$ per $pCi(gCa)^{-1}$

Bone marrow dose is required to assess the risk of induction of leukaemia, and dose to endosteal cells to estimate the risk of subsequent bone cancer.

Because of the relatively slow turnover of strontium-90 in bone (UNSCEAR uses a rate of 0.3 y^{-1}, corresponding to a half-life of 2.3 years) it is necessary to estimate future levels in bone using the information given in Figure 2. Concentration in bone (Figure 1) shows a peak in 1966, corresponding to the peak deposition in 1964 from tests prior to the French and Chinese series. On the basis of the deposition curve and the figures for concentration in milk for the years 1967 onwards it appears likely that not until 1969 was there any significant contribution from the French and Chinese tests to strontium-90 in bone concentrations. Thus the figures up to and including 1968 are attributable to earlier tests. The total exposure over the period 1956 to 1968 is 9.8 $pCi.y(gCa)^{-1}$. Before 1952 releases of strontium-90 relative to those which came later were small (see Table A4, Appendix A), and over the period 1952 to 1958 were relatively constant, so that the total exposure prior to 1956 was probably not more than 0.6 $pCi.y(gCa)^{-1}$.

The reduction in bone concentration over the period 1966 to 1968 corresponds to an effective half-life of 4 to 6 years. With no further injections into the atmosphere, levels in diet would drop off faster than those in bone (the figures for milk over the period 1965 to 1967 suggest a half-life between 2 and 3 years). As time goes on therefore, the effective half-life in bone could be expected to drop to reduce to the UNSCEAR value of 2.3 years. It will be assumed that the effective half-life of strontium-90 in bone following the cessation of testing is 5 years. It is therefore estimated that the exposure commitment from tests prior to 1964 and measured from 1968 onwards is the product of the concentration in 1968 and the subsequent mean life, i.e. $1.08 \times 5/0.693 = 7.8$ $pCi.y(gCa)^{-1}$.

Thus the total exposure attributable to tests prior to 1964 is $(0.6 + 9.8 - 1.08 + 7.8) = 17.1$ $pCi.y(gCa)^{-1}$ (1.08 is the exposure in 1968, included in both the figure 9.8 and the figure 7.8).

The average bone dose commitments from tests prior to 1964 are therefore estimated as:

Bone marrow	17.1 x 1.42	= 24 mrad.
Endosteal cells	17.1 x 1.95	= 33 mrad.

To derive a figure for the dose commitment from the French and Chinese tests, a comparison is made of the total deposition from tests prior to 1964 and from those from 1964 onwards. This requires a projection of deposition from 1972 onwards. Such a projection is shown in Figure 1; (its derivation is given in Appendix B). It is estimated that the population distribution weighted average deposition from tests prior to 1964 was 16.5 mCi.km^{-2} and that the deposition from tests in the period 1964-1972 will be 3.3 mCi.km^{-2}. (This includes the measured deposition of 2.5 mCi.km^{-2} over the period 1967-1971.) This gives the following figures for the dose commitments from French and Chinese tests to date:

Bone marrow	24 x 3.3/16.5 =	4.8 mrad.
Endosteal cells	33 x 3.3/16.5 =	6.6 mrad.

Caesium-137. Available figures for deposition, concentration in milk levels and levels in man are given in Figure 3. The figures for milk (from 1963 onwards) and for deposition (from 1966 onwards) are population weighted averages. The status of the earlier deposition figures (taken from UNSCEAR reports) is not known. The body burdens are straight averages of figures made in the period 1963-1968 at the AAEC Research Establishment, Lucas Heights (D.E. Parsons, AAEC unpublished report), 1965-1968 in Adelaide (UNSCEAR 1972), and 1970 in Melbourne (AWTSC 1972).

Because of the relatively rapid turnover of caesium-137 in man it is possible to relate annual deposition and body burdens directly. UNSCEAR uses the figure of 11 pCi.y(gK)$^{-1}$ per mCi.km^{-2} for the ratio of body burden to deposition. Comparison of the levels from Figure 3 for the period 1966 to 1970 gives a value of 30 for this ratio, comparing body burdens and deposition for the same years, and the same value if body burdens are compared with depositions for the previous year. These higher figures, as compared with the UNSCEAR value, may be partly due to comparisons of unweighted body burdens with weighted deposition levels, or may be due to differences in average dietary composition.

Interpreting the minimum in the deposition curve as the dividing point between deposition from tests prior to 1964 and that from the French and Chinese tests, the total deposition from the latter series up to the end of 1971 is 3.5 mCi.km^{-2}. Assuming that the projection of deposition made for strontium-90 also applies to caesium-137, then the total deposition estimate is 3.5 x 3.3/2.5 = 4.6 mCi.km^{-2} for caesium-137 from the French and Chinese tests.

This total deposition figure gives an exposure commitment of $4.6 \times 30 = 138$ pCi.y(gK)$^{-1}$, using the larger of the two ratios for body burden/deposition ratio found above.

This can then be converted to dose commitment using the UNSCEAR dose rate/body burden factor of 18 μrad y^{-1} per pCi(gK)$^{-1}$. This gives the following figure for whole body dose from internal caesium-137 from French and Chinese tests to date:

Whole body dose (internal caesium-137) $138 \times 18/1000 = 2.5$ mrad.

In addition to whole body dose from internal caesium-137, further whole body dose is received from radiation from the activity in the environment. The dose/deposition conversion factor (from UNSCEAR) is 1.44 mrad per mCi.km^{-2} for exposure in the open air and 0.46 mrad per mCi.km^{-2} after allowance is made for shielding by buildings and self shielding. Thus the dose commitment from external caesium-137 from French and Chinese tests to date is:

Whole body dose (external caesium-137) $0.46 \times 4.6 = 2.1$ mrad.

Short-Lived Gamma Emitters. The NRAC reports (1967-1971) contain estimates of the whole body doses received from deposited short-lived gamma emitters based on measurements of deposited beta activity and appropriate factors relating gamma emission to total beta activity, dose rate as a function of gamma energy etc. Table 1 shows the population distribution weighted averages for the years 1966-1971. Each year's dose is attributed to tests in that year. No factor for shielding is included.

TABLE 1

POPULATION DISTRIBUTION WEIGHTED AVERAGE DOSES FROM DEPOSITED SHORT-LIVED GAMMA EMITTERS

Year	Whole Body Dose (mrad)
1966	0.64
1967	0.10
1968	0.65
1969	0.0
1970	0.81
1971	1.4

There were no tests in 1969 and no significant fallout in 1972. Thus the total dose from tests over the period 1966-1972 was 3.6 mrad. Use of the same attenuation factor for building and self shielding as for external caesium-137 exposure gives the following estimate of whole body dose commitment from deposited short-lived gamma emitters from French tests:

Whole body dose (external short-lived gamma emitters)	3.6 x 0.32 = 1.2 mrad.

(Because of the relatively short half-life of these emitters and the on-average slow transfer of activity from the northern to the southern hemispheres the contribution of Chinese tests to this component is insignificant.)

Iodine-131. The NRAC reports (1967-1971) also contain estimates of average thyroid doses received by young children as a consequence of drinking cow's milk contaminated with this short-lived isotope. (Young children, i.e. 0-2 years of age, receive greater thyroid doses per unit intake than do other age groups and also, on average, drink more milk.)

Table 2 lists the population distribution weighted average thyroid doses received by young children from iodine-131 released by the French tests over the period 1966-1972; (as with the external short-lived gamma dose, there is no significant contribution from Chinese tests).

TABLE 2

POPULATION DISTRIBUTION WEIGHTED AVERAGE THYROID DOSES RECEIVED BY YOUNG CHILDREN FROM IODINE -131 IN MILK

Year	Thyroid Dose (mrad)
1966	42
1967	10
1968	15
1969	0
1970	16
1971	13
1972	0

Summed, this gives a thyroid dose commitment for young children from iodine-131 in milk as a consequence of the French test series of 96 mrad.

Carbon-14 and Tritium. In the absence of Australian measurements of these radioisotopes the dose commitments derived by UNSCEAR may be used. These are reproduced in Table 3.

TABLE 3

UNSCEAR ESTIMATES OF DOSE COMMITMENTS FROM TRITIUM AND CARBON-14, ALL TESTS TO THE END OF 1970

Source of Radiation	Tissue	Dose Commitment (mrad)		
		Northern Hemisphere	Southern Hemisphere	Global
Carbon-14	Gonads (whole body), bone marrow	12	12	12
	Bone lining (endosteal) Cells	15	15	15
Tritium	All	4	1	4

As these isotopes are produced by neutron activation or released from fusion weapons their occurrence is not proportional to fission yield. In the absence of complete information it will however be assumed that for a test series as a whole there is a fairly constant relationship between total energy release and the production of the above materials and fission yield, and that the ratio of the strontium-90 released by the French and Chinese tests (see Appendix A, Tables A1, A2 and A3) to the total released to the end of 1970 (1.3 and 20.4 MCi respectively) can be used to give estimates of the dose commitments for the French and Chinese tests, using the global dose commitment figures above (assuming that the French and Chinese test series are roughly equivalent and that they release the same quantities into the southern and northern hemispheres respectively). This procedure gives:

Carbon-14	whole body, bone marrow	12 x 1.3/20.4 = 0.8 mrad
	endosteal cells	15 x 1.3/20.4 = 1.0 mrad
Tritium	whole body	4 x 1.3/20.4 = 0.2 mrad

Summarised Estimates

The various dose commitments estimated above are summarised in Table 4.

TABLE 4

ESTIMATED AUSTRALIAN DOSE COMMITMENTS FROM THE FRENCH AND CHINESE SERIES OF NUCLEAR TESTS BASED ON AUSTRALIAN FALLOUT MEASUREMENTS (a)

Source of Radiation	Dose Commitment (mrad)			
	Whole Body and Gonads	Endosteal (Bone Lining) Cells	Bone Marrow	Thyroid
External				
short-lived	1.2	1.2	1.2	1.2
caesium-137	2.1	2.1	2.1	2.1
Internal				
tritium	0.2	0.2	0.2	0.2
carbon-14	0.8	1.0	0.8	0.8
strontium-90		6.6	4.8	
caesium-137	2.5	2.5	2.5	2.5
iodine-131				96 (b)
TOTALS	6.8	13.6	11.6	103

(a) Except for tritium and carbon-14, which are based on UNSCEAR figures.

(b) Young children : less for others.

4. ESTIMATES OF AUSTRALIAN DOSES FROM WORLD AVERAGE FIGURES

UNSCEAR (1972) has made estimates of dose commitments from all nuclear tests carried out before 1971 for the populations in the northern and southern hemispheres, and for populations in the north and south temperate zones ($40^\circ - 60^\circ$ latitude). The figures for the south temperate zone will be close to an estimate for Australia (mostly in the latitude range $20^\circ - 40^\circ$). Two adjustments may be made. Firstly, the deposition of strontium-90 in the south temperate zone was taken by UNSCEAR to be 22.1 $mCi.km^{-2}$, whereas the population distribution weighted average for Australia is 19 $mCi.km^{-2}$ (based on AWTSC figures for deposition weighted by the 1966 Australian census figures). This suggests that dose commitments from the fission products (but not tritium or carbon-14) should be reduced by the factor 19/22.1. Secondly, the ratio of $^{90}Sr(gCa)^{-1}$ in diet to that in milk was taken as 1.4, whereas the ratio for

Australia is reported as 1.1 (UNSCEAR 1972). In consequence dose commitment from strontium-90 is reducible by the factor 1.1/1.4. There may also be differences in the factor relating internal caesium dose commitment to environmental caesium levels, but the absence of specific data precludes adjustment.

To derive dose commitments from the French and Chinese tests over the period 1964-1972 we can use the ratio of the strontium-90 deposition in Australia estimate of 3.3 $mCi.km^{-2}$ to that measured up to the end of 1970, 10 $mCi.km^{-2}$, as an apportioning factor for the fission product components, except krypton-85. For krypton-85, tritium and carbon-14, dose commitments are apportioned in proportion to the estimated strontium-90 yields of the French and Chinese tests, 1.3 MCi (Tables A1 and A2, Appendix A) and to all tests to the end of 1970, 20.4 MCi (Tables A1, A2 and A4, Appendix A), as in the previous section.

The results of these modifications to the UNSCEAR dose commitments and their apportionment to give estimates of the French and Chinese test contributions to Australian dose commitments are given in Table 5.

TABLE 5

ESTIMATED AUSTRALIAN DOSE COMMITMENTS FROM THE FRENCH AND CHINESE SERIES OF NUCLEAR TESTS DERIVED FROM UNSCEAR SOUTH TEMPERATE ZONE FIGURES

Source of Radiation	Dose Commitment (mrad)		
	Whole-Body and Gonads	Bone-Lining (Endosteal) Cells	Bone Marrow
External			
short-lived	2.8	2.8	2.4
caesium-137	2.4	2.4	2.4
krypton- 85	1×10^{-5}	1×10^{-5}	1×10^{-5}
Internal			
tritium	0.2	0.2	0.2
carbon-14	0.8	1.0	0.8
iron- 55	4×10^{-2}	4×10^{-2}	4×10^{-2}
strontium-90		2.7	2.0
caesium-137	1.0	1.0	1.0
plutonium-239		7×10^{-3}	
TOTALS	7.2	10.1	9.2

5. SUMMARY OF DOSE ESTIMATES

Before comparing the figures in Tables 4 and 5 it should be noted that UNSCEAR figures do not give a thyroid dose commitment estimate. UNSCEAR gives figures for specific areas (UNSCEAR 1972) but does not give world average figures, presumably because of the great geographical variation in the use of cow's milk and also because of uncertainties arising from the need to give an age weighted figure. UNSCEAR also includes three radioisotopes not included in the local measurements (krypton-85, iron-55 and plutonium-239) but which do not significantly contribute to total dose commitment for any particular tissue.

External radiation doses based on local data (Table 4) are lower than those derived from UNSCEAR (Table 5), particularly for short-lived activities. This may be due to geographical factors or it may be a consequence of the sampling and computational techniques used in deriving doses from environmental data.

The figures for tritium and carbon-14 agree as they were derived from UNSCEAR data in both tables.

The figures for strontium-90 and caesium-137 are both higher when based on local data. The difference in measured caesium body burdens in relation to deposition when compared with expectation based on world average ratios has already been noted but the source of the strontium-90 difference has not been identified.

Overall there is reasonable agreement between the two sets of figures. When assessing the significance of fallout dose the higher of the figures given in Tables 4 and 5 for each body tissue and each source of radiation is used.

Dose Commitments from French and Chinese Tests Separately

Using the figures for fractional transfer from one hemisphere to the other discussed in Appendix A (20 per cent for strontium-90 and caesium-137, nil for short-lived activities and 50 per cent for tritium and carbon-14) the dose commitments of Tables 4 and 5 may be apportioned between the French and Chinese tests to give estimates of the dose commitments in Australia from each nation's tests separately.

The results of such apportionment are given in Table 6, using the higher of the estimates in Tables 4 and 5 for each of the radioisotopes listed.

TABLE 6

ESTIMATED AUSTRALIAN DOSE COMMITMENTS FROM THE FRENCH TEST SERIES AND FROM THE CHINESE TEST SERIES

Source of Radiation	Dose Commitment (mrad)							
	Whole Body and Gonads		Endosteal (Bone-Lining) Cells		Bone Marrow		Thyroid	
	Fr.	Ch.	Fr.	Ch.	Fr.	Ch.	Fr.	Ch.
External								
short-lived	2.8	0.0	2.8	0.0	2.8	0.0	2.8	0.0
caesium-137	1.9	0.5	1.9	0.5	1.9	0.5	1.9	0.5
Internal								
tritium	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
carbon-14	0.4	0.4	0.5	0.5	0.4	0.4	0.4	0.4
strontium-90			5.3	1.3	3.8	1.0		
caesium-137	2.0	0.5	2.0	0.5	2.0	0.5	2.0	0.5
iodine-131							96(a)	
TOTALS	7.2	1.5	12.6	2.9	11.0	2.5	103(a)	1.5

(a) *Young children: less for others.*

6. PUBLIC HEALTH ASPECTS OF RADIATION EXPOSURE

Following the discovery of X-rays and natural radioactivity at the end of the nineteenth century it was soon discovered that exposure to ionising radiation could have adverse effects on health. Large doses of radiation (more than a few hundred rads) caused immediate effects from which there might or might not be recovery, depending on the dose and fraction of the body exposed. It was also found that exposure resulted in an increased incidence of cancer and leukaemia in later years.

Animal experiments also showed that radiation exposure resulted in increased mutation rates - the off-spring of exposed animals were more likely to suffer from genetically caused ill-health.

These findings are the basis for setting limits to exposure for occupational radiation workers which have been found to be readily achievable with, to date, no demonstrable adverse effects on the health of those exposed below the limits.

Figures for the risk of cancer as a function of dose have been collected over the past two decades or so from as many sources as possible, and are thoroughly reviewed in UNSCEAR (1972) and BEIR (1972). In relation to the present assessment of the effects of dose of the order of 10 mrads it should be noted that the figures obtained relate in the main to persons who received doses of more than 100 rads over short periods of time and that no information is available on the biological effects of doses less than 1 rad spread over months or years. It is therefore necessary to make some assumption about the way in which the risk falls as dose decreases, and the period over which it is received increases.

The simplest assumption is that the risk is proportional to the dose and that the period over which it is received is of no consequence. This assumption has been adopted by the International Commission on Radiological Protection (ICRP), for the purpose of setting acceptable dose limits and legislators have generally followed their example. There are no grounds for supposing that risk increases faster than dose and some grounds for supposing (at least in some cases) that risk decreases as dose rate decreases. The assumption that risk is proportional to dose is therefore generally considered to be conservative, that is, likely to overestimate the consequences of low doses.

The Risk of Cancer Following Radiation Exposure

The major observed carcinogenic consequences of human exposure to external radiation are summarised in Table 7. Two points will be noted from this table. Firstly, there is considerable uncertainty in the risk factors. This arises from the statistical nature of the observations. In every case, the risk factors are based on the observation of a certain number of cases in an exposed population as compared with a somewhat smaller number expected or observed in a similar but unexposed population. Unless the observed excess is large, compared with expectation, the degree of uncertainty indicated by the ranges given in Table 7 is unavoidable. Secondly, the risk factors are based on observations over a period of 20 years or so. The observations are sufficient to show that the risk rate does vary with time after exposure but not to give any indication of likely rates outside the observation period.

For leukaemia the risk rate rises over the first 10 years following exposure and then drops, although it is still positive at 20 years. For other cancers it is not clear whether the peak risk rate has been reached at 20 years or not, (the observation of radiation induced cancer becomes more difficult the older the population becomes because the natural incidence rises rapidly for most forms as age increases. It may well be therefore that observations over the next 20 years will not add much to current assessment of risks, except for those in the irradiated populations who were children at the time of exposure).

TABLE 7

RISK FACTORS FOR CANCER AS A RESULT OF EXTERNAL RADIATION EXPOSURE

Type of Cancer and Period of Observation	Cases per Year per Million Persons per Rad		
	UNSCEAR Risk Factors (UNSCEAR 1972)	Academy of Sc. Risk Factor (BEIR 1972)	Suggested Values
Leukaemia (for approx. 20 years)	0.7-2	1-2	1.5
Thyroid (approx. 20 years)	1-2 (Male) 2-4 (Female)	1.6-9.3 (children)	2 for adults 6 for young children
Breast (approx. 25 years)	0.25-6 (Female)	1-8.4 (Female) (best value=6)	3 to give risk to whole population (Divide best value by 2)
Lung (approx. 25 years)	0.6-2	0.1-1.6	1
Other	2 approx.	0.1-1 (bone) 0.1-6 (stomach) 0.2-8 (other) 0.4-2.4 (total)	0.2 - - 1.5 (total)

Absolute risk for all cancer excluding leukaemia is 8.5 which may be compared with the US National Academy of Sciences value (BEIR 1972, Table 3-1, p.171) of 5.0 deaths/10^6 people/year/rad. (This value is for those aged 10 or more and is also reduced because of 50% cure for breast cancer.)

The risk factors of Table 7 are based on observations of groups of externally irradiated people. Dose commitments from fallout are the result of external irradiation and, in part, internal irradiation. There are no grounds for supposing that the carcinogenic consequences of internal irradiation differ from those of external radiation except in the case of irradiation of the thyroid by iodine-131, where in animals it has been shown that the risk factor from iodine-131 is at least a factor of three less than that from external irradiation. It is assumed that the carcinogenic risk from iodine-131 in the thyroid is one-third of that from external irradiation.

Genetic Effects of Radiation Exposure

There is no direct information on radiation induced genetic effects in man. It is therefore necessary to extrapolate from the very large amount of animal data in order to estimate the possible genetic consequences of radiation exposure in man (UNSCEAR 1972, BEIR 1972). This introduces rather more uncertainty into the assessment of genetic consequences than arises from the assessment of carcinogenic risks. Further difficulty arises inasmuch as the consequences of genetic defects vary very widely. At one extreme, a genetic defect may be such as to cause foetal death and at the other extreme it may produce no adverse effect. Those defects which lead to severe disability in the live born are generally regarded as most adverse, although in terms of public health if there were a very much larger number of minor defects than major, the overall significance of the minor defects could be the greater. However, the existence and frequency of such minor defects is not well established and studies of irradiated animal populations suggest they are not significant.

As an indication of the magnitude of the genetic consequences of human exposure to radiation, UNSCEAR has estimated (on the basis of mouse data) that a parental gonad dose of 1 rad gives rise to somewhere between 6 and 15 live births per million in the first generation suffering from genetic disease, with a total number over all generations of around 300. As the birth rate in developed communities is of the order of 2 per cent of the total population per year the first generation incidence rate is 1.2 to 3.0 x 10^{-7} per year per rad averaged over the total population. This is at least a factor of 20 down on the annual cancer incidence per rad, although this factor is offset by the cases occurring in subsequent generations, such that the total number of cases of genetic disease and of cancer appear to be the same.

7. EFFECTS OF FRENCH AND CHINESE WEAPONS TEST FALLOUT ON PUBLIC HEALTH IN AUSTRALIA

(a) Possible increases in cancer incidence

Table 8 combines the dose commitments of Table 6 with the risk factors of Table 7 to give estimates of the possible numbers of cases of cancer per year in Australia as a result of weapons test fallout from French and Chinese tests over the period 1964-1972. Population dose commitment is the product of individual dose commitment and total population taken to be 12.5 million people.

Summarising, the upper limit to the incidence in Australia over the next 20 years of all forms of cancer, including leukaemia, as a result of environmental contamination from the French and Chinese series of atmospheric nuclear test explosions over the period 1964-1972 is estimated to be:

From French tests	1.4 cases per year
From Chinese tests	0.2 cases per year

The upper limit figure for the French tests is made up of 0.7 per year thyroid cancer, 0.2 per year leukaemia and 0.5 per year for all forms of cancer (rounding off the figures of Table 8). It should be noted that, since there is no short-lived fallout in Australia from the Chinese tests, the thyroid cancer

TABLE 8

POSSIBLE CASES OF CANCER PER YEAR OVER THE NEXT 20 YEARS IN AUSTRALIA AS A RESULT OF FALLOUT FROM THE FRENCH AND CHINESE NUCLEAR TESTS OVER THE PERIOD 1964-1972

Tissue	Bone-Lining Cells		Bone Marrow		Thyroid		Whole Body	
Cancer Risk Factor (cases y^{-1} rad^{-1})	Bone 2×10^{-7}		Leukaemia 1.5×10^{-6}		Thyroid (a) 3×10^{-6}		All Other 5.5×10^{-6}	
Test Series	Fr.	Ch.	Fr.	Ch.	Fr.	Ch.	Fr.	Ch.
Individual dose commitment (mrad)	12.6	2.9	11.0	2.5	7.2	1.5	7.2	1.5
Population dose commitment (krad)	157	36	137	31	90	19	90	19
Cancer rate (cases y^{-1})	0.031	0.007	0.20	0.046	0.27 plus 0.40 (a)	0.057	0.50	0.105

(a) *This column estimates the rate from external irradiation of the thyroid only. As the dose commitment from internal irradiation of the thyroid (from iodine-131) is known only for young children it is necessary to make some assumptions in order to estimate the total population dose commitment. These assumptions are that the adult dose per unit exposure in diet is one tenth of the young child dose, that there is a linear fall in dose per unit exposure and risk per unit dose from age 1 (the young child) to age 15 (young adult) and that one third of the total population is under age 15. These assumptions give an Australian population dose commitment from iodine-131 of 300 krad and, using a risk coefficient one third of that for external irradiation, gives a thyroid incidence of 0.40 cases per year.*

component from Chinese tests is very small.

It must be noted that these numbers are derived using figures for the risk of cancer induction per unit dose which are not well established statistically and which derive from experience with doses of the order of 100 rads or more received over short periods of time. The linear extrapolation of these figures to doses of the order of 10 mrad or less received over a period of years may well overestimate the effect of these much lower doses and dose rates, that is, the above numbers probably overestimate the impact of nuclear tests on public health.

(b) Possible genetic effects

Extrapolations from animal data suggest that the overall consequences of radiation exposure in terms of cases of genetic disease produced (of varying degrees of severity) are of the same order as those in terms of cases of cancer produced, although the former are spread over many generations whereas the latter are not. Consequently the incidence of genetic disease (expressed as cases per year) is less than that of cancer.

Because of the uncertainties in the genetic risk estimates, no numerical estimate of the consequences of exposure to fallout from the French and Chinese tests is made, other than the observation that the incidence of genetic disease is almost certainly less than that of radiation induced cancer.

8. REFERENCES

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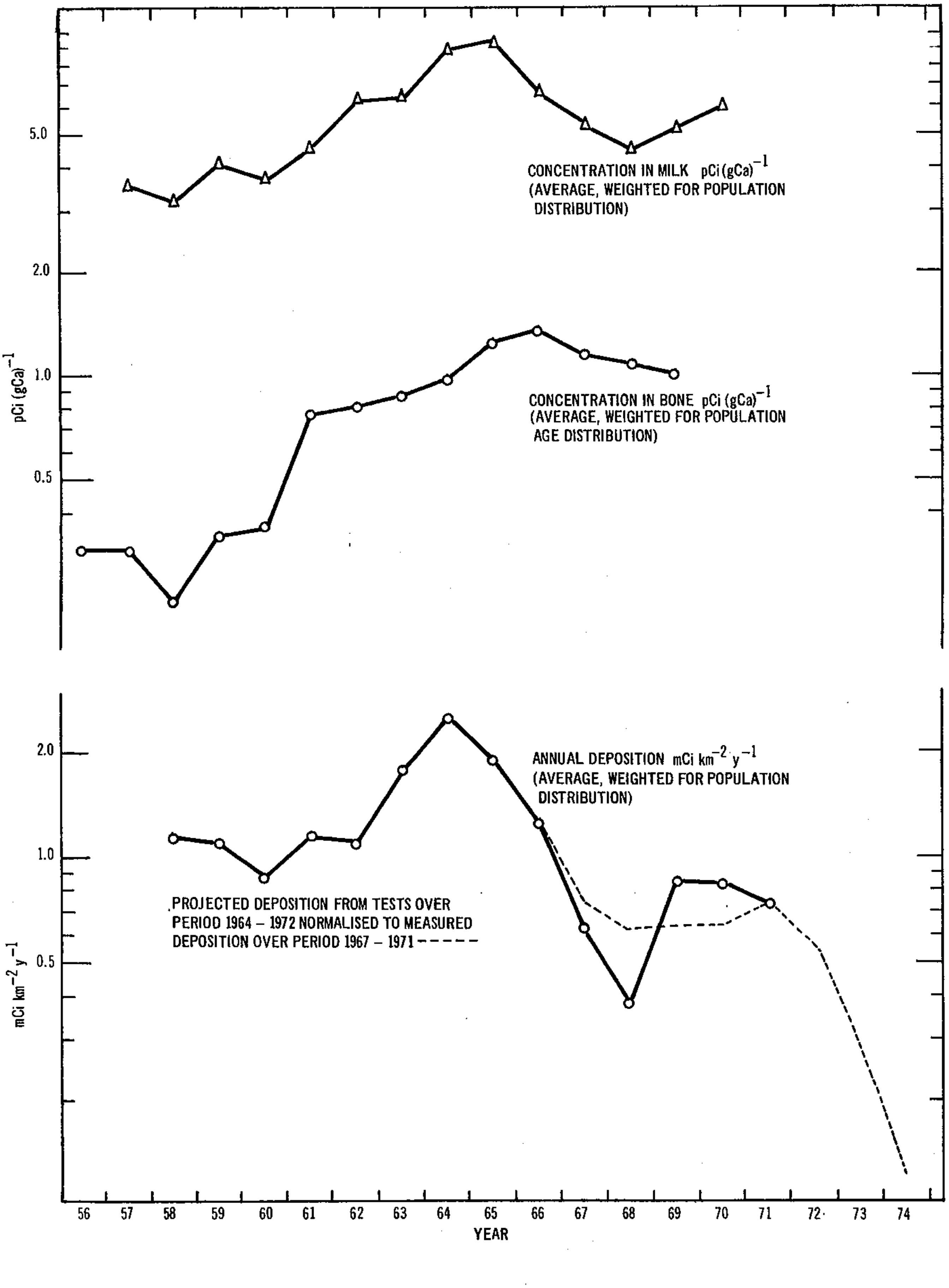

FIGURE 1. STRONTIUM-90 IN THE AUSTRALIAN ENVIRONMENT

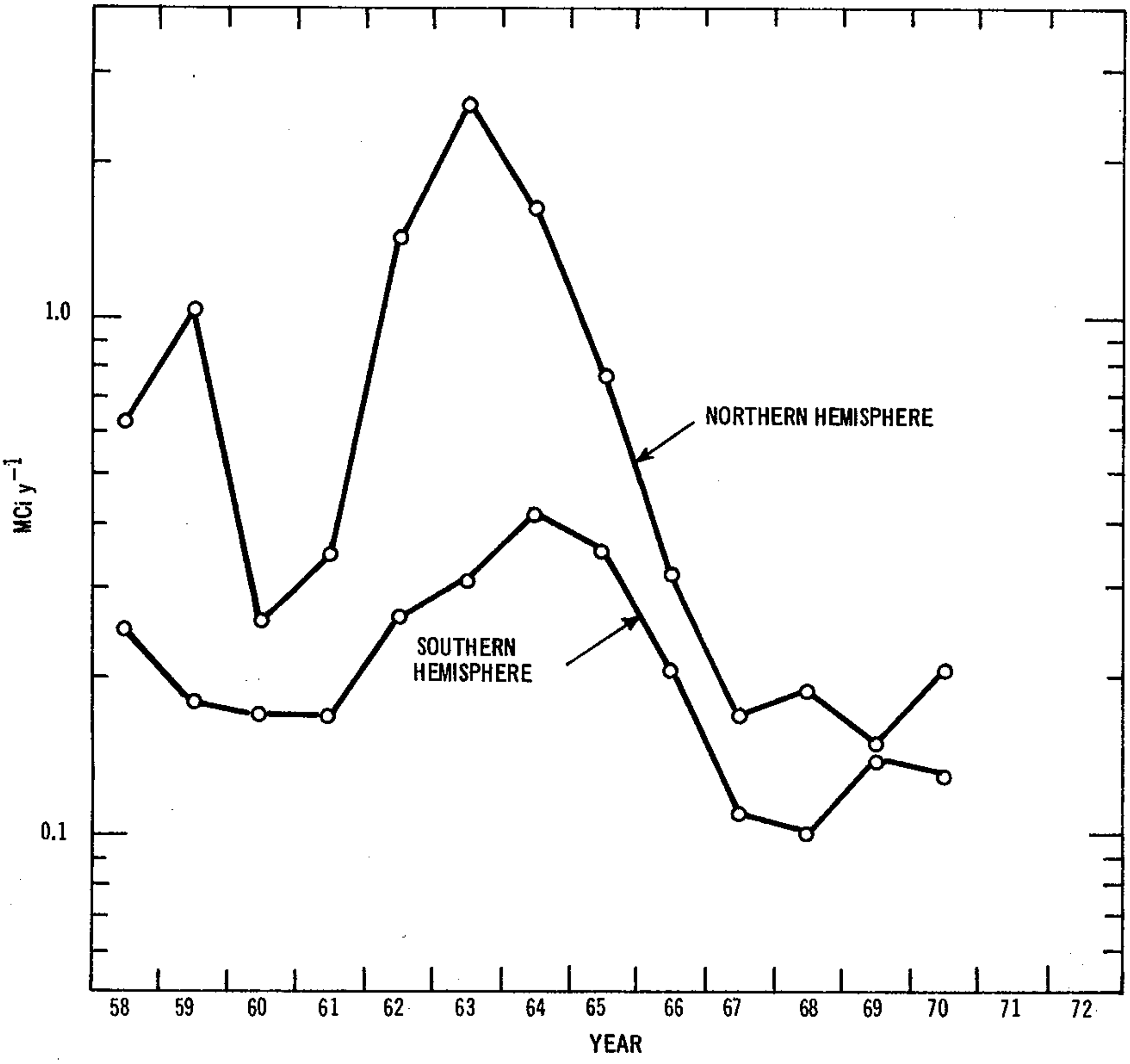

FIGURE 2. GLOBAL DEPOSITION OF STRONTIUM-90

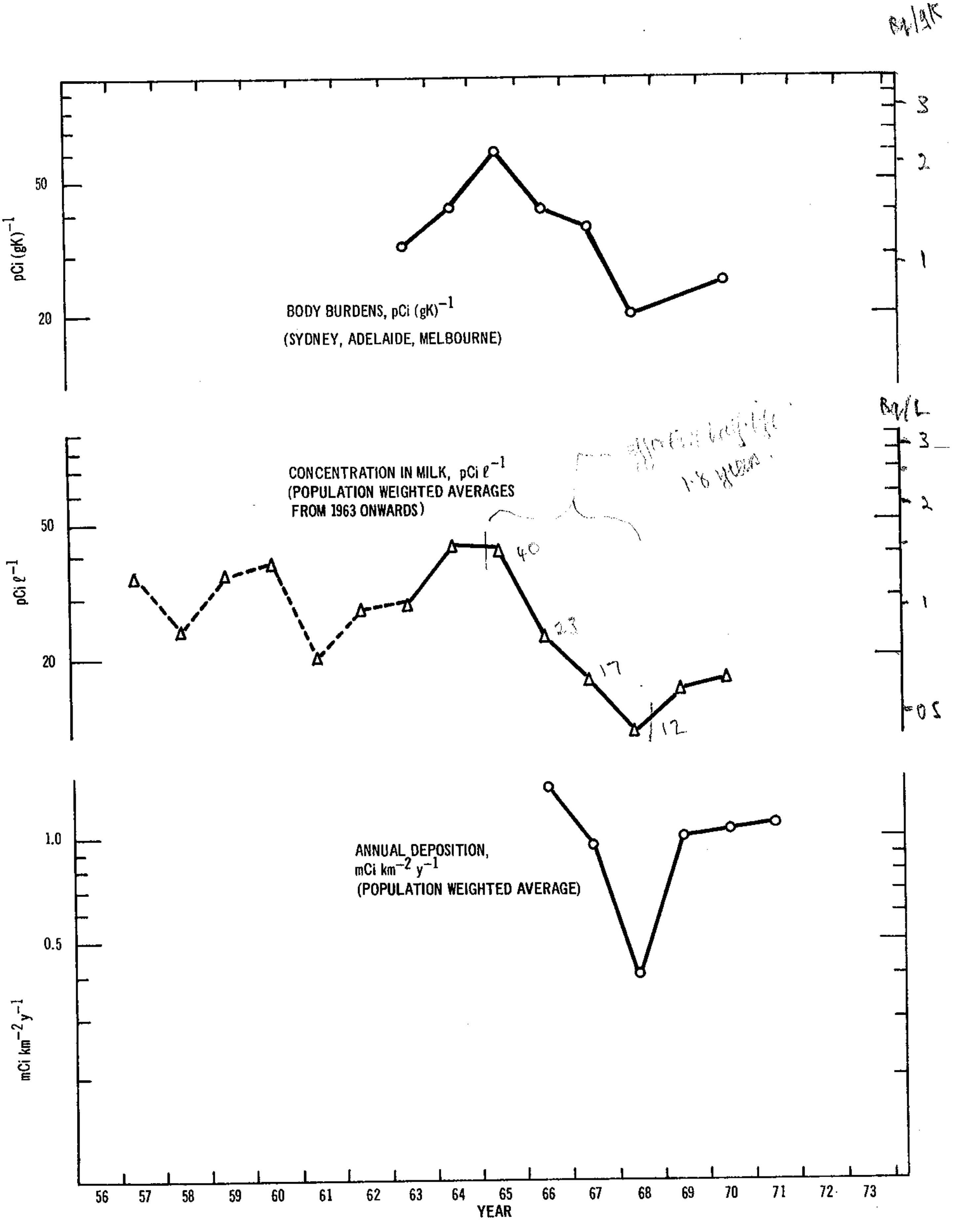

FIGURE 3. CAESIUM-137 IN THE AUSTRALIAN ENVIRONMENT

APPENDIX A

WEAPONS YIELDS AND RELEASES OF STRONTIUM-90 TO THE ATMOSPHERE

Table A1 summarises available information on the French Pacific tests to the end of 1972, including estimates of quantities of strontium-90 injected into the atmosphere as a result.

Table A2 summarises similar information on the Chinese tests. The total injection of strontium-90 to atmosphere in each case is about 650 kilocuries.

Table A3 lists the total fission yields of all tests prior to 1963 by country of origin and hemisphere. Some US and UK tests were held at Christmas Island, latitude 2° north and are listed as equatorial tests. This table has been compiled from information given in USAEC report HASL-142 (1964). There were some low yield French tests in the Sahara during 1961 and 1962, not included above, but which made no significant contribution to the northern hemisphere injection for that period. There were no tests in 1963; Chinese tests (Table A2) which started in 1964, were the only sources of injection to atmosphere in that year.

Table A4 lists injections of strontium-90 to atmosphere (northern and southern hemispheres) using the fission yields of Table A3, assuming 100 kCi of strontium-90 per megaton fission yield and that the equatorial injections were equally divided between northern and southern hemispheres.

These figures are somewhat greater than estimates of global strontium-90 inventory. For example, total world cumulative strontium-90 deposition at the end of 1966, corrected for decay between the year of deposition and that time, but not for decay between injection and deposition, is estimated to be 13.9 MCi (after decay this is 12.3 MCi), the local fallout, corrected for decay as above, 2.4 MCi, and the stratospheric content 0.3 MCi, giving an estimate of the total injection up to 1966 of 16.6 MCi (UNSCEAR 1972) compared with a figure of 19.2 MCi from Tables A1, A2 and A3.

(For the present purpose the uncertainty in these numbers is acceptable as only the ratio of the French and Chinese yields to total yields is used, and that only to derive figures for the dose commitments from tritium and carbon-14.)

Atmospheric Transfer of Material from One Hemisphere to the Other

The rate of exchange of airborne material from one hemisphere to the other is slower than the rate of deposition of particulate material. This is clearly illustrated when the stratospheric inventories for both hemispheres over the period 1963 to 1966 are examined (see data presented in Figure XV of Annex A, UNSCEAR 1972). At the start of this period the northern hemisphere contained the larger fraction of the total inventory and at the end the two hemispheres had much reduced (by deposition) but approximately equal inventories (due to interchange).

If it is assumed that the rates of deposition in each hemisphere are the same and the rates of exchange from one to the other also the same, the above data may be shown to give a deposition rate of 0.74 per year and an exchange rate of 0.23 per year.

Denoting the deposition rate by λ_d and the exchange rate by λ_e it may be shown that the fraction of the original inventory in one hemisphere transferred and deposited in the other hemisphere is $\lambda_e/(\lambda_d + 2\lambda_e)$. The above numerical values for λ_e and λ_d give a transfer fraction of 0.19.

For any particular explosion the exact transfer fraction will depend on the latitude of the explosion, the height reached by the debris and also the time of year the explosion took place; the above figure therefore represents an average over the conditions of the explosions prior to 1963. In the absence of detailed calculations for the French and Chinese tests it is assumed that approximately one fifth of the long-lived particulate fission products (strontium-90 and caesium-137) are transferred from one hemisphere to the other. For the short-lived activities (iodine-131 and gamma emitters mostly deposited within a few months of an explosion) no transfer is assumed, while for the long-lived gaseous materials (tritium and carbon-14) a 50 per cent transfer is assumed.

TABLE A1

FRENCH NUCLEAR TESTS IN THE SOUTH PACIFIC

1966-1972

Year	Date	Power of Device	Injection of Strontium-90 (kCi) to Atmosphere	Ref.
1966	July 3	25-30 kiloton	60	HASL-183
	July 20	70-80 kiloton		
	September 12	about 120 kiloton		
	September 25	about 150 kiloton		
	October 5	200-300 kiloton		
1967	June 6	low yield	0.9	HASL-210
	June 28	low yield		
	July 3	low yield		
1968	July 8	medium power		
	July 16	medium power		
	August 4	medium energy		
	August 25	hydrogen bomb (2 megaton)	230	HASL-227
	September 9	hydrogen bomb (2 megaton)		
1969		NO NUCLEAR TESTS IN THE PACIFIC		
1970	May 16	low power		
	May 23	low power		
	May 31	high power	240	HASL-257
	June 25	low power		
	July 4	hydrogen bomb		
	July 28	low power		
	August 3	low power		
	August 7	low power		
1971	June 6	low power		
	June 13	middle power	44	HASL-257
	July 5	low intensity		
	August 9	low intensity		
	August 15	hydrogen bomb (1 megaton)	50	(a)
1972	June 26	very low power		
	July 1	low yield		
	July 28	low yield		

(a) *Notional figure based on comparison with 1968 figures above.*

TABLE A2

CHINESE TESTS IN THE NORTHERN HEMISPHERE

1964-1972

Year	Date	Power of Device	Injection of Strontium-90 (kCi) to Atmosphere	Ref.
1964	October 16	low yield	2	HASL-183
1965	May 14	low yield		
1966	May 9 October 27 December 28	medium yield low yield medium yield	10	HASL-183
1967	June 17	hydrogen weapon (3 megaton)	170	HASL-210
	December 24	low yield		
1968	December 27	hydrogen weapon (3 megaton)	115	HASL-210
1969	September 22	low yield		
	September 29	hydrogen weapon (3 megaton)	150	HASL-242
1970	October 17	hydrogen weapon (3 megaton)	200	HASL-257
1971	November 18	low yield		
1972	January 17 March 18	low yield medium yield		

TABLE A3

FISSION YIELDS OF ALL WEAPONS TESTS, 1945-1962

Years	Fission Yield, Megatons			
	Country of Origin and Location of Injection to Atmosphere			
	US and UK			USSR
	Northern Hemisphere	Southern Hemisphere	Equator	Northern Hemisphere
1945-1951	0.7	0.0	0.0	< 0.1
1952-1954	37.0	< 0.1	0.0	0.5
1955-1956	9.1	0.1	0.0	4.0
1957-1958	4.0	0.1	15.0	21.0
1959-1960	0.0	0.0	0.0	0.0
1961-1962	4.0	0.0	12.0	85.0

TABLE A4

INJECTIONS OF STRONTIUM-90 TO ATMOSPHERE, 1945-1962

Years	Injection of Strontium-90, MCi	
	Northern Hemisphere	Southern Hemisphere
1945-1951	0.08	0.0
1952-1954	3.7	0.01
1955-1956	1.3	0.01
1957-1958	3.3	0.7
1959-1960	0.0	0.0
1961-1962	9.5	0.6

APPENDIX B

ESTIMATE OF STRONTIUM-90 DEPOSITION IN AUSTRALIA FROM 1972 ONWARD AS A RESULT OF FRENCH AND CHINESE TESTS 1964-1972

Comparison of global deposition of strontium-90 in the southern hemisphere (Figure 2 of the main text) and deposition in Australia (Figure 1 of the main text) shows that generally there is a fairly constant ratio between the levels. Hence a prediction of hemisphere deposition may reasonably be converted to local deposition by the use of an appropriate normalising factor.

Reference to Table A4 of Appendix A and Figure 2 of the main text indicates that an effectively single injection of 9.5 MCi in 1961-1962 in the northern hemisphere gave a relatively sharp deposition peak in the northern hemisphere and a broader peak in the southern hemisphere. As the required estimate of deposition relates (in the main) to injection in the same hemisphere as the deposit, the pattern of deposition over the period 1962-1966 in the northern hemisphere resulting from injection in the northern hemisphere is used as a basis for the estimate of deposition pattern in Australia from 1966 onwards from the French tests. This is then normalised by comparison with actual deposition over the period 1967-1971, with the result shown by the broken line in Figure 1.

The normalised projected deposition estimate overestimates for the years 1967 and 1968, underestimates for the years 1969 and 1970, and, fortuitously, agrees with the measured figure for 1971. These differences are assumed to be due to variations in local meteorology from year to year. Although only the French test contributions were considered in deriving the time dependence of the estimated deposition, the smaller contribution from the Chinese tests, being more spread in time, is assumed not to affect this significantly, while the normalisation procedure takes account of the total contribution of the Chinese tests.