[redacted]

Dr. R. CAIRNS

AAEC/E242

AAEC/E242

Dr. Cairns, I obtained two copies of AAEC/E242 from the Library & posted to Messrs Creef, [illegible]

Am 13/7/73.

Am 13/7/73

Mrs Mace p. ask Mr Creef to ensure he gets a copy of this as well as his [illegible].

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Return please as I want to finish reading it.

R Cairns, 13/7/73.

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AUSTRALIAN ATOMIC ENERGY COMMISSION
RESEARCH ESTABLISHMENT
LUCAS HEIGHTS

Am 20/2/74

Mrs Mace

p. return to the Library by hand.

R Cairns 20/2/74

EFFECTS ON THE SURROUNDING POPULATION OF POSTULATED MAJOR ACCIDENTS AT THE AAEC RESEARCH ESTABLISHMENT

by

J.C.E. BUTTON
E. CARRUTHERS
J.E. COOK
D.W. CRANCHER
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Sub-Committee appointed by the
Research Establishment Safety Committee

November 1972

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RESTRICTED

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PREFACE

As with many other forms of human activity the operation of nuclear establishments is accompanied by some risk to man. The magnitude of such risks may be very small, but it is proper to assess it and take it into account when introducing major new facilities, and continually to re-assess the safety of older ones in the light of new knowledge or changed environmental circumstances. Such assessments are not, or at any rate should not be peculiar to nuclear establishments since they are not alone in creating some public risk. Two kinds of public risk may be associated with nuclear plant: the risks associated with normal operation which must be allowed for in its discharge authorisations, and the risks associated with possible accidents in the plant. This document deals with the second of these, the hazards attributable to potential accidents.

There are difficulties in making such assessments. What sort of possible accidents should we consider? Evidently it must be the worst that is both possible and credible, even though most improbable. Unfortunately, it is not easy to secure agreement on what is credible, and to that extent the selection of the worst case must be subjective. At the Research Establishment there are several facilities which must be considered to have accident potential, and the consequences of accidents may differ from one to another. For example, a HIFAR accident will be seen primarily as a release of radioactive iodine, and a Critical Facility accident as a release of plutonium. This diversity of sources leads to a diversity of undesirable effects: possibly leukaemia and thyroid tumours in the one case, and lung cancer in the other. Acceptance of the assessment implies that we are able to equate the undesirability of these different effects.

For each major facility, a Maximum Credible Accident (MCA) can be defined and from these it is not too difficult to derive approximations of their effects in terms of illness in man, making use of generally accepted risk coefficients and keeping in mind their limitations of accuracy and interpretation. What is more difficult is to take this assessment of the worst that might happen and make the formal judgement that the risk is offset by the benefit of allowing the facility to operate. The judgement cannot be avoided by comparing the consequences of release, measured in rem doses, with various sets of reactor siting criteria; the doses spelt out in siting criteria should be translated into human consequences.

Such an assessment cannot be a once-for-all time procedure. The emphasis of operations must change and new facilities will come into use. Nor is our

concept of safety a static thing: acceptable standards change by evolution and we develop a better understanding of what we can reasonably demand.
The risk associated with a major nuclear facility is not determined solely by its nature and operation; it also depends on the distribution and density of the surrounding population, and population changes must be allowed for or further assessments made with changes. Finally, the risk coefficients used to predict the incidence of ill-effects have become more refined over the past decade, as observational and experimental evidence accumulate, and this is likely to continue. For all these reasons, assessments must be repeated from time to time.

This present assessment was carried out by a Sub-Committee appointed in February 1969 by the Research Establishment Safety Committee. This Sub-Committee was known as the Research Establishment Site Safety Assessment Sub-Committee (RESSASC).

The original terms of reference of this Sub-Committee were effectively to produce an updated assessment of the type previously undertaken in 1959 by Wilson and subsequently in 1963 by Fry. The request for the re-assessment arose out of Commission Decision No. 3107 which followed Commission consideration of a general review of problems of public safety and land usage in the vicinity of the Research Establishment presented as Commission Memorandum 208/1968. The information papers used by the RESSASC are filed on LH69/243 and the Minutes of the Committee Meetings are filed on LH69/242.

The assessment was protracted, partly because it was carried out as a part-time activity by members of the Sub-Committee and also because it involved continual refinement as assumptions were challenged and changed and better data and information became available. In its present form it was presented to the Research Establishment Safety Committee in December 1971. It is now out of date in some major respects. In particular, partly as a consequence of the report, a much more detailed safety assessment of HIFAR has been carried out; this is presented in the HIFAR Safety Document (August 1972). In addition, a Working Party is at present reviewing the need for restrictions on the use of land surrounding the Research Establishment in relation to the consequences of the MCA for HIFAR.

In the light of the new information which has become available, some of the findings in the present report require modification. It is nevertheless considered of value to print the report as a detailed documentation of a significant step which was taken to achieve a more analytical and systematic approach to matters of public safety. Apart from contributing to the clarification of issues of safety philosophy, the report has been of considerable value in providing information and analyses relevant to the consequences of various postulated MCAs, the potential of the site for future development, the adequacy of the land restrictions surrounding the site, the effectiveness of the existing safety procedures and protective devices, and the planning of emergency procedures in the unlikely event of a serious accident.

The Research Establishment Safety Committee wishes to place on record its appreciation of the efforts of the members of the Research Establishment Site Safety Assessment Sub-Committee in the preparation of its report.

R. Smith

R. SMITH

GMWatson

G.M. WATSON

for the Research Establishment
Safety Committee

SUMMARY AND CONCLUSIONS

The consequences of accidents in specific facilities at the Research Establishment are examined in terms of possible exposure of persons living around Lucas Heights to released airborne radioactive and toxic materials. In the case of radioactive materials, both individual and population doses are estimated, the latter over a range of meteorological conditions. Using currently available data on the risk of development of adverse effects in irradiated populations further estimates are made of the possible number of cases of such effects in the local population.

The HIFAR maximum credible accident (MCA) is taken to be a rupture of the primary circuit between the heavy water heat exchangers and the reactor tank inlet when operating at 11 MW (th) with a core of Mark IV fuel elements. Heat from molten fuel would create in the reactor sealed building an overpressure which would force some fractions of the released fission products through leaks in the containment. For a leakage rate of 1% of contained volume per 24 hours at 1.5 psig overpressure the fission products released to the atmosphere are estimated to be 660 curies of iodine-131, 4,000 gamma MeV-curies of radioactive rare gases and varying amounts of other fission products.

This release is postulated as occurring over a number of days under adverse weather conditions and is estimated to give doses to individuals at the one mile exclusion boundary:

- not greater than 100 child thyroid-rem
- not greater than 30 adult thyroid-rem
- less than one rem to the whole body.

I.S.C. (from below).
150 child thyroid-rem.
-
25 rem whole body

Doses to the surrounding population (for the year 2000, to allow for the consequences of development in the Menai area) would be:

- less than 3×10^5 thyroid-rem
- less than 200 man-rem whole body.

6×10^6 thyroid rem.
10^6 man rem

These figures may be compared with those given in the AAEC Interim Siting Criteria for Nuclear Reactors, which are:

- 150 child thyroid-rem to the individual
- 25 rem whole body to the individual
- 6×10^6 thyroid-rem to the population
- 10^6 man-rem whole body to the population.

J Cook
18/7/73
1 death

These doses could possibly cause a few hundred cases of thyroid nodules and about ten cases of thyroid cancers spread over at least 20 years. When identified, naturally occurring thyroid nodules require medical observation (few subsequently give rise to ill health); the prognosis for radiation induced nodules may, however, be different.

The actual number of cases of thyroid nodules and cancers could well be much smaller than given above (depending on weather conditions and wind direction). Averaging over all weather conditions gives figures of the order of one tenth of these estimates.

The numbers of thyroid cancers may also be overestimated inasmuch as experience with diagnostic and therapeutic use of iodine-131 indicates that the risks from internal dose to the thyroid are significantly less than the risks from external exposure, without there being sufficient information to enable accurate figures to be derived for the effects of iodine-131 doses. The risks from internal exposure to iodine-131 are assumed to be one third of those from external exposure, but the difference may well be greater than this.

0 deaths
for whole body

The population whole body dose of 200 man-rem resulting from the HIFAR MCA is too small to give rise to adverse effects such as leukaemia, other forms of cancer and possible genetic damage, which are observed for population whole body doses of the order of 10^5 man-rem or greater.

An assessment of the possible consequences of accidents in the other existing buildings at the Research Establishment gives upper limits to possible doses considerably smaller than the HIFAR MCA; the largest is about 10 rem to the child thyroid for the release of 20 curies of iodine-131 as a result of a massive building fire involving Isotope Production Section (Building 23), and of the order of a few rem to the child lung as a result of a massive building fire involving the cobalt-60 cell area (Building 23) or the plutonium chemistry laboratories (Building 2).

The MCA for the Critical Facility currently under construction is postulated to be complete vaporisation of 60 kg of plutonium within the containment; the plutonium dioxide released to the environment could possibly cause between one and fifteen cases of lung cancer in the year 2000 population surrounding the site.

It is concluded that accidents involving radioactive materials in other buildings and facilities at the Research Establishment would have insignificant effects.

Other hazardous and toxic materials (notably beryllium and beryllia) used or stored at the Research Establishment are also considered. The worst accident involving such materials is taken to be a massive building fire; it is concluded that the containment and storage is such that there is small risk of adverse effects in the surrounding population as a result of accidental releases to atmosphere.

In the interests of limiting individual exposures in the event of accidental releases of radioactive materials from the Research Establishment, retention of the one mile exclusion radius is recommended. However, retention of this area need not preclude its use for recreational purposes. Should any reduction in the exclusion area be considered for any reason, it would be necessary to undertake a re-assessment of all facilities and to introduce those additional engineered safety features found necessary by such re-assessment.

In terms of the possible population exposure in the event of accidental releases of radioactive materials from the Research Establishment, there appear to be no reasons for maintaining the previously applied limits on population densities beyond the one mile exclusion radius. However, in future development of the site environs, care should be taken over the siting of hospitals (because of possible evacuation difficulties); for preference, they should not be erected within a radius of three miles from the centre of the exclusion area.

1. INTRODUCTION

Previous safety assessments of the AAEC Research Establishment site, carried out in 1959 (A.R.W. Wilson) and 1963 (R.M. Fry), reviewed the hazards attributable to potential accidents involving nuclear facilities at the Research Establishment and recommended restrictions on land zoning and housing settlement around the site. Changed conditions around the site caused by possible land transfers from Commonwealth to State, potential acquisition of land by the AAEC and the probable development of populated areas in the future have indicated the need for an updated assessment. A general review of the safety situation at and around the AAEC Research Establishment was carried out by a Working Party set up in November 1968 (Commission Memorandum 208/1968).

Such assessments require consideration of the nature and magnitude of foreseeable accidental releases of radioactive and toxic materials to the environment, the resultant exposure of the public, the consequent effects and the feasibility and effects of the introduction of countermeasures. In considering exposure of populations the ICRP (1965 and 1966) points out that it is not yet possible to balance risks and benefits since to do so requires a more quantitative appraisal of both the probable biological damage and the probable benefits than is now possible.

In the event of accidents involving environmental contamination all possible steps would be taken to limit exposure of individuals and the population surrounding the Research Establishment. The exposure limits adopted would to some extent depend on the circumstances at the time of the accident and, in particular, on the need to balance the risk from exposure against the risks arising from the consequences of possible countermeasures which may be introduced.

In the present assessment, recent (year 1970) and projected (year 2000) population distributions are considered in conjunction with the Pasquill atmospheric dispersion model (Pasquill 1961) and with currently proposed risk criteria from the literature to determine the effects of accidentally released materials in the surrounding population; personnel on site are not included. Consideration is given to existing facilities at the Research Establishment, together with those under construction and others which conceivably might be provided in the future.

In particular, consideration is given to the effects of:

(i) the HIFAR maximum credible accident (MCA);
(ii) an addition of reactivity to the MOATA core;
(iii) the maximum credible accident in the critical facility under construction;
(iv) releases of radioactive materials from other facilities at the Research Establishment;
(v) releases of chemically toxic materials.

This study reveals that the HIFAR MCA presents the greatest hazard, as did the previous studies. However, the earlier safety assessments used some assumptions and information which are no longer valid. The updated information used for the present assessment recognises that:

(i) a study of credible accident mechanisms for HIFAR has led to the definition and analysis of the course and consequences of the MCA;
(ii) the Mark IV fuel element now in use has less inherent protection against fuel meltdown than had Mark II and Mark III elements;
(iii) because the ^{235}U content of fuel elements has been increased, the core has an increased fissile inventory;
(iv) measurements of the containment leakage rate show it to be about 1% of contained volume per 24 hours at an overpressure of 1.5 psig - the previous assessments assumed leakage rates of 0.5% and 0.1% per 24 hours;
(v) experimental work (e.g. Bruce et al. (1963), Parker et al. (1967)) has shown that molten metallic fuel would release greater amounts of volatile fission products than were previously assumed.

In addition, meteorological data obtained from local observations are incorporated in the meteorological model used to assess the consequences of any postulated accidental release from the Research Establishment.

2. POSSIBLE METHODS OF ASSESSMENT

The assessment of the possible magnitude of releases of radioactive or toxic material from a nuclear reactor or other facility, and the assessment of the possible consequences in terms of adverse effects on public health, cannot be entirely objective because of uncertainties both in the models used and in the appropriate numerical values of the many parameters involved. A choice of possible methods of assessment is therefore open.

The two factors which chiefly determine the consequences of an accidental release of radioactive material to the environment are the population distribution around the site and the meteorological conditions at the time of the release. The former determines the number of people exposed and the latter determines the magnitude of exposures, through the dependence of degree of dispersion on atmospheric stability.

The population may be exposed to released radioactive materials by:

(i) external radiation (e.g. direct radiation from gamma sources exposed by an accident, from beta/gamma emitters in the passing cloud of released radioactive material or from such material deposited on the ground);

(ii) internal radiation from:

- ingested material (e.g. contaminated foodstuffs);
- inhaled airborne radioactive material.

Previous assessments estimated the doses received by individuals at varying distances in the event of accidental releases occurring under conditions of minimum dispersion (i.e. inversion conditions). More recently risk coefficients have been proposed (ICRP 1966, Dolphin and Marley 1969) which permit estimation of the risks of subsequent development of injuries (such as leukaemia or thyroid cancer) in exposed populations. Using such coefficients it is possible to determine not only the extent of any emergency countermeasures which may be required, but also to estimate the possible number of casualties which may occur in the exposed population.

A major variable in possible methods is the extent to which knowledge or judgement of the probability of the accident and of particular consequences are included in the assessment. If the consequences are always trivial, then the probability is of little concern and a simple non-probabilistic method is acceptable. If the consequences under some circumstances are not trivial (i.e. if deaths could result) the probabilities of such events are of concern and it becomes necessary to attempt to consider magnitude and probability together.

2.1 The Non-Probabilistic Method

The non-probabilistic method involves the following steps:

(i) The maximum credible accident is defined;

(ii) The quantity of hazardous material released to the environment as a result is determined;

(iii) The resulting maximum credible doses to individuals and to the local population as a whole are derived;

(iv) The maximum credible doses are compared with doses considered acceptable under accident conditions.

The disadvantage of the non-probabilistic method is the subjectivity involved, particularly in deriving maximum credible doses, where uncertainty in determining appropriate adverse meteorological conditions generally leads to their arbitrary definition. Such subjectivity may lead to conclusions that may not be optimum on more detailed analysis.

2.2 The Probabilistic Method

The probabilistic method involves the following steps:

(i) possible accidents and their frequency of occurrence are defined;

(ii) the possible quantities of hazardous material released to the environment are determined;

(iii) the range of possible doses and their frequencies in the local population are derived;

(iv) the casualty rate as a result of such doses and frequencies is derived;

(v) the casualty rate is compared with casualty rates from other sources, e.g. the population casualty rate from other industrial accidents or the normal frequency of the same conditions arising from other sources in the population.

The major restriction on the use of this method is that generally information on accident probabilities is not available. (A more complete description of the method has been given by Farmer (1967).)

2.3 The Methods Used in this Assessment

In this assessment, both the non-probabilistic method and the following intermediate approach have been used:

(i) the maximum credible accident is defined;

(ii) the quantity of hazardous material released to the environment as a result is determined;

(iii) the range of possible doses to the population as a function of the range of possible meteorological conditions is derived;

(iv) the upper limits of possible casualties in the local population for such dose distributions are derived.

For the HIFAR MCA (which leads to a release extending over several days) the possible casualties are assessed (a) by averaging over all wind directions and dispersion conditions and (b) for adverse meteorological conditions; the latter gives a maximum casualty figure and also serves as a guide to the extent of emergency countermeasures which may be required. For other facilities at the Research Establishment accidental releases of radioactive materials are postulated as occurring over a few hours. The effects of releases of toxic non-radioactive materials are also considered on the basis that they occur over a period of a few hours. The methods used are outlined in Figure 1.

3. INFORMATION REQUIRED FOR A SAFETY ASSESSMENT

3.1 Materials that could be Released

To assess the effects of a release of radioactive and/or toxic materials to the environment, a knowledge is required of the total amount of material contained in a given facility, its chemical and physical form and its particle size, the fraction likely to be released during the course of an accident, the time scale of the release and the mode of dispersion of the released material into the atmosphere.

3.2 Atmospheric Dispersion

A complete description of degree of dispersion at a particular locality as a function of time and distance requires a steady source of airborne material, a detector array extending over the area of interest and extensive measurements carried out over a period of at least a year. Such measurements are not available for the area around Lucas Heights. Some information has been deduced from measurements of short term wind direction fluctuations (Charash 1965) but, as with all such models, its extrapolation to the range of distances of interest to this study must be uncertain.

Accordingly, a notional model for atmospheric dispersion is adopted to take into account both local information and the more general information (Sutton 1947, Pasquill 1961). The derivation of this model is given in Appendix A.

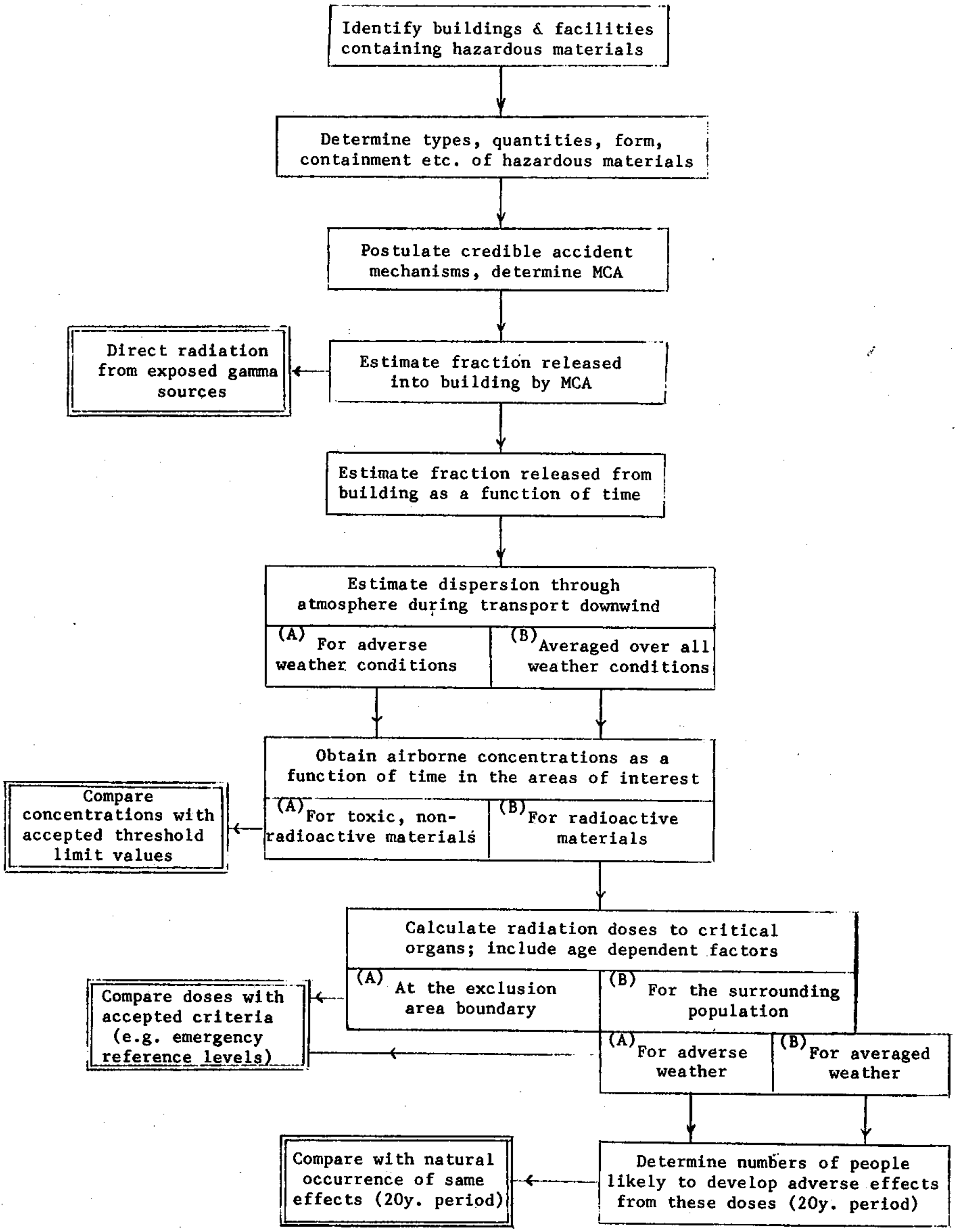

FIGURE 1. FLOWSHEET OUTLINING THE METHODS USED

For calculating maximum doses downwind of releases, the time integral of airborne concentration is assumed to be that on the axis of a plume with characteristics appropriate to inversion conditions.

For calculating population doses, concentrations across the plume are averaged over 30° sectors. As population dose is an integral function, the choice of angle is not critical provided the population distribution is reasonably uniform.

Predictions made in the above manner do not take account of topographical effects, but two features at Lucas Heights are possibly of some importance. First, at night, there will only be very limited diffusion of material entering the Woronora Valley adjacent to the site and moving down the valley to the settlement (at present, about 500 persons) some three miles from HIFAR (see Appendix A). Second, Lucas Heights is elevated relative to Sydney generally, particularly at distances greater than 5 miles, and consequently exposure at such distances may well be less than is given by the model, which relates to diffusion over level terrain.

3.3 Population and Age Distributions

In assessing the integrated risk to the general public and in considering possible emergency actions to reduce the consequences to local communities of a significant release, two population distributions are used - that for 1970 (Bureau of Census and Statistics, 1971) and the State Planning Authority's projected year 2000 population; both populations are assumed to have the same age distribution as that obtained from the N.S.W. 1966 census average. In considering specific communities (e.g. Engadine), the 1966 figures for these areas are used, and newly developed areas in the year 2000 are assumed to have the current age distribution for Engadine. Relevant population figures are shown in Tables 1 to 3 and in Figures 2 and 3. For those effects where an age-dependent sensitivity exists (e.g. thyroid cancer), the transition from child to adult is assumed to be at age 16 years, to be consistent with ICRP recommendations. Since dose per unit exposure and risk coefficient decrease with age, this assumed step function leads to an overestimation of casualties. Since figures for life expectancy in Australia are not significantly different from those in the U.K. and the U.S.A., risk coefficients derived for these countries are considered to be applicable to Australia.

Although the existing facilities (e.g. HIFAR) may not necessarily remain in operation until the year 2000, the Menai area can reasonably be expected

TABLE 1

POPULATION CENTRED ON HIFAR, 1970

Range Miles	Sector, bearings increasing clockwise from True North										
	0°-30°	30°-60°	60°-90°	90°-120°	120°-165°	165°-195°	195°-240°	240°-270°	270°-300°	300°-330°	330°-360°
1 - 2	-	200	1000	4000	500	-	-	-	-	-	-
2 - 3	-	1000	2000	2000	2000	-	-	-	-	-	-
3 - 4	200	1000	3500	1000	500	50	-	-	-	-	-
4 - 5	1000	2000	3500	50	-	50	-	-	-	-	-
5 - 7	33500	17000	20000	2000	-	400	-	-	1000	1000	2500
7 - 10	108000	145000	29000	8000	-	3000	-	26000	4000	5000	20000
10 - 15	167000	320000	23000	-	-	5000	1000	1000	3000	12000	163000

Note: No residents in the range 0 - 1 mile

TABLE 2

PROJECTED POPULATION CENTRED ON HIFAR, YEAR 2000

Range Miles	Sector, bearings increasing clockwise from True North										
	0°-30°	30°-60°	60°-90°	90°-120°	120°-165°	165°-195°	195°-240°	240°-270°	270°-300°	300°-330°	330°-360°
1 - 2	2000	2000	2000	5000	700	-	-	-	-	1000	2000
2 - 3	2000	7000	7000	3000	2500	-	-	-	-	2000	2000
3 - 4	3000	13000	5000	1500	500	1000	-	-	-	7000	5000
4 - 5	5000	18000	3500	50	-	1000	-	-	-	10000	8000
5 - 7	35000	22500	21500	2000	-	2000	-	-	30000	20000	50000
7 - 10	114000	154000	30500	9000	-	8000	-	100000	50000	30000	30000
10 - 15	176000	338000	24500	-	-	25000	60000	50000	50000	62000	250000

<u>Note</u>: No residents in the range 0 - 1 mile

TABLE 3 AGE DISTRIBUTION OF POPULATION IN DEVELOPING AREA

Age Next Birthday (bracketed by consecutive entries)	% of Population
0	2.90
1	3.17
2	3.69
3	3.00
4	3.77
10	12.78
16	11.39
20	6.59
25	7.60
30	11.39
35	9.17
40	7.36
45	5.30
50	3.43
55	2.72
60	1.92
65	1.57
70	1.27
75	0.81
>75	0.97

Note: For the purpose of this assessment the following percentage population distribution is assumed:

Children	(0-16 years)	41%
Adults	(>16 years)	59%

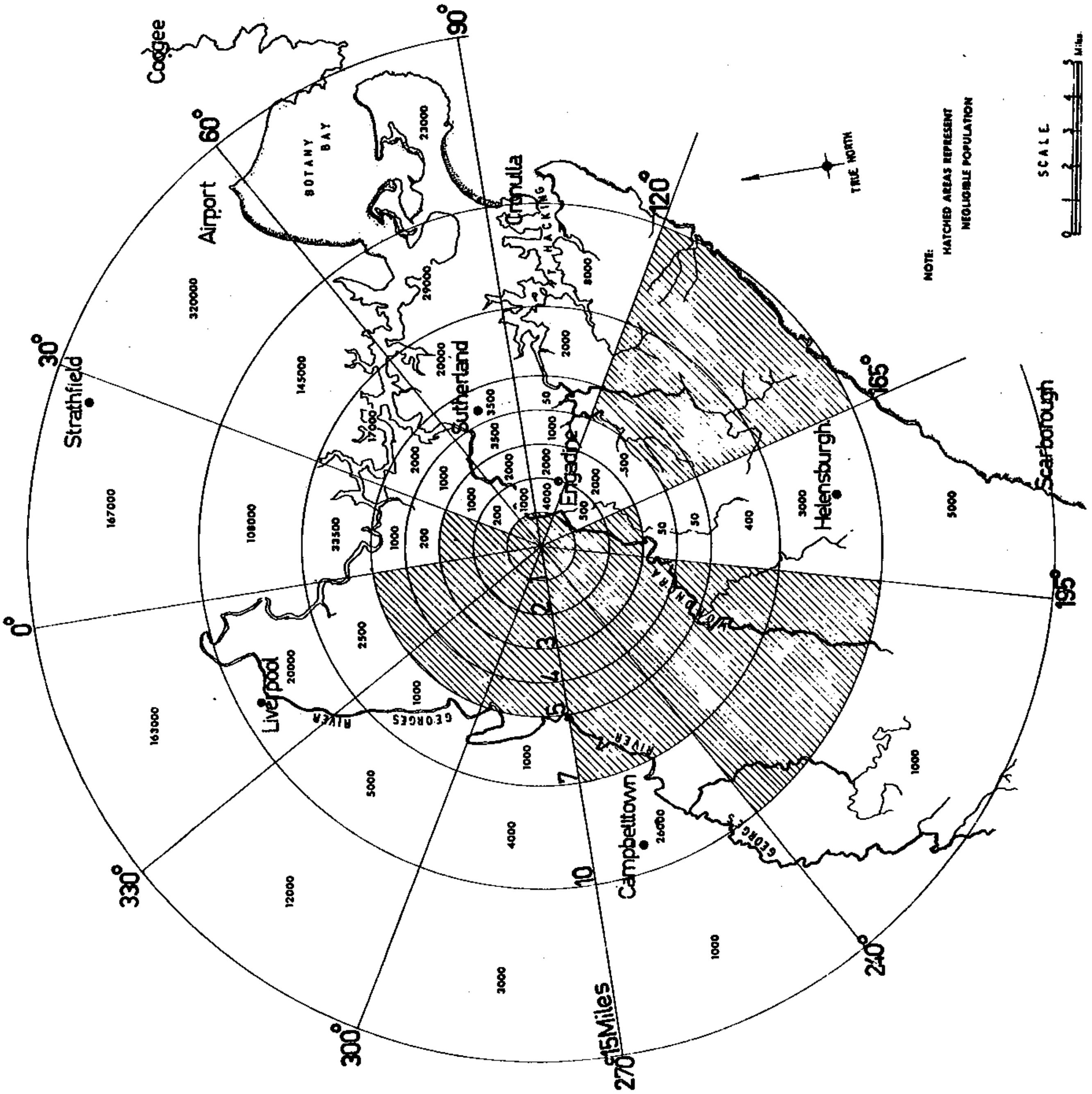

FIGURE 2. MAP OF POPULATION BY SECTORS (YEAR 1970)

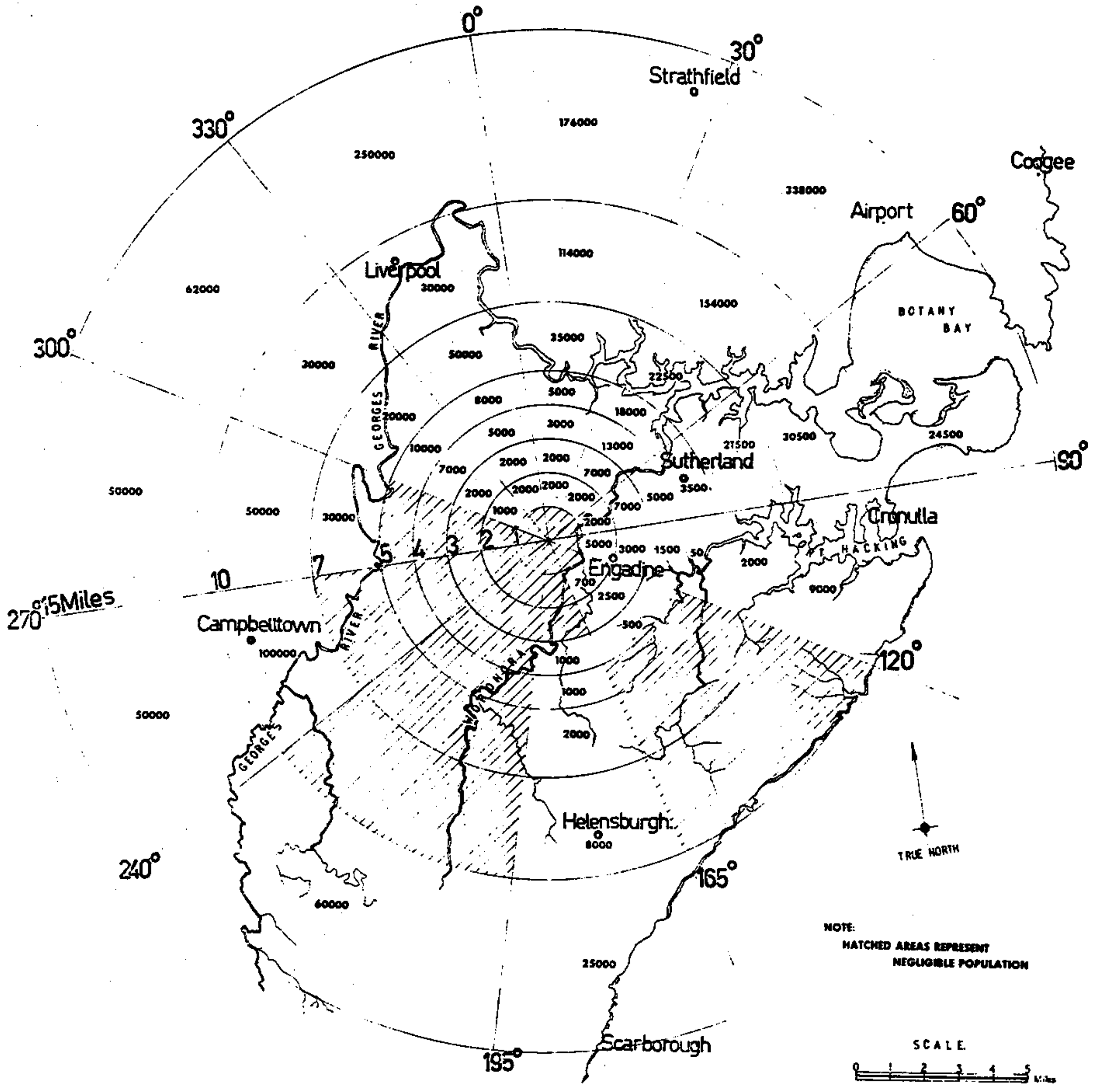

FIGURE 3. MAP OF POPULATION BY SECTORS (YEAR 2000)

to develop along the State Planning Authority's projected lines during the next decade.

3.4 Dose Evaluation

3.4.1 Ionising Radiations and Radioactive Materials

Pathways for human exposure which may exist during an accidental release of radioactive material include:

(i) external irradiation from beta-gamma emitters deposited on the ground and in the passing radioactive cloud;

(ii) internal irradiation from the consumption of contaminated foodstuffs (e.g. milk, eggs from free range hens, vegetables etc.);

(iii) internal irradiation from inhalation of air contaminated with radioactive material.

The external dose from the cloud of airborne emitters is calculated by assuming that the dose rate is that arising from a semi-infinite cloud containing the radioactive material and no account is taken of cloud depletion. If $\bar{E}$ MeV is the average gamma or beta energy emitted per disintegration and C the activity concentration in Ci m^{-3} the dose rate is given by 0.25 $C\bar{E}$ rad s^{-1} (USAEC 1957).

External irradiation from radionuclides deposited on the ground and in the passing cloud would only be of significance in the case of the HIFAR MCA.

The internal radiation hazard from contaminated foodstuffs is amenable to control by restriction of consumption; it is assumed that, if necessary, such control would be exercised, so that the population dose via this pathway would be minimal.

With the above assumptions, inhalation of air contaminated with radioactive material is shown to be the most restrictive exposure pathway. The inhalation exposure of an individual downwind from a release of airborne radioactive material is the product of the average airborne concentration to which he is exposed and the duration of exposure. The average airborne concentration is the product of the average rate of release and the airborne concentration factor* (appropriate to distance from the release, the duration

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*The airborne concentration factor is the quotient of airborne concentration (at the point of interest) by the release rate. It has the dimensions of time per unit volume and is the inverse of a dilution parameter.

of the release and the prevailing meteorological conditions). The numerical values used for the airborne concentration factors are taken from Pasquill (1961) and Bryant (1964), and are applied to meteorological data for Lucas Heights (Charash and Bendun 1968) (see Appendix A).

The dose to the individual as a result of the exposure depends on the properties of the radioactive material concerned and in some cases (e.g. exposure of the thyroid to radioiodine) on age.

The relationship between time integrated airborne exposure and dose as a function of age of the person exposed is taken from Dunster (1968) for iodine-131, strontium-89, strontium-90 and caesium-137, from Dolphin and Dunster (1961) for plutonium and inferred for cobalt-60 from the data given by Dolphin and Dunster (1961) and ICRP (1959). The figures are given in Table 4.

TABLE 4 - EXPOSURE-DOSE RELATIONSHIPS

Nuclide	Child/Adult	Critical Organ	Dose per Unit Exposure (rem m^3s^{-1} Ci^{-1})
Cobalt-60	Child	Lung	520
(insoluble)	Adult	Lung	180
Iodine-131	Child	Thyroid	810
(soluble)	Adult	Thyroid	280
Caesium-137	Child	Whole Body	3.4
(soluble)	Adult	Whole Body	11
Plutonium-239	Child	Lung	125,000
(insoluble)	Adult	Lung	44,000
Strontium-89	Child	Bone	190
(soluble)	Adult	Bone	42
			(rem $yr^{-1}m^3s^{-1}Ci^{-1}$)
Strontium-90	Child	Bone	1,800
(soluble)	Adult	Bone	420
Plutonium-239	Child	Bone	170,000
(soluble)	Adult	Bone	33,000

To derive the possible number of cases of injury as a result of a postulated accidental release to atmosphere, individual doses must be summed; this summation is carried out by estimating the average exposure and resulting dose in 30° annular sectors of one mile radial increments. For the present assessment, integration of doses to the population is discontinued when the doses to individuals are equal to the ICRP, NH and MRCA* recommended figures for annual dose limits to members of the public (see Table 5).

TABLE 5 - ICRP ANNUAL DOSE LIMITS FOR MEMBERS OF THE PUBLIC

Organ or Tissue	Dose Limit for Members of the Public
Gonads, red bone marrow	0.5 rem in a year
Skin, bone, thyroid	3 rem in a year[(a)]
Hands, forearms, feet and ankles	7.5 rem in a year
Other single organs	1.5 rem in a year

Note: (a) 1.5 rem in a year to the thyroid of children up to 16 years of age.

3.4.2 Chemically toxic materials

The exposure of persons to the inhalation of gases or aerosols produced by accidents involving chemically toxic materials (such as beryllia and fluorine) is evaluated in a manner similar to that used to determine the inhalation exposure arising from a release of airborne radioactive material.

3.5 Consequences of Exposure

3.5.1 Ionising radiation and radioactive materials

Risks from exposure to ionising radiation are usually evaluated on the basis of a linear equation of the form:

$$R - R_b = \alpha D$$

where R is the incidence of a particular biological effect in an irradiated population,

R_b is the natural incidence of the same biological effect in an unirradiated population,

D is the average dose (rad) to the organs or tissue involved,

α is the risk coefficient (assumed constant).

The assumption of a linear relationship between risk and dose is probably conservative; the observed values of risk for adults are based on high radiation doses (usually above 100 rad) and the use of the risk coefficient "α" for estimating biological effects at low doses (say, 1 rad) is a considerable extrapolation of the observed data, except in the case of foetal

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* NH and MRCA Radiation Protection Standards are based on the most recent recommendations of the ICRP.

radiosensitivity, where doses of one to five rad can be leukaemogenic.

Risk estimates can be made in either absolute or relative terms. In absolute terms, risks may be expressed as the number of disabilities expected per unit dose of radiation in the lifetimes of a million members of a population. Estimates expressed in this way (e.g. x cases per year in a million exposed persons for each unit dose received) could be misinterpreted as implying considerably greater accuracy than the facts justify. A fairer impression can be conveyed by defining "orders of risk", a fifth order risk being a risk of death or injury in the range 10^{-5} to 10^{-4} (i.e. 10 to 100 disabilities would be expected in a population of one million persons each of whom receives unit exposure). Using this method of representation all radiation induced disabilities (except thyroid nodule induction) are fifth order risks; thyroid nodule induction in children under five years of age is a fourth order risk (i.e. in the range 10^{-4} to 10^{-3}).

In considering relative risks, the risk of a certain effect being caused by unit dose of radiation is compared with the risk of the same effect arising from unidentified natural causes.

The risk coefficients used are presented in Table 6 and are consistent with ICRP (1966) or Dolphin and Marley (1969). The risks from insoluble plutonium in lungs and the risk of production of thyroid nodules in children following intake of iodine-131, are derived separately (see Appendices B and C).

The data used for determining risk coefficients invariably relate to exposures delivered at high dose rates and a significant safety factor, possibly leading to an over estimate, may be introduced by applying the same risk coefficient to doses accumulated over longer periods (e.g. days (iodine-131) to years (plutonium-239)). Evidence on radiation induced leukaemia in humans can be interpreted as demonstrating no significant dose rate effect, but some animal experiments indicate significant dose rate dependence for genetic aberrations.

The use of a risk coefficient should not be interpreted as implying a uniform time distribution of disabilities; following a single exposure, the casualty distribution will be a near normal one with a mean latent period. For thyroid carcinoma the latent period has a mean value of about 10 years and ranges from 3 years to over 25 years. Leukaemic cases would show a similar history with the peak incidence occurring between the fifth and seventh year after exposure (ICRP 1966).

TABLE 6 - RISK COEFFICIENTS (DOSE-RISK RELATIONSHIP)

Risk		Cases per 10^6 man-rad	Reference
Leukaemia		20	ICRP (1966)
All other malignant neoplasms		80	D & M (1969)
Thyroid cancer	Children, external radiation	100	D & M (1969)
	Adults, " "	30	" "
	Children, iodine-131	30	" "
	Adults, " "	10	" "
Thyroid nodules	Children, iodine-131	1,000	Appendix C
Lung cancer	Beta-gamma irradiation	10	D & M (1969)
	Plutonium-239	400	Appendix B
Bone tumours	Any radiation	10 x Q.F.(a)	D & M (1969)
Genetic effects	Any radiation Gonad dose	0.1% increase over natural incidence per rad.	ICRP (1966)

Note: (a) Q.F. - Quality Factor

In view of the difficulty of assessing the genetic risks of radiation (ICRP 1966) no rigorous derivation of genetic effects is attempted in this study. ICRP estimates that exposure of a parental generation of one million persons to 1 rad (i.e. 10^6 man-rad) would result in a number of genetic deaths during the first 10 generations equivalent to 0.1% of the natural incidence. The population doses arising from the HIFAR MCA are listed in Table 9 for various sealed building leakage rates. They are seen to be considerably lower than the order of population dose required to produce significant genetic defects.

3.5.2 Chemically toxic materials

For chemically toxic materials there is generally no linear relationship between total exposure and adverse consequences. The adverse consequences of overexposure to chemically toxic materials are frequently immediate or appear within weeks and the risk of such effects increases very rapidly above a threshold level.

Unlike radioactive materials, under accident conditions limiting concentrations for toxic materials are based on acute effects and it is inappropriate to average concentrations over periods of more than a few minutes when comparing environmental measurements or predictions with recommended threshold limit values.

The only chemically toxic materials of interest in this assessment are beryllia and fluorine. Operations involving beryllia at the Research Establishment are now minimal, although significant amounts are stored. Consideration of fluorine is necessary because of the proposal to commence a research project involving electrolytic cell production of fluorine with a maximum output rate of one kg h^{-1}.

For occupational exposure to beryllium a threshold limit value of 2 μg per cubic metre of air is generally used, with an upper limit of 25 $\mu g\ m^{-3}$ measured over any 30 minute period. These are equivalent to a time integral of concentration for an eight hour day of 16 $\mu g\ h\ m^{-3}$ and for any half hour period 12.5 $\mu g\ h\ m^{-3}$. For non-occupational exposure the threshold limit value generally used is 0.01 $\mu g\ m^{-3}$ averaged over one month (Stokinger 1966), which is equivalent to a time integral of concentration of 7.5 $\mu g\ h\ m^{-3}$. There is no short term exposure limit available in the literature for application to members of the general public.

The recommended threshold limit value for fluorine is 0.2 mg m^{-3} (0.12 ppm) (American Conference of Governmental Industrial Hygienists 1968); 5 mg m^{-3} (3 ppm) can be detected by its smell, while 50 ppm is intolerable (Rudge 1962). The threshold limit value for hydrofluoric acid is 2 mg m^{-3} (American Conference of Governmental Industrial Hygienists 1968).

4. ASSESSMENT OF SPECIFIC FACILITIES AT THE RESEARCH ESTABLISHMENT

Possible accidents have been considered for the existing facilities at the Research Establishment. In the case of HIFAR and the Critical Facility, the method of analysis outlined in Section 2.3 has been used to estimate exposures of the local population. The analyses show that significant quantities of fission products would be released to the environment in the case of the HIFAR MCA. Possible accidents in other facilities at the Research Establishment are shown to give rise to smaller releases of radioactive materials and consequently lower potential exposures in the local population. These accidents are assessed using a non-probabilistic method (Section 2.1) and the credible doses derived are found to be less than doses of the order of the maximum permissible annual dose limit for occupational exposure (ICRP 1959).

In the non-probabilistic method the maximum credible doses are compared with doses considered acceptable under accident conditions e.g. with an emergency reference level* or an accepted threshold limit value.

4.1 Reactor HIFAR

Accident mechanisms for HIFAR have been analysed; from these it is postulated that complete loss of heavy water from the reactor vessel is possible and credible, although highly improbable. A rupture of the primary circuit between the heavy water heat exchangers and the reactor tank inlet when operating with a core of Mark IV fuel elements would give rise to the worst consequences in the form of fuel meltdown and an increased internal pressure in the reactor sealed building because of the decay heat from the liberated fission products. A fraction of these fission products will be expelled through minor leaks in the reactor sealed building by the overpressure.

Leakage tests of the reactor sealed building are carried out at intervals of approximately six months and every effort is made to keep the leakage rate as low as possible; a leakage rate of 1% per 24 hours at 1.5 psig overpressure can be practicably maintained.

An analysis of such an accident (the HIFAR MCA) has been made by Reactor Operations Section and endorsed by the Reactor Safety Committee (Parsons 1971). This MCA is briefly summarised in Appendix E; Figure E1 shows the variation with time of the reactor sealed building overpressure; Table E1 lists the amounts of fission products which would be released to the environment.

Exposure to external radiation occurs from the cloud of airborne material and from radioactivity deposited on the ground. Beattie and Bryant (1970) summarise current information on the radiological consequences of airborne material from fission product releases, giving data in particular for iodine-131, strontium-90, caesium-137 and ruthenium-106. Inspection of their data in relation to the quantities of gamma emitting radioisotopes released in the HIFAR MCA indicates that doses to individual members of the local population would be less than 0.01 rad from airborne material and less than one rad from deposited material.

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* Emergency reference level. A value, usually of dose but sometimes of an environmental measurement, which divides situations in which counter-measures are unlikely to be justified from those in which counter-measures are desirable if they can be carried out safety and effectively. (Dunster 1968).

Exposure to internal radiation arises from inhalation of airborne material and ingestion of foodstuffs contaminated via deposition. Inhalation is considered later. The data of Beattie and Bryant (1970) in relation to ingested radionuclides show that iodine-131 is the only material for which the emergency reference level in milk would be exceeded at distances greater than one mile (the residential exclusion radius). (Iodine can concentrate in milk from cows and goats, and in poultry eggs.) Under inversion conditions a release of 660 Ci of iodine-131 could give sufficient milk contamination to cause child thyroid doses in excess of 25 rad at distances up to seven miles from the reactor. There are currently no commercial dairies within 12 miles of the site, but some cows are kept at Menai (three miles) and the milk is used locally. In the event of the HIFAR MCA, it is apparent that local milk and egg contamination should be measured and the State Health Authorities informed and advised of any necessary action.

Casualties in the population arising from combined inhalation and cloud-borne external irradiation as a result of the postulated HIFAR MCA (with a 1% per 24 hours sealed building leakage rate) may be predicted from Figures F1 and F2 (Appendix F). A total release of 660 Ci of iodine-131 corresponds to a total release of 870 Ci of iodine-131 equivalent (taking account of tellurium and other radioiodines). The release of the iodine-131 equivalent is taken as 380 Ci during the first day, 280 Ci during the second day and 210 Ci during the remainder of the release period. Because the HIFAR MCA release is prolonged, the assumption of continuous inversion conditions used to derive the adverse consequences in Figures F1 and F2 is unduly pessimistic, since inversions do not persist by day at Lucas Heights. The figures for adverse consequences in Table 7 have therefore been derived on the assumptions that inversions occur only during 50% of the release period and that there is no change in wind direction. (These figures are derived from Figures F1 and F2 by assuming an ^{131}I equivalent release of 870/2 Ci.)

In Table 8, the estimated maximum number of casualties resulting from the HIFAR MCA are compared with the number of cases expected from natural causes in the exposed group over a twenty year period.

TABLE 7

CONSEQUENCES OF HIFAR MCA

Consequences	1970 Population		2000 Population	
	Upper Limits of Consequences		Upper Limits of Consequences	
	Average Case	Adverse Case	Average Case	Adverse Case
^{131}I equivalent (870 Ci)				
Thyroid nodules	4	100	15	240
Thyroid cancer	<1	3	<1	8
Rare gases $^{(a)}$				
Leukaemia	$\ll 1$	$\ll 1$	$\ll 1$	$\ll 1$
Cancers other than leukaemia	$\ll 1$	$\ll 1$	$\ll 1$	$\ll 1$

Note: (a) Based on a release of 13,600 Ci of ^{133}Xe (0.030 gamma MeV/disintegration). This is equivalent to 408 gamma MeV Ci and to allow for other rare gases (mainly ^{88}Kr and ^{135}Xe) has been multiplied by a factor of ten to give an effective total release of about 4×10^3 gamma MeV Ci. The consequences of this release are negligible since a release of about 1.2×10^5 gamma MeV Ci is required to give one leukaemia casualty under adverse conditions for the year 2000 population.

TABLE 8

ESTIMATED MAXIMUM CASUALTIES

COMPARED WITH EXPECTED CASES FROM NATURAL CAUSES

OVER A 20 YEAR PERIOD

Condition	Estimated maximum number of cases resulting from the HIFAR MCA (year 2000 population)	Expected cases from natural causes in the exposed group
Cancers other than thyroid cancer	$\ll 1$	500
Leukaemia	$\ll 1$	20
Thyroid cancer		
children	7	< 1
adults	1	1
Thyroid nodules		
children	240	Not known
adults	0	Not known

Note: (a) The exposed group consists of 16,000 persons under age 16 receiving thyroid doses of more than 1.5 rad and 5,000 persons above age 16 receiving doses of more than 3 rad.

(b) Expected cases from natural causes have been derived from Doll, Payne and Waterhouse (1966), using U.K., U.S.A. and N.Z. data, assuming the population age distribution given in Table 3 of the present report and allowing for ageing but not mortality over the 20 year period of the estimate.

The postulated release of 50 Ci of tritium over a period of 150 days may be compared with the figure of 40 Ci of tritium per day derived by Cook (1969) as the authorised working discharge limit for HIFAR; such a release of tritium is therefore not likely to give rise to adverse population effects.

The AAEC Interim Siting Criteria (Appendix D) were formulated for application to nuclear power stations. However, it is of interest to compare the individual and population doses arising from the HIFAR MCA with Criterion C of the AAEC Interim Siting Criteria dose limits. From Table 9, it can be seen that predicted doses for a leakage rate of 1% do not exceed the Interim Siting Criteria dose limits. This table also lists the predicted doses for postulated higher leakage rates from the reactor sealed building; leakage rates of 3% per 24 hours and 10% per 24 hours are considered with corresponding increases of released fission products. Under the conditions assumed for a loss of coolant accident, HIFAR would be unlikely to meet Criterion B of the Interim Siting Criteria.

4.2 Reactor MOATA

In 1961, a hazards analysis of the reactor MOATA (AAEC RSC Paper 1961) demonstrated that the hypothetical maximum credible accident would be a sudden addition of reactivity to the core, and deduced that:

(i) under the conditions assumed to cause the transient, the maximum possible fuel temperature would be 100°C and there would be no fission product release;

(ii) the energy produced during the transient would be more than 40 MWs but probably would not exceed 50 MWs;

(iii) this energy deposition would take at least 40 seconds in which to occur, after the initial reactivity addition;

(iv) this time is probably adequate to take remedial manual action.

The Research Establishment Reactor Safety Committee accepted this analysis, and the literature on Argonaut type research reactors (e.g. Lennox and Kelber 1956, Hicks and Eltham 1959) supports the view that the design is "eversafe". Thus it is concluded that if, by some improbable means, there were a sudden addition of reactivity during 10 kW(th) operation, no hazardous situation would be created at the Research Establishment or its environs.

If the reactor were uprated, operation at 100 kW(th) could lead to a significant increase in the fission product inventory of the MOATA fuel, depending upon the time periods of higher power utilisation. Nevertheless, a number of overseas reactors of similar type (mainly sited on university campuses) have been uprated (e.g. Hughes et al. 1961, Maclain 1963, and Birien 1961) and in terms of off-site consequences there appears to be no reason why MOATA cannot be safely uprated.

4.3 Critical Facility

The Critical Facility currently under construction may eventually be

TABLE 9. INDIVIDUAL AND POPULATION DOSES ARISING FROM HIFAR MCA

Leak Rate	Individual child thyroid dose at 1 mile (rem) (a)	Year 2000 Population thyroid dose (thyroid rem)	Individual whole body dose (rem) (c)	Year 2000 Population whole body dose (man-rem)	Total release of iodine-131 equivalent (curies) (d)
1% per 24 hours	100 (30)(b)	3×10^5	0.13	< 200	870
3% per 24 hours	300 (100)(b)	10^6	0.5	< 600	2610
10% per 24 hours	1000 (300)(b)	3×10^6	1.3	2500	8700
Interim Siting Criteria Dose Limits	150	6×10^6	25	10^6	-

Note: (a) These doses are extreme values assuming a steady wind direction into the most densely populated sector throughout the entire period of release, 50% occurrence of inversion conditions and wind speed 0.4m s^{-1}. Changes in wind direction would give significant reduction by factors up to 80 (Bryant 1964). As the HIFAR MCA would release two thirds of its activity in two days and the remainder over a period of weeks, the assumptions are pessimistic.

(b) The figures in brackets are equivalent adult thyroid doses.

(c) These figures refer only to cloud doses and do not include any contribution from direct radiation from the shell. The direct radiation contribution is considered to be negligible when compared with the cloud dose.

(d) Iodine-131 equivalent takes account of tellurium and all other radioiodines.

used for fast reactor studies using plutonium. Experiments will be carried out using a split table machine housed in a concrete cell of volume 2.3×10^3 m^3, with walls 140 cm. thick, designed to have a leakage rate not exceeding 2% of cell volume per 24 hours at 1.5 psi overpressure.

The currently envisaged MCA for the facility is an integrated pulse of 10^{19} neutrons (an energy release equivalent to that from 30 kg of TNT) with the complete vaporisation and oxidation of 60 kg of plutonium. Allowing for heat transfer from the cell air to the structural concrete and determining the overpressure as a function of time, calculations show that the design leakage rate will result in a release of 50 g of plutonium (as oxide) to the environment (50 g of plutonium is 3 Ci ^{239}Pu). No allowance has been included in the current hazards analysis for the preferential retention of particulate material (relative to air) along the leakage paths whereby the material escapes from the building. Also, the MCA pessimistically assumes that all the available energy goes into vaporising the plutonium and that all this vaporised material becomes airborne. It is considered therefore that accidental releases from the postulated accident will be well below 50 g. However, taking this figure as an extreme upper limit, reference to Figures F1 and F2 gives the following upper limits to estimated casualties:

TABLE 10

CONSEQUENCES OF COMPLETE VAPORISATION OF 60 kg PLUTONIUM IN THE CRITICAL FACILITY

Consequences	1970 Population		2000 Population	
	Average Conditions	Adverse Weather	Average Conditions	Adverse Weather
^{239}Pu (3 Ci) Lung Cancer	<1	7	1	15

4.4 Other Facilities and Materials

A survey has been made of the location, physical form and containment of all other significant stocks of hazardous materials, including beryllium, at the Research Establishment. In each case a major building fire is postulated as the worst accident and the potential releases assessed by the method outlined by Flew and Lister (1969). This method assumes that the quantity of material released to the environment depends upon:

- the fraction of the material involved in the accident
- the fraction of the involved material converted into an aerosol
- the fraction of the aerosol released from its primary containment
- the fraction of aerosol released from the building.

Data on the fraction converted to aerosol form and released to the immediate environment as airborne material are listed in Table 11 for various materials; Table 12 shows the maximum stocks and estimated maximum releases to atmosphere. The significance of these releases is indicated by calculating the estimated doses to members of the nearest resident population at Engadine. Table 13 shows the distances of the various buildings from the nearest homes and the airborne concentration factors appropriate to these distances for a short-term ground level release under inversion conditions (Pasquill stability category F, wind speed 0.4 m s^{-1}). Table 14 shows estimated doses for these conditions and compares them with emergency reference levels (Appendix G).

In the case of iodine-131 (20 Ci release from Isotope Production Section, Building 23), the maximum credible dose to the child thyroid is 60% of the emergency reference level. Figure F1 shows that a release of 20 Ci iodine-131 during adverse weather could cause one thyroid nodule in the local population (year 1970).

The major stock of beryllium is in Building 37 (approximately 2000 kg of beryllia and 400 kg beryllium metal and metal powder stored in metal containers); the building is of brick construction and contains no obvious source of ignition. The estimated beryllium exposure of 9.5 μg h m^{-3} (Table 14) is about 25 per cent greater than the recommended non-occupational threshold limit value of 7.5 μg h m^{-3} (or 0.01 μg m^{-3} over 1 month) given in Stokinger (1966), and is about 75% of the occupational short-term upper limit of 12.5 μg h m^{-3}.

Fluorine production is to be studied in a new building adjacent to Building 57. The proposed output of 1 kg h^{-1} will be converted at the same rate to calcium or other fluorides; none of the output will be stored. In the event of malfunction of the process equipment fluorine could be released to the ventilation system at the rate of 17 g min^{-1}. It is anticipated that operator action would terminate production within two minutes of a malfunction alarm, that the released material would be absorbed by reaction in a charcoal bed and that the total release to atmosphere would be less than 0.3 g in the two minute period. This would give a concentration of less than 0.01 mg m^{-3} at 0.5 miles (the exclusion area boundary) under adverse weather conditions. Concurrently, hydrofluoric acid would be released at a rate of 1.7 g min^{-1}, giving concentrations at the exclusion area boundary of less than 0.1 mg m^{-3}. These concentrations are each less than five per cent of the respective threshold limit values.

It is concluded that the stocks of hazardous materials considered here are adequately contained and stored and that the risk of adverse effects in the neighbouring resident population in the event of major accidents is small.

TABLE 11

CONVERSION OF VARIOUS MATERIALS TO AEROSOL FORM UNDER ACCIDENT CONDITIONS

Material	Fraction Converted to Aerosol and Released as Airborne Material Within the Immediate Environment
Beryllium oxide powder	1%
Sintered beryllium oxide	10^{-4}%
Solid beryllium metal	10^{-6}%
Beryllium metal powder	10^{-2}%
Plutonium metal	0.1%
Plutonium salts in solution	0.1%
Dry plutonium compound powders	1%

Note: These figures are considered to be conservative. Those for beryllium are derived from Warren and Copland (1968), Blumenthal and Santy (1965), and Stuart and Price (1964).
Those for plutonium are taken from Mishima (1965, 1966) and Mishima et al. (1968a, 1968b).

TABLE 12

MAXIMUM STOCKS AND ESTIMATED MAXIMUM RELEASES FROM FACILITIES OTHER THAN NUCLEAR REACTORS

Material	Building	Stock	Estimated Maximum Release (b)
Beryllium	37	2411 kg	20 g
Cobalt-60	23	2.9×10^5 Ci$^{(a)}$	5.7 Ci
Iodine-131	23	20 Ci	20 Ci
Natural uranium	59	2×10^6 kg	20 kg
Enriched uranium	3	17.4 kg	50 g
Thorium			
(maximum release)$^{(c)}$	37	873 kg	8.7 kg
(maximum stock)	59	4×10^4 kg	0.4 kg
Plutonium			
(maximum release)	2	134 g	0.16 g
(maximum stock)	22	4.08 kg	0.04 g
Used HIFAR fuel	27	10^4 Ci ^{90}Sr$^{(d)}$ 10^4 Ci ^{137}Cs	0.2 Ci 30 Ci

Note: (a) Upper figure.

(b) Although given to two figures, as derived, accuracy is generally no better than order of magnitude.

(c) Maximum releases of thorium and plutonium would take place from buildings other than those with maximum stock; the estimated releases are determined by the form of the materials and by their containment.

(d) Major fission product components of irradiated fuel cooled for more than two years.

TABLE 13

AIRBORNE CONCENTRATION FACTORS AT THE ONE MILE EXCLUSION BOUNDARY FOR SHORT-TERM RELEASES FROM VARIOUS BUILDINGS

Building	Distance to nearest homes (miles)	Airborne Concentration Factor (s m^{-3})
2	0.7	1.5×10^{-3}
3	0.6	1.7×10^{-3}
22	0.9	1.0×10^{-3}
23	1.0	8.5×10^{-4}
37	0.6	1.7×10^{-3}
59	1.0	8.5×10^{-4}
27	0.5	2.5×10^{-3}

Note: Pasquill Class F, wind speed 0.4 m s^{-1} assumed.

4.5 Possible Future Facilities

It is not possible to assess the quantitative effects on the surrounding population of accidents in plant or facilities not yet in the design stage. However, comments can be made and guide lines stated. By presupposing a MCA it is possible to indicate those factors which need to be considered during the design of facilities so that acceptable limiting release rates would not be exceeded should such a severe accident occur.

4.5.1 Reactors

In assessing the safety of siting additional reactors at Lucas Heights, two requirements must be met. One is to ensure that the agreed AAEC/State operational discharge authorisations are not exceeded. This requirement would need, at most, some additional effluent treatment plant and the negotiation of airborne effluent discharge limits for additional discharge points.

The second requirement is that the reactor would need to comply with a set of accident criteria such as the Interim Siting Criteria (see Appendix D). Whether or not these criteria are met would depend upon the type and power level of the reactor and the incorporated safety features. Assuming a water moderated and cooled materials testing reactor of, say, 100 MW thermal power, a full core meltdown (through failure of an engineered safety feature) could be postulated as the most severe accident. If half the iodine-131

TABLE 14. UPPER LIMITS TO DOSES AT ENGADINE FROM ACCIDENTS IN FACILITIES OTHER THAN NUCLEAR REACTORS

Material	Release	Exposure	Dose to Critical Organ (rem)		Critical Organ	Emergency Reference Level Doses (rem)	Fraction of Emergency Reference Levels	
			Adult	Child			Adult	Child
Beryllium	20 g	9.5 μg h m^{-3}	-(a)	-(a)	-	-	-	-
Cobalt-60 (insoluble)	5.7 Ci	5.0 x 10^{-3} Ci s m^{-3}	1.0	2.5	Lung	15	0.07	0.17
Iodine-131 (soluble)	20 Ci	1.7 x 10^{-2} "	4.5	14.0	Thyroid	25	0.18	0.6
Natural uranium (insoluble)	20 kg	5.5 x 10^{-6} "	0.15	0.4	Lung	15	0.01	0.03
Enriched uranium (insoluble)	50 g	5.5 x 10^{-6} "	0.02	0.055	Lung	15	0.001	0.004
Natural thorium (insoluble)	8.7 kg	1.85 x 10^{-6} "	0.02	0.06	Lung	15	0.001	0.004
Plutonium-239 (insoluble)	0.16 g	1.5 x 10^{-5} "	0.5	2.5	Lung	15	0.03	0.17
Used HIFAR fuel	0.2 Ci ^{90}Sr	5 x 10^{-4} "	0.2 (per yr)	0.9 (per yr)	Bone	1.5 (per yr)	0.1	0.6
	30 Ci ^{137}Cs	7.5 x 10^{-2} "	0.8	0.26	Whole Body	10	0.008	0.003

Note: (a) Beryllium, a toxic material and non-radioactive, is included here for convenience. The recommended exposure limit is 7.5 μg h m^{-3}.

inventory is released from the fuel, then approximately 1.25 x 10^6 Ci of iodine-131 would need to be contained and controlled; the amount released to the environment must be less than this by a factor of 10^3 if the Interim Siting Criteria are to be met.

A total reduction factor of between 2 x 10^3 and 5 x 10^3 could be obtained from three high integrity engineered safety features (e.g. a containment building, a containment cooling system and an atmospheric clean-up plant provided with iodine absorbers).

The Interim Siting Criteria, however, require that one of the above engineered safety features fails at the same time as the core melts, so that a fourth system may be necessary to guarantee the required total reduction factor; this could be an emergency core cooling system to prevent core melting. However, the performance of such systems under possible accident conditions is difficult to assess and a very thorough engineering evaluation is required for their acceptance.

The modus operandi of a flexible materials testing reactor is such that minor releases of radioactivity are not improbable, but in this regard, the one mile exclusion area would permit operation within the criteria.

It is concluded that a large research reactor could be designed and operated to comply with the Interim Siting Criteria, but four highly reliable engineered safety features may be needed.

4.5.2 Chemical Reprocessing Plant

A flowsheet has been proposed for reprocessing HIFAR fuel elements (Cairns et al. 1965) and a preliminary hazards evaluation has been carried out for a pilot plant of this type (Button 1965). This type of plant sited at the Research Establishment would need to be contained within appropriate secondary containment (i.e. a building, operating at a pressure less than that of ambient atmosphere, with provision for a controlled leakage path to atmosphere (via high efficiency filters and a suitable stack) for use in the event of an accidental release of radioactive materials from the primary containment).

In the event of an accident in the pilot plant there would be no radioiodines released from fuel elements irradiated for 100 days at a power of 15 MW and cooled for 365 days. The preliminary hazards evaluation concluded that in the absence of secondary containment the release to the environment of up to 30 Ci of mixed fission products would not be an incredible event.

Calculations showed that individual members of the public should not be exposed to a cloud dose in excess of 10^{-2} Ci s m^{-3} from the mixed fission products present in the first cycle feed solution. Under inversion conditions from a stack 37 m high, a release of 40 Ci of the mixture corresponds to the maximum permissible cloud dosage at the point of maximum concentration (5300 m from the stack). For a ground level release under inversion conditions, the maximum permissible cloud dosage at a distance of 1600 m (cf. one mile exclusion radius) would be realised for a release of 45 Ci, and at a distance of 150 m (nearest point of Research Establishment boundary fence to Building 2) would be realised for a release of one Ci of the mixture. A high integrity secondary containment could be expected to reduce possible exposures by a factor of 100 to 1000.

Safe methods of storage and disposal of high level wastes are required for this type of plant. Tank storage is considered undesirable, other than as an interim measure, and if used it must guarantee adequate safeguards in respect of radiation shielding, leak tightness, spare tank capacity and acceptable solutions to credible problems posed by fission product self-heating and off-gassing. Conversion of high activity liquid waste to solid form is essential as it enables storage and disposal to be carried out with less risk.

5. COUNTERMEASURES

In the case of accidents and of environmental contamination when exposures may not be subject to control, the ICRP points out that the concept of a fixed maximum permissible dose ceases to be meaningful; instead, other considerations arise, such as the need to balance the risk from the radiation against the risks from particular countermeasures which may be invoked.

Following an accidental release of radioactive or toxic material giving rise to environmental contamination, a number of countermeasures are conceivable including:

(i) evacuation of selected groups of the population;
(ii) restriction of access to areas affected by released materials;
(iii) restriction on the use of contaminated foodstuffs;
(iv) prophylactic measures to minimise effects of internally deposited materials.

The decision to use any given countermeasure would need to be made after considering both its potential effectiveness in reducing subsequent exposure of the public and its effects in the normal life of the community. To help guide those responsible for initiating countermeasures emergency reference levels have been proposed; these are guideline values below which the implementation of countermeasures is unlikely to be justified unless such countermeasures have a very small impact on the population. Where doses resulting from an emergency are likely to be greater than the emergency reference level, countermeasures should be considered if they are likely to result in a significant dose reduction and if they can be implemented without appreciable risk to the community. Pending an NH and MRC recommendation on emergency reference levels, those suggested for use by the AAEC are listed in Appendix G and are based on levels used by the UKAEA (Dunster, 1968).

Discussions with members of the Local Liaison Working Party have indicated that evacuation of a limited number of persons (e.g. 100) would be feasible, although such action would introduce a number of problems. Evacuation of large numbers of persons (e.g. 2000) would be a major undertaking involving many problems. One potentially sensitive area near the Research Establishment site is the Woronora settlement of some 500 persons; this settlement does not lend itself to easy evacuation. This study shows that only in the case of the HIFAR MCA is there a possibility of emergency reference levels being exceeded and, under normal weather conditions, evacuation would not be necessary. Therefore, no credit is given for evacuation as a countermeasure.

Restriction of access to areas affected by released material would be necessary if such access could give rise to the possibility of further spread of contamination (e.g. by vehicle tyres) or if disturbance of deposited radioactive or toxic materials could give rise to inhalation problems. This type of countermeasure would be implemented by instituting police road blocks at strategic points.

Restrictions on the use of contaminated foodstuffs would need to be instituted when analyses of samples show that unacceptable levels of contamination exist. This type of countermeasure poses problems of providing supplies of uncontaminated foodstuffs and reimbursement of the persons (e.g. primary producers) required to dispose of contaminated foods. The need for implementing such a countermeasure needs careful consideration and the risk from the effect balanced against disquiet and other reactions which may be produced by its introduction. The AAEC would provide advice on the need for restricting the use of foodstuffs after analyses of samples; the public health authorities would be required to activate the mechanism of confiscation. The main example of implementation of this type of countermeasure was the Windscale accident of 1957 (HMSO 1957) when milk for human consumption was restricted over an area of about 200 square miles.

The main prophylactic measure which has been suggested to counteract internally deposited radioactive materials is the administration of stable iodide following a release of radioiodines. Within the U.K., stocks of potassium iodide tablets are held at various reactor sites (e.g. CEGB) for issue to the public in an emergency. The AAEC could be expected to recommend the use of prophylactic measures (e.g. potassium iodide tablets) following a release of radioactive materials, but the final decision to use them would rest with the public health authorities. To be effective, stable iodide needs to be administered within a few hours after exposure to radioiodine.

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APPENDIX A

ATMOSPHERIC DISPERSION AND METEOROLOGICAL FACTORS AT LUCAS HEIGHTS

1. ATMOSPHERIC DISPERSION

The dispersion of airborne material is strongly dependent on atmospheric turbulence, being least under very stable conditions (at night, with clear skies and very low wind speeds) and greatest in very unstable conditions (by day, with clear skies and strong sunshine). Early measurements of dispersion were mainly carried out under conditions of intermediate stability (by day, with moderate wind speeds and cloud cover); results were summarised on a theoretical basis by Sutton (1947).

Pasquill (1961) reviewed the available information (chiefly from the U.S. and the U.K.) and proposed an empirical method for estimating dispersion as a function of atmospheric stability. His estimates have been usefully summarised by Bryant (1964). Table A1 reproduces Pasquill's key to his stability categories, which are correlated with wind speed, insolation and cloud cover (stability increases from A to F). Note that no designation is given in the case of stable atmospheres with wind speeds less than 2 m s^{-1}. Pasquill comments "because of the lack of quantitative knowledge of vertical spread and because in practice the surface plume is unlikely to have any definable travel, no estimates are attempted for this case." Table A2 gives predicted concentrations measured over a few minutes (if measurement were continued over longer periods average concentrations would be lower because of the effects of low frequency changes in wind direction on the axis of a plume of airborne material at 1 mile from an elevated point source). If the release occurs at ground level and over flat country, axial concentrations would be twice those given in the table, since the material below the axis of the elevated plume would be reflected upwards (assuming no deposition to the ground). If the terrain is not flat, turbulence patterns become modified and predictions become less accurate. Similar considerations apply if atmospheric stability characteristics change with height.

TABLE A1

KEY TO PASQUILL'S ATMOSPHERIC STABILITY CATEGORIES

(PASQUILL 1961)

Surface wind speed (m s-1)	Insolation			Night	
	Strong	Moderate	Slight	Thinly overcast or ≥4/8 low cloud	≤3/8 cloud
<2	A	A-B	B	-	-
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

TABLE A2

PLUME AXIS CONCENTRATIONS AND PLUME WIDTHS ONE MILE FROM AN ELEVATED SOURCE

(MEASURED OVER A FEW MINUTES)

(PASQUILL 1961)

Atmospheric stability category		Concentration units per m^3 for unit per sec release rate for wind speeds ($m\ s^{-1}$) of:			Plume width (m) (independent of wind speed)
		0.5	2.0	5.0	
A	Unstable	3×10^{-7}	-	-	1100
B	Unstable	8×10^{-6}	2×10^{-6}	8×10^{-7}	880
C	Unstable	-	6×10^{-6}	2×10^{-6}	550
D	Neutral	-	-	6×10^{-6}	400
E	Stable	-	4×10^{-5}	2×10^{-5}	275
F	Stable	-	1×10^{-4}	-	190

Notes: (a) dashes indicate incompatible stability categories and wind speeds;

(b) plume width is the distance across the plume between locations with one tenth the axial concentration.

Note from Table A2 that as the atmosphere becomes more stable plume axis concentrations increase, i.e. dispersion decreases. Pasquill emphasises that his system gives only approximate estimates of the magnitudes of concentrations; for distances of travel of a few hundred metres in open country the results are expected to be within a factor of two for all stabilities except extremes, and for neutral and moderately unstable conditions within a factor of two for distances of a few kilometres. The major source of uncertainty at greater distances is the unpredictability of stability with height.

No measurements of dispersion as such have been made at Lucas Heights. However, Charash (1965) has analysed horizontal and vertical wind direction fluctuations measured at 50 metres above the ground as a function of atmospheric stability and used these analyses to predict atmospheric dispersion from an elevated point source. He uses five stability categories, correlated with season, time of day, cloud cover, wind, temperature and visibility. Table A3 gives predicted concentrations measured over a few minutes on the axis of a plume of airborne material, together with plume widths, for such a source. Charash qualifies his predictions as follows: "The formulae presented may only be applied to diffusion from elevated sources and to travel distances of up to about 1.5 km, since the turbulence parameters are derived from measurements at a fixed height 50 m above the ground. Beyond these limits an error is introduced, whose magnitude depends on the prevailing degree of homogeneity of turbulence."

TABLE A3

PREDICTED PLUME AXIS CONCENTRATIONS AND PLUME WIDTHS ONE MILE FROM AN ELEVATED SOURCE (IF MEASURED OVER A FEW MINUTES) (CHARASH 1965)

Atmospheric Stability Category	Concentration units per m^3 for unit per sec release rate for wind speeds ($m\ s^{-1}$) of:			Plume width (m) for wind speeds ($m\ s^{-1}$) of:		
	0.5	2.0	5.0	0.5	2.0	5.0
Unstable	6×10^{-6}	2×10^{-6}	6×10^{-7}	825	825	825
Neutral	3×10^{-5}	1×10^{-5}	3×10^{-6}	425	320	350
Stable	6×10^{-4}	6×10^{-5}	2×10^{-5}	100	130	135
Inversion	4×10^{-2}	2×10^{-3}	-	8	18	-
Strong inversion	7×10^{-1}	1×10^{-1}	-	1	2	-

2. CHOICE OF DISPERSION MODEL

Comparison of the axial concentrations for unit release rate predicted on the Pasquill and Charash models from Tables A2 and A3 shows very good agreement (within a factor of 2) when figures for Charash's categories unstable, neutral and stable are compared with those for Pasquill categories B, D and E. This suggests that there is basically no great difference between them and either model could be used. The authors are also agreed on the limit of reliable application, in terms of travel distances.

The advantages of the Charash model are that it is based on local data and that it does give predictions under inversion conditions. Against it is the fact that it is not based on measurements of dispersion as such.

The advantages of the Pasquill model are that it is based on dispersion measurements and that numerical solutions are readily available (Bryant 1964).

The inclusion of inversion predictions in Charash's model would appear to favour its use. However, the inversion plumes predicted are very narrow, down to one metre in width at 1 mile for the strong inversion conditions (plume width is defined here as the lateral distance between points with concentrations one tenth of the axial level; concentrations above half the axial level occur over a lateral width just under half the plume width). For the accidental releases envisaged at Lucas Heights, such as leakage from the HIFAR shell or massive building fires, sources will have dimensions of the order of ten metres or more. Under atmospheric conditions of low dispersion it is therefore necessary to integrate over source dimensions to derive realistic downwind concentrations. Because only assumptions about source dimensions can be made, the value of such a derivation is questionable. If instead, predictions are limited to cases where plume widths are greater than source sizes, the difficulty inherent in allowing for source size is avoided. For example, if the Charash stable condition is the most restrictive used, the associated plume width at 1 mile is 100 metres for a wind speed of 0.5 m s^{-1}; i.e. a width of 50 metres with a concentration greater than half the axial level. Another factor affecting plume width is meandering of the plume with time. For an extended release during inversion conditions (over many days in the HIFAR MCA case) it is incredible that a narrow plume would not move laterally over distances significantly greater than the width. It is concluded that the inversion and strong inversion category predictions of Charash's model are not readily applicable to the circumstances of interest to this assessment and that an adequate assessment can be made by substituting Pasquill's stable category predictions.

3. FREQUENCY OF OCCURRENCE OF PASQUILL'S CATEGORIES

STABILITY CATEGORIES AT LUCAS HEIGHTS

Meteorological data collected at Lucas Heights (Charash and Bendun 1968) do not include observations of the frequency of occurrence of the various possible degrees of atmospheric stability. Therefore their data are examined in relation to the parameters that correlate with stability. Pasquill categorises the stability of the atmosphere in terms of time of day, amount of cloud cover and wind speed (Table A1). The available meteorological data relevant to the determination of frequency of occurrence of the various stability categories at Lucas Heights indicate that:

(i) on average, there is 50% cloud cover throughout the year at 0900 and 1500 hours;

(ii) inversions (atmospheric stability states categorised by Pasquill as classes E and F) occur 42% of the total time, almost entirely between sunset and sunrise, and do not persist throughout the day;

(iii) wind speed frequency distributions are as given in Table A4.

TABLE A4

WIND SPEED FREQUENCY DISTRIBUTION AT LUCAS HEIGHTS

Wind Speed Range Knots	Frequency of Occurrence						
	0300 hours	0900 hours	1500 hours	2100 hours	Average of 0900 and 1500 hours	Night Average 2100 hours 0300 hours	24 hour Average
<1	0.29	0.08	0.04	0.29	0.06	0.29	0.175
1-6	0.55	0.66	0.52	0.52	0.59	0.535	0.562
6-17	0.16	0.23	0.40	0.19	0.315	0.175	0.245
17-27	-	0.025	0.035	-	0.03	-	0.015
≥28	-	0.005	0.005	-	0.005	-	0.003

The information from this table is plotted in Figure A1 in the form of the cumulative frequency of occurrence against the logarithm of the reciprocal of the wind speed. This has been done since dispersion is inversely proportional to the wind speed (Pasquill 1961) and average dispersion is proportional to the mean reciprocal of the wind speed. The mean reciprocal wind speeds from these distributions are:

- by day - 0.91 s m^{-1} (i.e. 1.1 m s^{-1});
- by night - 2.25 s m^{-1} (i.e. 0.44 m s^{-1});
- over 24 hours - 1.51 s m^{-1} (i.e. 0.66 m s^{-1}).

The derivation of mean reciprocal wind speeds is strongly dependent on the extrapolation used for frequency of occurrence below one knot (0.45 m s^{-1}) and the extrapolation used in Figure A1 has not been extended above 19 s m^{-1}; consequently not all cases may be included and in particular the extrapolation for night conditions does not include two per cent of cases in this category.

After inspection of the Lucas Heights meteorological data in conjunction with the definitions of the Pasquill stability categories, the following frequency distribution has been compiled (Table A5).

TABLE A5

NOTIONAL PASQUILL STABILITY CATEGORY FREQUENCIES AT LUCAS HEIGHTS WITH INVERSE MEAN RECIPROCAL WIND SPEEDS

Stability Category	Frequency of Occurrence and Inverse Mean Reciprocal Wind Speed (m s^{-1})		
	Day	Night	24 hours
A	0.14, 1.0		0.14, 1.0
B	0.14, 1.0		0.14, 1.0
C	0.15, 1.0		0.15, 1.0
D	0.07, 2.0	0.08, 2.0	0.15, 2.0
E		0.14, 0.4	0.14, 0.4
F		0.28, 0.4	0.28, 0.4

This distribution gives an inverse mean reciprocal wind speed by day of 1.1 m s^{-1}, by night of 0.45 m s^{-1}, and throughout the 24 hours of 0.65 m s^{-1}, and hence agrees with the values derived from Figure A1; it gives a 42 per cent occurrence of classes E and F and hence agrees with observation at Lucas Heights, and the approximately equal distribution amongst categories A to E is used in the absence of any strong indication to the contrary.

3.1 Prevailing Winds

Figure A3 gives the per cent frequency of occurrence of winds between one and six knots (0.45 and 2.7 m s^{-1}) as a function of wind direction at Lucas Heights (Charash and Bendun 1968). At 0300 hours, winds from a southerly direction occur at more than twice the average frequency, but for other times and for the distribution for all hours taken together, the deviations from the average frequency are less than a factor of two. These observed deviations are considered insufficient to warrant a more rigorous assessment of prevailing wind effects in the overall assessment of meteorological dispersion.

3.2 Concentrations in The Woronora Valley

Assuming that radioactive or toxic material released into the Woronora Valley becomes uniformly mixed as it travels down the valley, airborne concentrations may be calculated if the rate of release and the volume flow rate are known.

Examination of a 2½" to the mile contour map of the area shows that the valley cross section up to 200 ft above the valley floor is approximately constant at 10^5 ft^2 (10^4 m^2) from the Research Establishment site to the Woronora settlement three miles away, while the area to 400 ft above the valley floor (where 400 ft is appropriate) increases from 10^4 to 5 x 10^5 m^2 over the same distance.

Assuming a wind velocity down the valley of 0.4 m s^{-1} and 10^4 m^2 cross section gives an exposure factor of 2.5 x 10^{-4} s m^{-3}. The exposure factor for the Engadine sector in the distance range one to two miles, averaged over 30^o, is also 2.5 x 10^{-4} s m^{-3} for Pasquill Class F, wind speed 0.4 m s^{-1}.

It is concluded that exposure in the Woronora Valley settlement would be of the same order as that in Engadine.

4. REFERENCES

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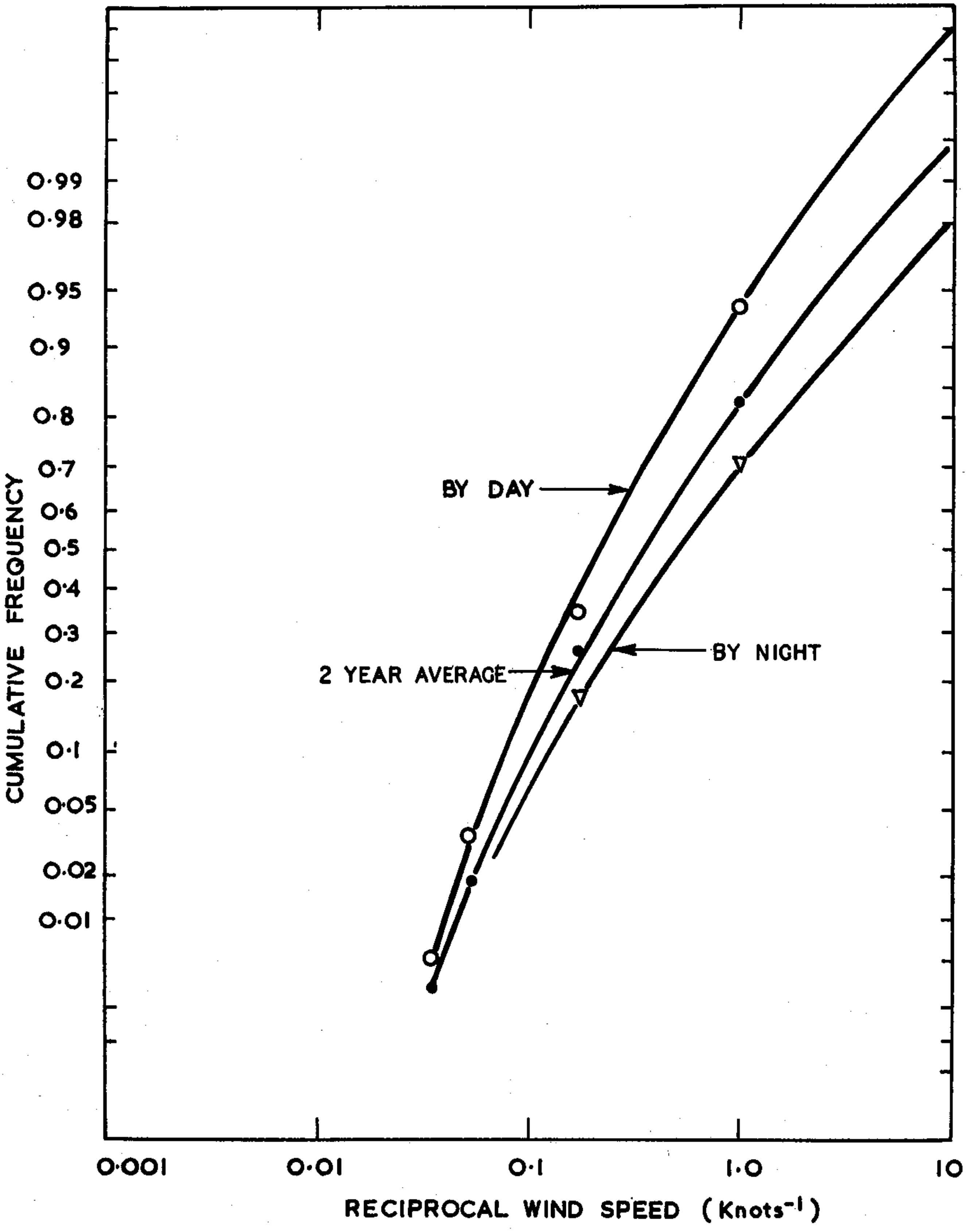

FIGURE A1. CUMULATIVE FREQUENCY DISTRIBUTION FOR RECIPROCAL WIND SPEED

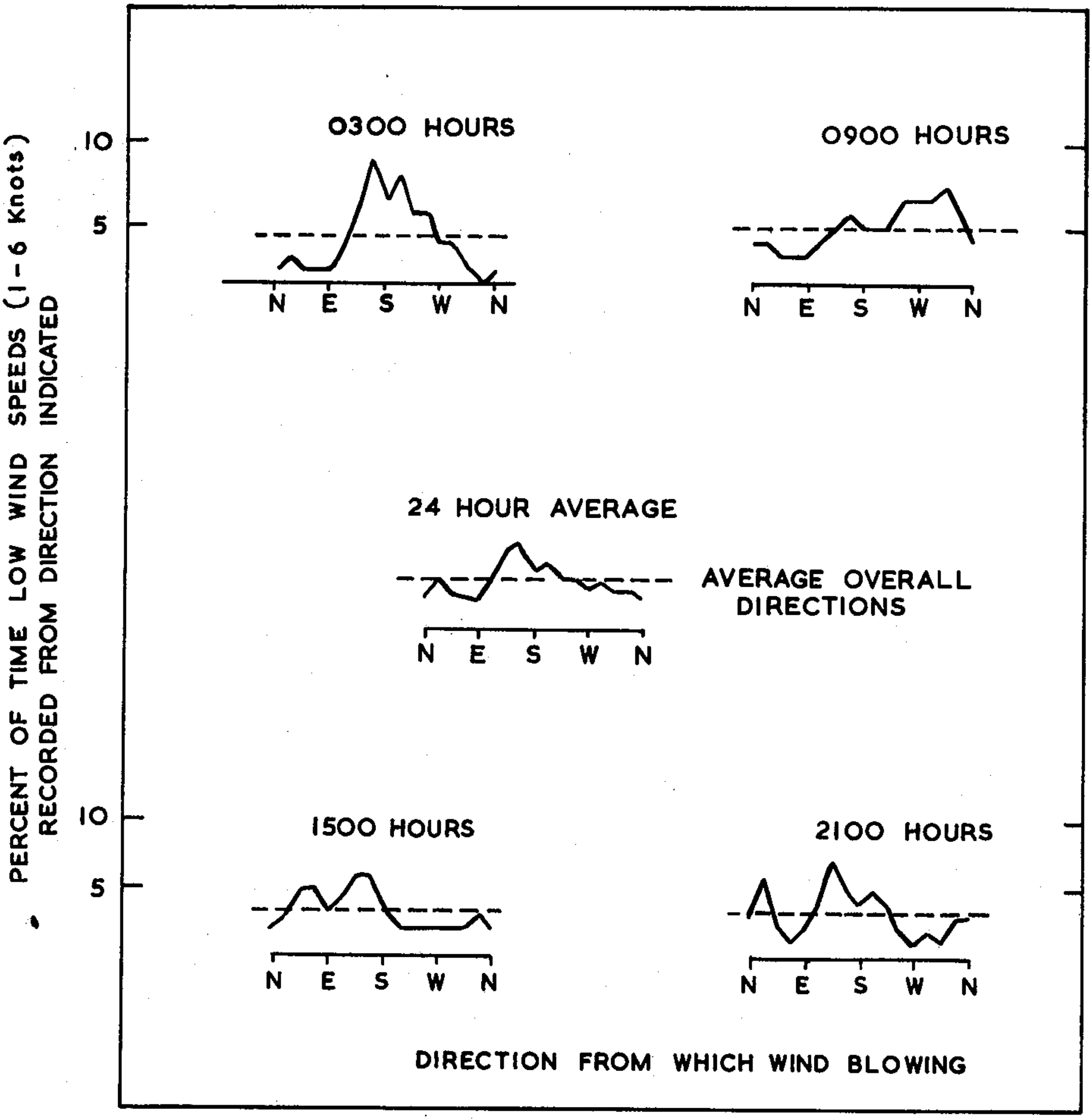

FIGURE A2. WIND DIRECTION FREQUENCIES AT LUCAS HEIGHTS

APPENDIX B

RISK COEFFICIENTS FOR LUNG CANCER FOLLOWING INHALATION OF INSOLUBLE PLUTONIUM AS PARTICULATE

1. RADIATION INDUCED LUNG CANCER IN MAN

Lung cancer in man following the inhalation of radioactive material has occurred in uranium miners (e.g. Lundin et al. 1969). Lundin's data show a relationship between cumulative radon and radon daughter product exposure and lung cancer risk (see Figure B1). The risk rate is approximately 2.5×10^{-4} per year for an accumulated exposure of 100 working level months. The working level is a concentration in air of 1.3×10^{5} MeV of potential alpha particle energy per litre, from radon, radium A and radium C, or approximately 100 pCi of radon-222 per litre plus short-lived daughter products in equilibrium (e.g. U.S. Federal Radiation Council 1967).

The cancers produced are mainly small cell undifferentiated bronchial carcinomas (U.S. Federal Radiation Council 1967). Recent models for the dose distribution in the structure of the lung following the inhalation of radon and daughter products indicate that certain sections of the bronchial epithelium receive the largest doses, from deposition of daughter products on the bronchi walls (Altshuler et al. 1964, Jacobi 1964, Haque and Collinson 1967). These estimates have been reviewed by Parker (1969) and he concludes that an exposure of 1 working level month gives a dose of 3 to 15 rad to the most highly exposed basal cells of the bronchial epithelium. Thus the observed risk rate of 2.5×10^{-4} per year per 100 WLM (see Figure 3) is attributed to a bronchial epithelium dose in the range of 300 to 1500 rad. An exposure of 10^{6} bronchial epithelium rad might therefore be expected to give between 0.2 and 1 bronchial carcinomas per year. Taking a figure of 20 for the years at risk gives a total risk of 4 to 20 cases per 10^{6} bronchial epithelium rad. For the case of external radiation exposure, Dolphin and Marley (1969) adopt a figure of 10 lung cancer cases per 10^{6} man-rad. The apparent order of magnitude agreement is probably fortuitous in view of the widely different microscopic and macroscopic dose distributions in the organ of interest.

In the case of insoluble plutonium dioxide in the lungs the dose distributions are different again and the alveolar region may be at greater risk than the bronchial epithelium. This possibility is supported by the observations reported following inhalation of plutonium dioxide aerosols by beagles (Park et al. 1967). Initial lung burdens were in the range one to five µCi; in the following 7 years, 12 dogs showed pulmonary neoplasia, including 11 cases of bronchiolo-alveolar carcinoma, two of bronchiolar adenocarcinoma and only one bronchial carcinoma. There was also one lymphangiosarcoma in a mediastrial lymph node and two neoplasia of the vasculature of the lung. It appears therefore that following inhalation of insoluble plutonium dioxide by beagles, the bronchiolo-alveolar tissue is at greater risk than the bronchi.

Park et al. (1967 and 1968) show the estimated average lung doses for each of the 25 dogs reported dead or sacrificed during the first seven years; the cumulative exposure is approximately 150,000 rad; if the remaining 15 dogs had similar exposures the total cumulative dose to the 40 dogs was approximately 240,000 rad; the total exposure was probably between these two figures since the dogs with higher doses had shorter lives. This exposure resulted in 17 lung cancers in an average exposure time of about 5 years, which gives an average risk rate of about 20 lung cancers per year for a population exposure of 10^6 lung rads. Although deductive comparison probably cannot be justified, note that this figure is 10 to 100 times greater than the bronchial epithelium risk rate in man; part of this difference is possibly attributable to the difference between dose averaged over the whole lung and dose to a restricted fraction.

A discussion of the possible lung cancer risk arising from inhalation of insoluble PuO_2 particulate has been given by Geesaman (1968). He reviews the reported carcinogenic effects of intense localised doses of radiation to mammalian skin and lung, including the beagle experiments, and he concludes that the lung cancer risk may be as high as 10^{-3} to 10^{-4} per oxide particle embedded in the lung. (It is not clear over what time period this risk applies.) This conclusion indicates that the risk of lung cancer associated with the ICRP Publication 2 (ICRP 1959) plutonium-239 maximum permissible lung burden of 16 nCi is unity (a mass median particle of 0.3 micron gives a lung content of 3×10^6 particles of $^{239}PuO_2$ at the maximum permissible lung burdens).

There are, however, numbers of people with more than 16 nCi of PuO_2 in their lungs (e.g. Mann and Kirchner (1967) report 24 cases from an accident which occurred in 1965). As far as is known no lung cancer deaths have been reported amongst occupationally exposed persons to date; such cases may not have been made public, but it seems unlikely that any major lethality could have been suppressed. In the particular case of the 1965 exposures it is possible that no adverse effects have so far been reported because of the existence of a dormant period between exposure and obvious onset of malignancy. On the whole the apparent absence of lung cancer amongst persons occupationally exposed to plutonium suggests that Geesaman's conclusion is over-pessimistic.

1.1 Dose Distribution in Lung Following Inhalation of Insoluble PuO_2

Altshuler et al. (1964) use the following model for the non-alveolar regions:

Region	Mucus Flow Transit Time t (minutes)	Surface Area A (cm^2)
Trachea	8	60
Main bronchi	6	38
Lobar bronchi	11	45
Segmental bronchi	37	94
Subsegmental bronchi	82	180
Terminal bronchi	1980	3400

Over the range of the alpha particles emitted, the transfer of 1 μCi of ^{239}Pu up this train from the alveoli gives an average dose of:

$$\frac{3.7 \times 10^4 \times E \times t \times 60}{A \times d} \quad \text{MeV cm}^{-3} \ \mu\text{Ci}^{-1}$$

$$= 3.55 \times 10^2 \ Et/Ad \qquad \text{rad } \mu\text{Ci}^{-1}$$

Where E is the alpha energy in MeV and d is the alpha range in tissue (5.15 MeV and 37×10^{-4} cm respectively for ^{239}Pu).

Altshuler et al. (1964) assume that the dose varies linearly from twice this average at the surface of the mucus layer carrying the activity to zero at a depth equal to the range of the alpha particle. Haque (1966) shows that this is a reasonable approximation, particularly for the smaller bronchi, but that it overestimates for the trachea. Altshuler et al. also assume that the sensitive basal cells are at least 36 microns from the mucus surface, which would lead effectively to zero dose from ^{239}Pu alphas of range 37 microns. The effective depth of 30 microns adopted by Haque is therefore used to give a positive result. The dose per μCi thus becomes:

$$(3.55 \times 10^{-2} \times 5.15 \text{ t/A} \times 37 \times 10^{-4}) \times 2 \times 7/37$$

$$= 18.7 \text{ t/A rad } \mu\text{Ci}^{-1}$$

This gives the following doses per μCi passing up through the bronchial tree:

Region	Dose per μCi
Trachea	2.5 rad
Main bronchi	3.0
Lobar bronchi	4.6
Segmental bronchi	7.4
Subsegmental bronchi	8.5
Terminal bronchi	10.9

The dose per μCi to alveolar tissue is given by:

$$3.7 \times 10^{4} \times 5.15 \times 1.6 \times 10^{-6} \times \frac{3.15 \times 10^{7}}{0.693} \times \frac{1}{750} \times \frac{1}{100} = 184 \text{ rad.}$$

(Altshuler et al. quote the alveolar mass as 750 grams; the effective half-life is taken as 1 year (ICRP 1959).)

The ICRP lung retention model has 12½% of the intake retained with an effective half-life of one year in the lower respiratory tract, and 25% immediately re-exhaled, the remaining 62½% deposited mainly in the upper respiratory tract and passing up the tract and subsequently swallowed within 24 hours. Thus for 1 μCi retained in the alveolar region, there may be 5 μCi traversing the main bronchi and trachea, giving doses five times those shown in the foregoing table. It is apparent, however, that the average dose (184 rad) to alveolar tissue is at least ten times greater than the dose to the bronchial epithelium.

There is currently no direct evidence which enables the risk of lung cancer in man following inhalation of insoluble plutonium to be established. The following indirect evidence concerning lung cancer is available:

10 cases per 10^{6} man-rad external radiation (Dolphin and Marley 1969),

0.2 - 1.0 cases/year per 10^{6} rad to bronchial epithelium from radon and daughters (uranium miners, this Appendix),

20 cases/year per 10^6 rad averaged over lung (PuO_2 in beagles, this Appendix).

The most restrictive of these numbers is that from the beagles and if applied directly to man without any adjustment for differences in life span (70 years versus 15 years for beagles (Park et al. 1968), it gives a total risk of 400 cases per 10^6 rad averaged over lung (assuming a 20 year period at risk following exposure).) The Dolphin and Marley figure, assuming an RBE of 10, is 100 cases per 10^6 rad.

This study uses a risk rate following exposure to insoluble plutonium of 400 cases of lung cancer per 10^6 rad averaged over lung (i.e. 40 cases per 10^6 rem).

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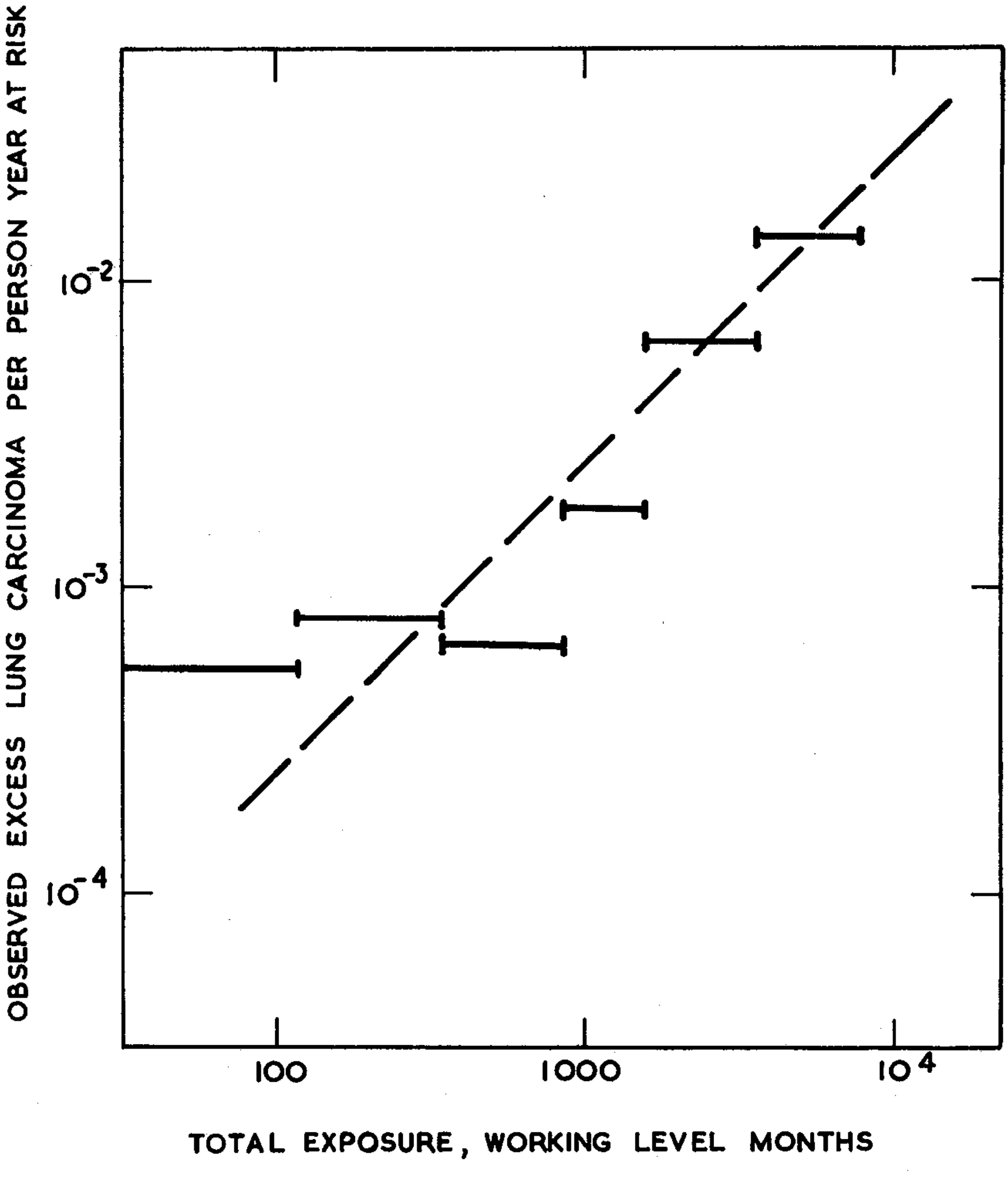

FIGURE B1. LUNG CANCER IN URANIUM MINERS
(After PARKER (1969) - Table 3)

APPENDIX C

THYROID CANCER AND THYROID NODULES FOLLOWING IRRADIATION

1. RISK OF THYROID CANCER

The risk of thyroid cancer as a result of the therapeutic use of external radiation was recognised in the 1950s, principally in a group of children exposed to X-rays for thymic enlargement in infancy. Information available in the literature up to 1963 was reviewed by the ICRP (ICRP 1966), which concluded that following a dose of 10^6 man-rad (e.g. 2000 children each receiving 500 rad to the thyroid) 10 to 20 cases of thyroid cancer would arise in a period of 10 to 20 years following irradiation. They also received information on the follow-up of adults receiving external irradiation and on the consequences of radioiodine therapy, which suggested that the risk for adults exposed to external irradiation is less than that for children, while the risk from radioiodine therapy is smaller still.

A further review of the risk of thyroid cancer following irradiation was made (Dolphin 1968) using more recently published data, in particular for the consequences of external irradiation. He concluded from the follow-up of the infants given X-irradiation for thymic enlargement (Hempelmann et al. 1967) that the risk of thyroid cancer for children is about 100 cases per 10^6 thyroid-rad, with a mean latent period of 20 years, while the risk for adults is lower at about 30 to 40 cases per 10^6 thyroid-rad.

In a further paper (Dolphin and Marley 1969) the available data and conclusions relating to risks from external irradiation of the thyroid remained unchanged, while the assessment of risk from internal irradiation was incomplete because of paucity of data, although what was available (Conard et al. 1966, Sheline et al. 1962) suggested that the risk from irradiation of the thyroid by iodine-131 is less than that from X-rays.

Following Dolphin and Marley, risk coefficients for the induction of thyroid cancer by external irradiation of the thyroid are taken as 100 and 30 per 10^6 thyroid-rad for children and adults, while for internal irradiation by iodine-131, the respective figures are 30 and 10 per 10^6 thyroid-rad.

2. RISK OF THYROID NODULES

Dolphin (1968) also reviewed the possible occurrence of thyroid cancers and nodules following the intake of radioiodine. The two groups of persons exposed to radioiodine whose case histories have been followed up are a group of patients treated for toxic goitre (Sheline et al. 1962) and a group of Marshall Islanders exposed to fallout radioiodines together with some external radiation (Conard et al. 1967).

Dolphin (1968) gives the following table showing how the occurrence of nodules varies with age.

Age range at time of irradiation (years)	Sheline et al. (1962)(a)		Conard et al. (1967)(b)	
	No. at risk	Nodules	No. at risk	Nodules
0 - 9	5	4(c)	19	13
10 - 19	6	2	12	0
20 - 29	39	2		
30 - 39	50			
40 - 49				
50 - 59	70		24	2(c)
60+	12			
Total	182	8	55	15

Note: (a) Range of dose to thyroid 5000 to 30,000 rad

(b) Range of dose to thyroid: 700 to 1,400 rad from radioiodine plus 175 rad from external gamma irradiation. The dose to an adult thyroid is smaller than the dose to a child thyroid by a factor of 2 to 5. These data refer to Rongelap Island only.

(c) One case of follicular carcinoma.

These data indicate that younger persons are at greater risk for the production of thyroid nodules than older persons, and show that 75% of thyroid nodules have occurred in persons under the age of 10 years at time of irradiation.

It is not known whether any relationship exists between thyroid nodules and the possible later development of cancer; one medical opinion (Brit. Med.

J. 1964) recommends the excision of such nodules occurring in persons under 40 years of age. A survey of normal thyroid glands (Mortensen et al. 1955) indicates the occurrence of nodules in about 50% of cases; the percentage varies with age from 10% in very young persons to 90% in very old persons. The evidence of the very high frequency of thyroid nodules and the very low incidence of thyroid cancer suggest that very few thyroid nodules become malignant.

Pincus et al. (1967) present observations of the prevalence of thyroid abnormalities in persons treated with relatively high doses of X-rays (mean dose 353 roentgens with a range of 130 to 1070 roentgens in air) for thymic enlargement during infancy. They estimate that the risk of developing thyroid nodularity, after exposure in infancy to X-ray doses in this range, is about 30% (i.e. a risk rate of the order of 1000 cases per 10^6 thyroid-rad).

A risk rate of 1,000 cases per 10^6 man-rem for the production of thyroid nodules in children exposed to radioiodine is adopted in this assessment after considering the data available from the literature.

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APPENDIX D

INTERIM CRITERIA FOR THE SITING OF NUCLEAR REACTORS IN AUSTRALIA

(COMMISSION MEMORANDUM 100/1969)

1. STATEMENT OF CRITERIA

The criteria consist of radiological dose-limits which should not be exceeded under the following conditions:

A. Dose limits applying to normal operation

The release of activity during normal operation - e.g., from the discharge of station effluents, the discharge from pressure relief valves, etc. - should not result in the general public receiving doses in excess of the limits specified by the National Health and Medical Research Council of Australia (NH and MRCA).

These are as follows:

Organ or Tissue	Dose limits for members of the public
Gonads, red bone-marrow	0.5 rem in a year
Skin, bone, thyroid	3 rem in a year*
Hands & forearms, feet & ankles	7.5 rem in a year
Other single organs	1.5 rem in a year

*1.5 rem in a year to the thyroid of children up to 16 years of age.

These doses are to be applied to the appropriate critical groups within the population along the critical exposure pathways. For preliminary siting studies when the critical group may not be clearly defined, a suitable hypothetical critical group should be postulated.

B. Dose limits applying in the case of a failure of a single item of plant equipment

The release of activity as the result of a failure of a single item of plant equipment (as defined in paragraphs 1 and 2 of the attached guide to the application of the criteria) should not result in the public receiving doses exceeding the dose limits specified by the NH and MRCA as given under 'A' above. This would be additional to any doses received as a result of normal operation.

Appropriately conservative short-term dispersion and depletion parameters should be used in estimating doses.

C. Dose limits applying in the case of a maximum credible accident

The release of activity as the result of a maximum credible accident (as defined in paragraph 3 of the attached guide to the application of the criteria) should not result in the public receiving doses in excess of the following limits:

25 rem individual whole body and 10^6 man-rem to the population,
150 rem individual thyroid (child) and 6×10^6 thyroid-rem to the population.

A failure of this severity would be an extremely remote contingency and the dose limits are considered appropriate to "once in a lifetime" exposure from an uncontrolled source.

Appropriately conservative dispersion and depletion parameters should be used in estimating doses.

2. GUIDE TO THE APPLICATION OF CRITERIA

1. For the purpose of the Criteria, a single item of plant equipment is defined as: any major component or system which performs a distinctive function in the normal operation of the reactor and its associated plant (e.g. primary circuit piping or emergency core cooling), or for the protection of the public (e.g. containment).

2. For the purpose of Criterion B, only credible failures are to be considered.

3. The maximum credible accident is defined for the purpose of Criterion C as: any accident which could be considered feasible and which results in the maximum release of fission products outside the reactor containment system. This hypothetical accident represents the upper limit of credible potential hazard to the public, and must be based on the coincidental unrelated failure of not less than two single items of plant equipment as defined in '1' above.

4. In order to comply with the dose limits specified in the Criteria, the population should be limited in the immediate vicinity of the station. Two possible arrangements are:

(i) A total exclusion area of a size to be determined by the dose limits specified in Criteria A, B and C.

(ii) A combination of exclusion and low population (i.e. controllable) zones. In this case, the exposure of persons in the low population zone should be amenable to control by emergency countermeasures. The effectiveness of these countermeasures would need to be adequately demonstrated and guaranteed.

In both cases, however, the population distribution should represent the maximum projected by the competent Planning Authority over the life of the plant. If these data are not available, then a hypothetical population distribution of extreme characteristics should be postulated.

APPENDIX E

SUMMARY OF HIFAR ACCIDENT MECHANISMS

Safety studies of reactors similar to HIFAR have been carried out by the UKAEA and have been reported (Barrett 1965). However, a more recent safety analysis has been carried out by the AAEC and this study differs in some important respects from the U.K. evaluation. In particular, the AAEC analysis considers that a failure of the primary circuit leading to a rapid loss of coolant is a credible (although unlikely) accident, whereas the U.K. study claims that such an event is incredible. The main findings of the AAEC study are summarised and discussed below.

HIFAR fuel elements are made from a uranium-aluminium alloy encased in an aluminium cladding approximately 0.02" thick. If hazardous quantities of the enclosed fission products are to be released, there has to be a massive breakdown of the cladding, such as would occur from fuel element melting. There are several conceivable ways by which fuel elements could reach, or exceed, the melting point of aluminium (about 660^{o}C). These include:

(i) unloading an irradiated element from the reactor without allowing sufficient time for the fission product heat to decay to a safe temperature,

(ii) having a sudden addition of reactivity to the reactor core, so that a "reactivity (or power) excursion" occurs,

(iii) rapidly losing the D_2O coolant whilst the reactor is at power.

The first case would result, at worst, in the release of the fission product inventory of a single element to the reactor sealed building (RSB).

Regarding the second case, it was judged, on the basis of SPERT results, that credible reactivity additions in HIFAR would not lead to full core meltdown and significant amounts of D_2O would remain in the tank for heat removal.

The design of the Mark III fuel elements afforded some protection against fuel meltdown following a rupture of the reactor's primary circuit. Similar protection is not available when the concentric tube Mark IV elements are in use, and such a rupture could result in complete core meltdown and the release of the full fission product inventory. This third case is therefore considered to be the "maximum credible accident" (MCA) for HIFAR. A brief discussion of the postulated course of such an accident follows.

The worst primary coolant circuit rupture would occur between the D_2O heat exchangers and the reactor tank inlet, so that the top reflector, inner fuel element channels and reactor tank plenum chamber would be drained and a direct connection between the reactor tank and the D_2O plant room would be established for the passage of steam. The reactor would shut down due to loss of moderator even if earlier warnings and trips such as D_2O level, D_2O flow, fuel element temperatures, activity warnings etc. had not led to manual or automatic shutdown action. Fission product heating would cause most of the fuel to melt and would evaporate the D_2O remaining in the tank. The steam so generated would pass into the plant room and then into the RSB, gaining heat from the fuel and losing heat to the H_2O cooled pipework on the way. The released fission products would be carried by the steam into the RSB. The heat and steam in the RSB would cause its internal pressure to rise and some of its contents to leak to the external environment.

Assuming that the fuel elements are voided 10 seconds after reactor shutdown from 11 MW, half the core would be melted in about 150 seconds. The remaining D_2O would be evaporated over about 24 hours, and conservative calculations (e.g. an assumption of limited heat removal by the light water circulating in the heat exchangers) give a heat release of 1.7 MWh and, in the absence of cooling, an increase in building pressure to 3.2 psi.

The six RSB space conditioning units are each capable of removing 80,000 BTU h^{-1} (23 kW); they are arranged to provide three independent cooling systems (two units per system) each having the reliability required of an engineered safety feature. Assuming that one system fails simultaneously with the primary circuit and that another is undergoing maintenance, the remaining two units will reduce the net heat release to the RSB to 0.86 MWh and the pressure rise to 1.3 psi. Two space conditioning units would restore the building pressure to atmospheric approximately 48 hours after the initiation of the incident.

Assuming that the containment leakage rate is proportional to the square root of the overpressure, and knowing that the measured leakage rate of the containment is 1% of contained volume per 24 hours at 1.5 psi (i.e. 100 $ft^3\ h^{-1}$ at 1.5 psi overpressure), then the leakage rate at any time is

$$104 \left(\frac{\Delta P}{1.5}\right)^{\frac{1}{2}} ft^3\ h^{-1}$$

where ΔP is the RSB overpressure in psi. The variation of the RSB overpressure with time is plotted in Figure E1.

Although 30% of the fuel will not melt initially, its subsequent behaviour is uncertain, so all the fuel in the core is assumed to melt 150 seconds after shutdown. The released fission products are assumed to be instantly transported into the RSB and dispersed throughout the building, where some will be deposited and some will escape through leaks in the containment.

The fission products considered are those having a half-life greater than one day, a yield of more than 0.1%, and a total activity at shutdown greater than 100 Ci (Cook 1963). The activity at shutdown is taken as that quoted for 48 days irradiation normalised to a reactor power of 11 MW.

The activity release rate of radioisotopes escaping from the RSB may now be evaluated from:

$$Q_i = I\,P_i F_i \frac{v}{V}\ \mathrm{Ci\ h^{-1}}$$

where Q_i = activity release rate of isotope i from the RSB at time t (Ci h^{-1})

I = total activity of isotope i at time t (Ci)

P_i = fraction of isotope i released from the fuel

F_i = fraction of P_i not deposited in the RSB

v = RSB leak rate at time t (ft^3 h^{-1})

V = Volume of RSB (ft^3).

Where P_i and F_i have been reported they have been used (P_i from Parker et al. (1963) for fuel melted at 1000°C in steam/air mixtures; F_i from Barton et al. (1963)). Where they have not been reported they are assumed to be:

	P_i	F_i
Noble gases	1.0	1.0
Others	0.1	0.5

During the period when the pressure in the RSB is increasing, the radioactivity released is therefore approximated by:

$$\int Q_i\,dt = I_o\,P_i\,F_i\,\frac{\bar{v}}{V}\int e^{-\lambda_i t}\,dt$$

and assuming a linear pressure drop, during the period when the RSB is being depressurised due to cooling, the radioactivity released is approximated by:

$$\int_{t_1}^{t_2} Q_i \, dt = \frac{104}{\sqrt{1.5}} I_o P_i F_i \, e^{-\lambda_i \left(\frac{t_1 + t_2}{2}\right)} \int_{t_1}^{t_2} \frac{v}{V} \, dt.$$

After the RSB pressure is restored to its initial value, the containment leakage rate will be governed by atmospheric pressure changes. These changes will be brought about by barometric pressure variations and local pressure changes caused by the wind. Using barometric pressure records for Lucas Heights (Charash and Bendun 1968), the daily outward leakage is taken to be that caused by a pressure 2 mb below mean pressure for 12 hours per day. Assuming low wind speeds, the integrated release between the second and 150th days of the incident may be calculated from:

$$\int Q_i \, dt = 0.695 \times 10^{-3} \, I_o \, P_i \, F_i \int e^{-\lambda_i t} \, dt$$

For high wind velocities, once the wind pressures become significant compared with the barometric pressure, the activity release will increase. In the limit, when the barometric pressure change is small compared with the wind pressure, $Q_i \propto u$ (where u is the wind velocity). Since the cloud dose to a person varies as Q_i/u, then the cloud dosage does not increase with wind speed although the fission product release does.

Table E1 gives the fission products released to the environment calculated in the above manner. Some 50 Ci of tritium from the heavy water will also be released over the 150 day period, with an initial release rate of about 7 Ci per day. It is considered that clean up action would be effective by the 150th day.

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TABLE E1 FISSION PRODUCTS RELEASED FROM HIFAR MCA

Fission Product	Core Investment at shutdown I_o - curies	Fraction released from fuel P_i	Fraction not deposited in RSB F_i	Release, (curies) (time 0 to 150 days)			
				Pressurisation period 0 - 26 hours	Depressurisation period 26 - 54 hours	Post-Depressurisation period 54 hours - 150 days	Total
^{131}I	3.03×10^5	0.96	0.1	240	220	200	660
^{85}Kr	2.94×10^2	1.0	1.0	2.6	2.6	30	35
^{89}Sr	2.28×10^5	0.1	0.05	9.8	9.9	51.0	71
^{90}Sr	2.21×10^3	0.1	0.05	0.1	0.1	1.1	1.3
^{90}I*	2.02×10^3	0.1	0.05	0.09	0.09	1.1	1.3
^{95}Zr	2.89×10^5	0.1	0.05	12	13	72	97
^{95}Nb*	1.05×10^5	0.1	0.05	4.6	4.9	69	78
^{99}Mo	6.6×10^5	0.1	0.05	25	19	5.3	50
^{91}Y	2.7×10^5	0.1	0.05	12	12	64	87
^{103}Ru	1.74×10^5	0.05	0.1	7.5	7.5	32	47
^{106}Ru	3.67×10^3	0.05	0.1	0.16	0.16	1.6	2.0
^{105}Rh	1.0×10^5	0.05	0.1	3.7	2.2	0.29	6.2
^{131m}Te	5.0×10^4	0.23	0.06	4.5	2.5	0.25	7.2
^{132}Te	4.8×10^5	0.23	0.06	51	41	13	106
^{133m}Xe*	1.7×10^4	1.0	1.0	140	120	31	290
^{133}Xe*	7.0×10^5	1.0	1.0	5700	5100	2800	13600
^{137}Cs	2.21×10^3	0.11	0.05	0.11	0.11	1.2	1.5
^{140}Ba	6.2×10^5	0.1	0.05	26	25	35	87
^{141}Ce	4.2×10^5	0.1	0.05	18.0	18.0	61	97
^{143}Ce	6.9×10^3	0.1	0.05	0.23	0.13	0.01	0.37
^{144}Ce	0.71×10^5	0.1	0.05	3.1	3.1	31	37
^{143}Pr	5.86×10^5	0.1	0.05	25	24	36	85
^{147}Nd	2.72×10^5	0.1	0.05	11	11	13	36
^{147}Pm*	0.65×10^4	0.1	0.05	0.34	0.36	5.3	6.0
^{149}Pm	1.4×10^5	0.1	0.05	5.2	3.7	0.79	9.7
^{151}Pm	5.5×10^4	0.1	0.05	1.8	0.9	0.08	2.7
^{153}Sm	1.79×10^4	0.1	0.05	0.65	0.44	0.08	1.2

* Release includes contribution from parent released to RSB

Tritium 50 Ci over 150 days with initial release rate of about 7 Ci daily

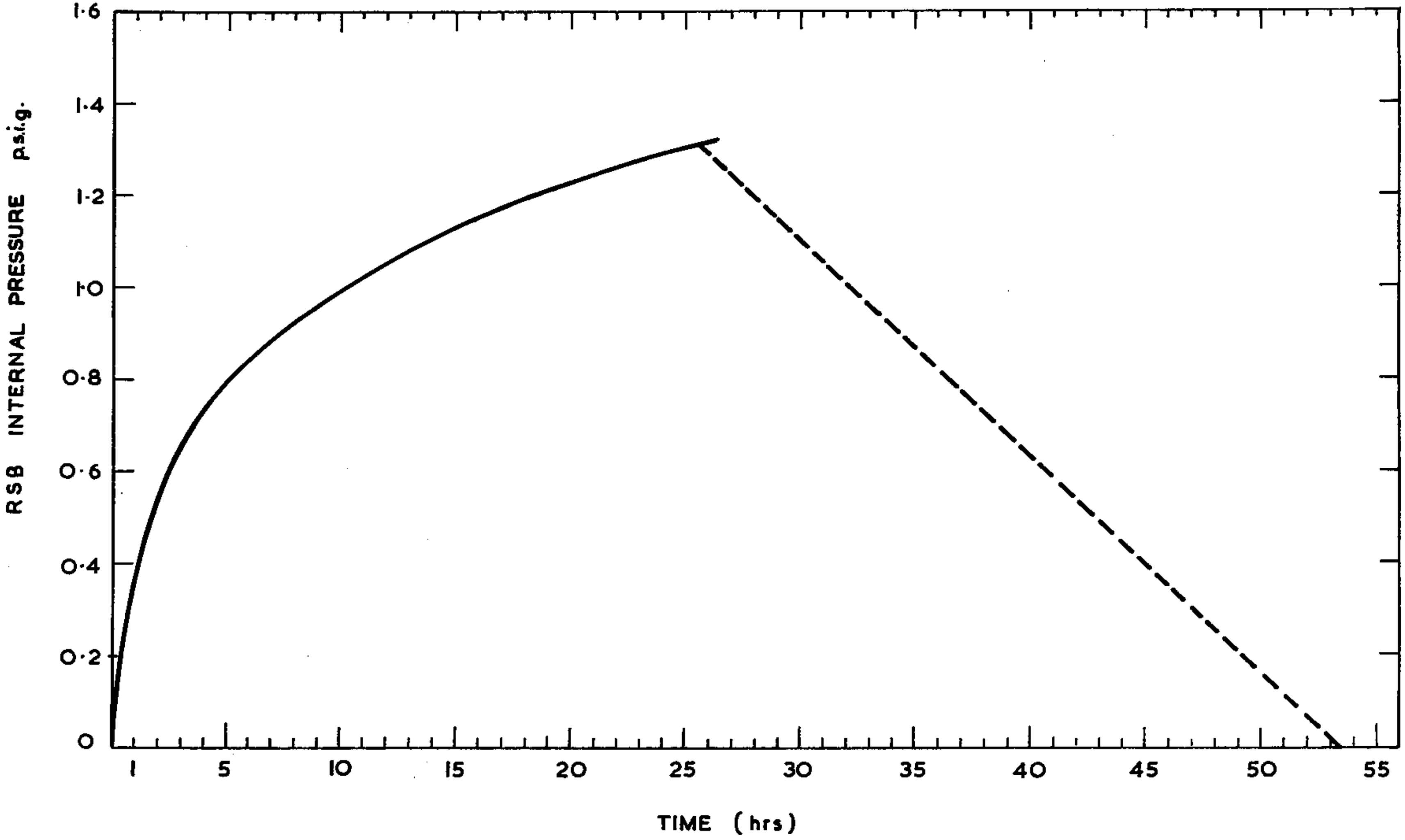

FIGURE E1. R.S.B. PRESSURE FOLLOWING FAILURE OF D_2O PIPEWORK (WORST CASE)

REACTOR POWER 11MW; H_2O CIRCUIT OPERATES; SPACE CONDITIONERS - 2 UNITS OPERATE

APPENDIX F

CONSEQUENCES OF RELEASES OF RADIOACTIVE MATERIALS

The average consequences from a release of airborne radioactive material may be calculated by averaging the summation of each 30° sector over the six Pasquill meteorological conditions (See Table A1). No weighting for prevailing winds is made, since there are no significant prevailing wind directions indicated by the Lucas Heights meteorological data at the low wind speeds which contribute most to population exposure.

The following expression gives the average number of possible cases of injury in the surrounding population:

$$\frac{1}{12}\, q_i \sum_{s=1}^{12} \sum_{k=1}^{6} \sum_{a=1}^{2} \sum_{\ell=1}^{L} f_a \cdot F_{ia} \cdot R_{ia} \cdot P_k \cdot C_{\ell k} \cdot N_{s\ell}$$

where q_i - activity of isotope i released (curies)

f_a - fraction of exposed population in age interval "a" (2 cases considered)

F_{ia} - dose in rem to the organ of interest for isotope "i" and age interval "a" per unit time integral of airborne concentration (rem $\mathrm{Ci}^{-1}\ \mathrm{s}^{-1}\ \mathrm{m}^3$)

R_{ia} - risk in the age interval "a" of subsequent injury per unit dose to the organ of interest from exposure to isotope "i" (cases per rem)

P_k - probability of occurrence of meteorological condition "k" (six cases considered)

$C_{\ell k}$ - time integral of airborne concentration per unit release downwind of the release under meteorological condition "k" averaged over 30° and a distance interval ℓ to $(\ell + 1)$ miles ($\mathrm{s\ m}^{-3}$)

$N_{s\ell}$ - total population in the 30° sector "s" (12 cases in all) and the distance interval ℓ to $(\ell + 1)$ miles

The limit for summation over distance is set by the condition that the average dose in the distance interval ℓ to $(\ell + 1)$ is not less than the annual dose limit for members of the public (see Table 5). In addition, for inversion conditions (Pasquill Classes E and F, k = 5 and 6), the summation is discontinued at distances greater than the average distance travelled by the released material under inversion conditions. As the average duration of inversions at Lucas Heights is about 12 hours, the average travel time of material released during an inversion is six hours which corresponds, for a wind speed of 0.4 m s^{-1} (0.9 miles per hour) to a distance of 5.4 miles.

Denoting the annual dose limit by D_{ia}, L is the lowest value of ℓ for which

$$q_i \cdot C_{\ell k} \cdot F_{ia} < D_{ia}$$

with the additional restriction that if k = 5 or 6, L is not more than 5 (i.e. 5.4 rounded down to 5).

This procedure is justified by analysing the average consequences for inversions lasting one to twelve hours (i.e. assuming that the release could occur at any time), which gives figures approximately the same as those for an inversion lasting about six hours. For comparative purposes, inversion conditions with a wind speed of 1.0 m s^{-1} have also been considered for the case of iodine-131 induced thyroid cancers.

The maximum probable number of casualties is derived by doubling the maximum value of the following expression:

$$q_i \sum_{a=1}^{2} \sum_{\ell=1}^{L} f_a \cdot F_{ia} \cdot R_{ia} \cdot C_{\ell k} \cdot N_{s\ell}$$

The value is doubled to allow for the case where the release occurs at the start of a 12 hour inversion, rather than the six hour duration considered in deriving the overall average. The factor of two has been derived from inspecting the results obtained for inversions lasting one to twelve hours.

The results obtained by applying these methods to releases of iodine-131, plutonium-239 and rare gases are presented in Figures F1 and F2. Iodine-131 and plutonium-239 give rise to an inhalation risk and rare gases give rise to an external radiation risk.

The following data and assumptions have been used in deriving Figures F1 and F2 -

(i) Population location distribution for 1970 and 2000 as listed in Tables 1 and 2;

(ii) Population age distribution comprising children (0 to 16 years) 41% and adults 59% as shown in Table 3;

(iii) Meteorological conditions are Pasquill classes A to F inclusive, with windspeeds and frequencies of occurrence as shown in the following table, and averaged uniformly over 30° sectors at all distances.

Class	A	B	C	D	E	F
Windspeed (m s^{-1})	1	1	1	2	0.4	0.4
Frequency	0.14	0.14	0.14	0.14	0.16	0.28

(iv) Other data are given in the following Table:

Isotope	Age Group	Annual dose limit (rem)	Dose per unit Exposure $\left(\frac{\text{rem m}^3}{\text{Ci sec}}\right)$	Risk per unit Dose $\left(\frac{\text{cases}}{\text{rem}}\right)$	Consequence Considered
^{239}Pu	Child	1.5	1.2×10^5	4×10^{-5}	lung cancer
	Adult	1.5	4.4×10^4	4×10^{-5}	lung cancer
^{131}I	Child	1.5	8.1×10^2	3×10^{-5}	thyroid carcinoma
	Adult	3.0	2.8×10^2	1×10^{-5}	thyroid carcinoma
	Child	1.5	8.1×10^2	1×10^{-3}	thyroid nodules
	Adult	3.0	2.8×10^2	0	thyroid nodules
Noble gases (Gamma MeV)	Child	0.5	2.5×10^{-1}	2×10^{-5}	(i) leukaemia
	Adult	0.5	2.5×10^{-1}	2×10^{-5}	leukaemia
	Child/ Adult	0.5	2.5×10^{-1}	8×10^{-5}	(ii) cancers other than leukaemia

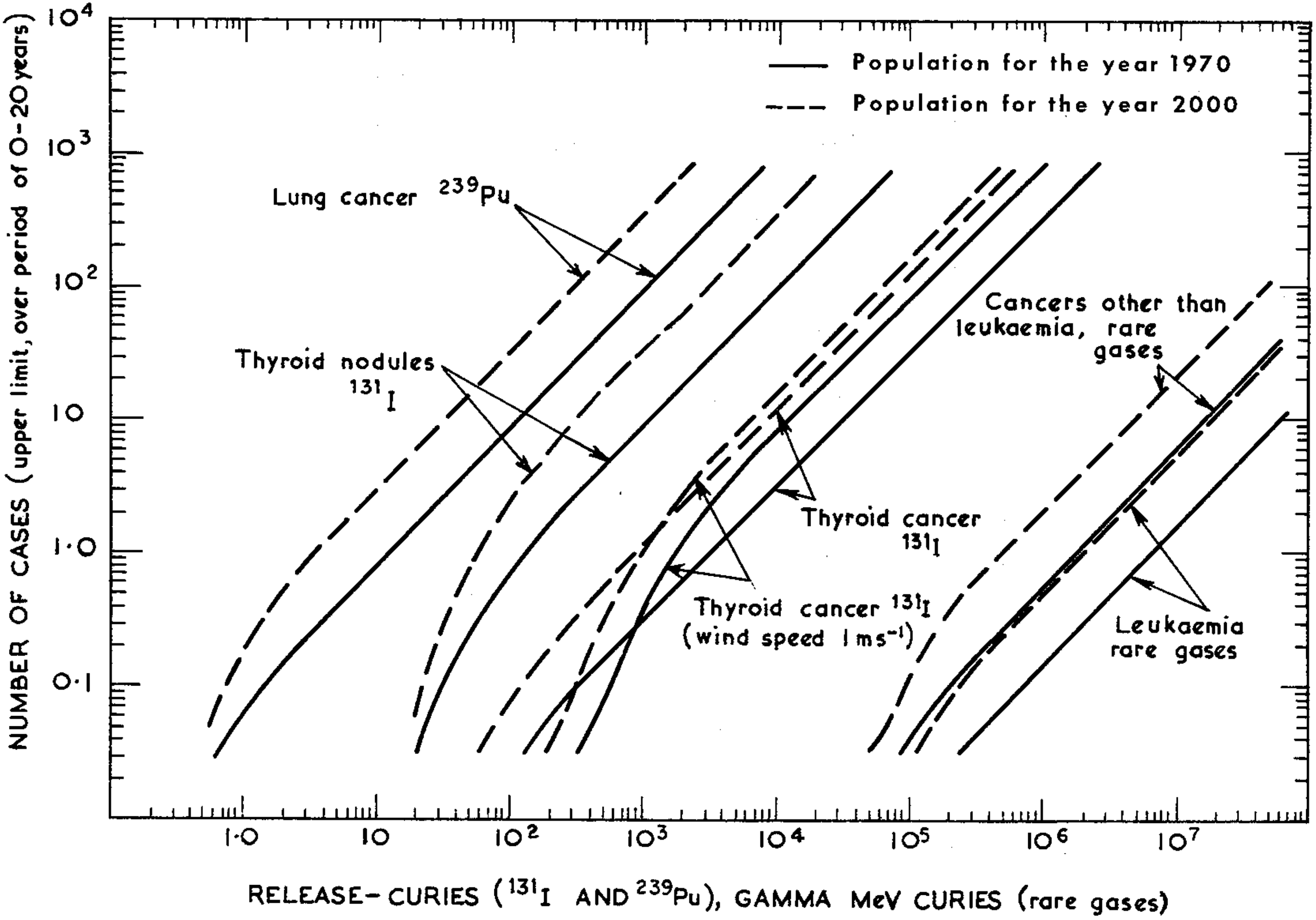

FIGURE F1. AVERAGE CASUALTIES FOLLOWING OFF-SITE EXPOSURE
(average over all weather conditions and wind directions)

Wind speed during inversions 0.4 m s^{-1} unless otherwise stated

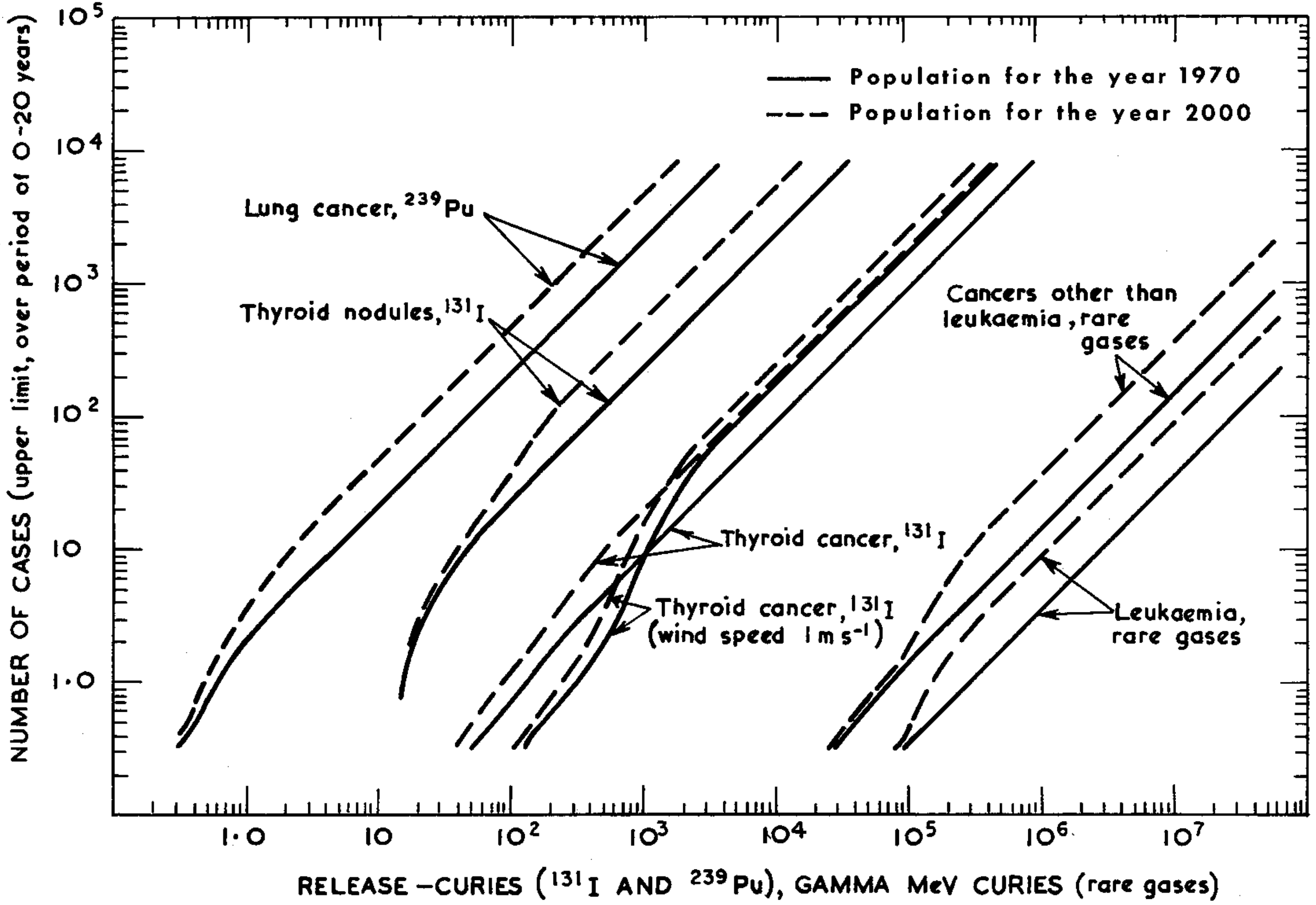

FIGURE F2. MAXIMUM CASUALTIES FOLLOWING OFF-SITE EXPOSURE (adverse weather conditions, wind blowing into sector receiving greatest population dose)

Wind speed assumed 0.4 m s unless otherwise stated

APPENDIX G

EMERGENCY REFERENCE LEVELS

1. EMERGENCY REFERENCE LEVELS FOR IODINE-131 AND CAESIUM-137

Parameter	Units	Iodine-131		Caesium-137	
		6 month old child(a)	Adult	6-month old child(a)	Adult
Critical organ	-	Thyroid	Thyroid	Whole body	Whole body
ERL of dose to critical organ	rad	25	25	10	10
Dose per microcurie inhaled	rad μCi^{-1}	11.6	1.23	0.049	0.047
Dose per microcurie ingested	rad μCi^{-1}	15.5	1.64	0.066	0.062
ERL of cloud dosage	Ci s m^{-3}	0.03(b)	0.088	2.9	0.93(c)
ERL in milk(d)	μCi ℓ^{-1}	0.25	3.0	6.7	9.8
ERL on pasture(e)	μCi m^{-2}	1.5	22	22	33

Note: (a) The values for the 6-month old child can be taken as typical of children in the first year of life.

(b) Where there is a dose contribution from other iodine isotopes and tellurium-132, the values for iodine-131 should be reduced by a factor of two or, in the case of a release of short-lived fission products from a criticality accident, by a factor of ten.

(c) The adult is the limiting case due to the much shorter half-life of caesium-137 in children than in adults.

(d) The tabulated values are for the maximum levels reached after a single deposition.

(e) The levels on pasture are the initial activities of the total deposits.

2. EMERGENCY REFERENCE LEVELS FOR STRONTIUM-89 AND STRONTIUM-90

Parameter	Units	Strontium-89		Strontium-90	
		6-month old child[(a)]	Adult	6-month old child[(a)]	Adult
Critical organ	-	Bone	Bone	Bone	Bone
ERL of dose to critical organ	-	15 rad	15 rad	1.5 rad y^{-1}	1.5 rad y^{-1}
ERL of cloud dosage	Ci s m^{-3}	<u>0.079</u>	0.36	<u>0.00083</u>	0.0036
ERL in milk	μCi g^{-1}Ca	0.2	0.2	0.002	0.002
ERL on pasture	μCi m^{-2}	10	10	0.1	0.1

Note: (a) The values for the 6-month old child can be taken as typical of children in the first year of life.

3. EMERGENCY REFERENCE LEVELS FOR AIRBORNE EXPOSURE TO PLUTONIUM-239

Form	Airborne Exposure (Ci s m^{-3})		Dose Limit
	Adult	Child	
Soluble	4.5×10^{-5}	10^{-5}	1.5 rem y^{-1} to bone
Insoluble	3.4×10^{-4}	1.2×10^{-4}	15 rem to lung

4. REFERENCES

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