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RESEARCH ESTABLISHMENT

LUCAS HEIGHTS

SITE EMERGENCY RELEASES AND SITE EMERGENCY STOCKS – RECOMMENDED VALUES FOR USE AT THE RESEARCH ESTABLISHMENT

by

J. E. COOK

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ABSTRACT

Figures are given for the quantities of hazardous materials which, if released to atmosphere or if involved in an accident capable of leading to a release to atmosphere at the Australian Atomic Energy Commission Research Establishment, Lucas Heights, are the minimum amounts which could give rise to a situation requiring appraisal by the Site Emergency Organisation. Such a situation is defined as one in which potential involuntary exposures of individuals to radiation and radioactive materials may involve a subsequent risk to the exposed individual of long term adverse somatic effects (e.g. carcinogenesis) in excess of 10^{-4}. The circumstances of an accident involving more than a site emergency stock must be investigated immediately to evaluate actual risks and to initiate emergency action if necessary. The dependence of such an evaluation on the physical and chemical forms of the material, its containment and prevailing weather conditions are described in general terms.

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The following descriptors have been selected from the INIS Thesaurus to describe the subject content of this report for information retrieval purposes. for further details please refer to IAEA–INIS–12 (INIS: Manual for Indexing) and IAEA–INIS–13 (INIS: Thesaurus) published in Vienna by the International Atomic Energy Agency.

ADULTS; ATMOSPHERES; BIOLOGICAL RADIATION EFFECTS; CHILDREN; CRITICAL ORGANS; DOSE,RESPONSE RELATIONSHIPS; EXTERNAL IRRADIATION; INGESTION; INHALATION; ORGANS; MAXIMUM ACCEPTABLE CONTAMINATI; MAXIMUM PERMISSIBLE CONCENTRAT; MILK; RADIATION DOSES; RADIATION HAZARDS; RADIATION PROTECTION; RADIOISOTOPES; RADIONUCLIDE MIGRATION; REACTOR ACCIDENTS: RECOMMENDATIONS; TOXICITY; WEATHER

CONTENTS

CONTENTS (Cont'd.)

1. INTRODUCTION

In formulating plans to deal with possible accidents, relationships are needed between the quantities of radioactive or chemically toxic materials held in buildings and the possible magnitudes of hazards which might develop downwind if the materials were released to atmosphere in airborne form as a result of fires, explosions or similar accidents. Some years ago, this problem was considered by Cook (1964) in two stages. Figures were derived for the amounts of some commoner materials which, if released to atmosphere, could give rise to exposure above defined reference levels at distances up to 100 m from the point of release. These amounts were called site hazardous releases. Secondly, the fractions of stocks of these materials which might be rendered airborne under accident conditions were considered. Combination of airborne release factors with site hazardous releases provided values for site hazardous stocks.

Flew and Lister (1969) extended the above treatment by suggesting further modifying factors which may be applied in assessing site hazardous stocks to take account of containment and distribution of the materials within buildings. Additionally they amended, where appropriate, data used by Cook, in the light of subsequent information and recommendations.

This report somewhat modifies the philosophy of these earlier papers inasmuch as the use of the word 'hazardous' in the phrase 'site hazardous release' implies that a hazard is likely to exist if the quantity of material released to atmosphere exceeds a site hazardous release. This is, in fact, unlikely for such quantities because of the strong dependence of the consequent hazard on prevailing conditions, e.g. wind speed and direction, atmospheric turbulence, duration of release and effective height of release. The quantities of interest therefore are called 'site emergency releases' and 'site emergency stocks' and are defined somewhat more restrictively than in the earlier papers. The discharge to atmosphere of a site emergency release or the involvement in an accident of a site emergency stock requires only that the Site Emergency Organisation be alerted to appraise the situation; it does not necessarily imply that a serious hazard will arise.

Site emergency release and stock figures for use at the AAEC Research Establishment (Lucas Heights) are further reduced relative to the figures used in the UK on account of the generally more severe inversion conditions which occur at Lucas Heights (E. Charash, AAEC unpublished report). These give rise to a greater probability of higher downwind concentrations and exposures for given releases.

2. EMERGENCY REFERENCE LEVELS

Emergency reference levels for dose and exposure which may be considered acceptable for Lucas Heights are derivable from the recommendations of the National Health and Medical Research Council for emergency reference levels of risk (NH and MRC 1973), in terms of subsequent development of major adverse somatic effects (e.g. carcinogenesis). Table 1 sets out the recommended emergency reference levels for risk in terms of possible emergency actions or countermeasures for some specified and unspecified exposure situations. If an accident is likely to result in risks which exceed the emergency reference levels set out in Table 1, the appropriate actions must be taken unless it can be shown that no significant reduction in risk will result, or that subsequent additional risk to others will exceed the reduction likely to be achieved.

The individual risk level of 10^{-4} in an accident situation may be used to distinguish an incident (requiring remedial action only) from an emergency (requiring action to reduce exposure where possible). In the present report, site emergency releases and site emergency stocks are related to this level of risk to the involuntarily exposed individuals.

It should be noted that the range of risk separating the situation requiring no action from that in which action is virtually mandatory is of the order of two decades, whereas the quantities of materials held which require assessment cover many more decades. Consequently, the actual choice of emergency reference levels within this range does not greatly affect the final number of situations judged to have site emergency potential.

3. RISK AS A FUNCTION OF DOSE

Current knowledge of the long-term risks of major adverse somatic effects (in the main, the development of various forms of cancer generally resulting in death) is derived from epidemiological studies with doses mainly in the range 100 to 1,000 rad (UNSCEAR 1972, BEIR 1972). Table 2 shows the risk/dose coefficients taken from these two reviews and used in this report. The figures for risk from internal irradiation by alpha emitters are derived in Appendix A.

4. DOSE-EXPOSURE RELATIONSHIPS

The dose-exposure routes of interest are:

- Inhalation.
- External radiation from airborne and deposited activity.
- Ingestion of contaminated milk (not of major importance at Lucas Heights because little milk is produced locally).

- Ingestion via other routes (contaminated vegetables, tank water, etc).

5. INHALATION

The ICRP recommendations on maximum permissible concentrations for radioactive materials in air provide the most extensive set of figures for deriving the dose to adults as a result of inhalation exposure (ICRP 1959). The ICRP has not considered the factors required for deriving dose to children. For some isotopes such information is available (Dunster 1968, Beattie and Bryant 1970).

Table 3 lists the dose for adults to the critical organ via inhalation per unit airborne exposure (time integral of airborne exposure) for the range of isotopes of interest (after ICRP 1959, 1964). The dose per unit exposure has been obtained as the ratio of the appropriate annual dose limit and the annual exposure limit, the latter being 2,000 MPC-hours, where 2,000 is the number of working hours in the year and MPC is the maximum permissible concentration in air for occupational exposure, except for those cases where bone is the critical organ and the effective half-life of the isotope in bone is long. In such cases, the dose rate per unit exposure has been derived by comparing the amount retained per unit exposure with the maximum permissible body burden and taking this fraction of the annual dose limit. (A breathing rate of 20 m^3 in 24 hours is assumed in this calculation.) The expressions used were:

for whole body	6.95×10^{-7} $(MPC)^{-1}$ rem per Ci s m^{-3}
for skin, thyroid, bone	4.16×10^{-6} $(MPC)^{-1}$ rem per Ci s m^{-3}
for all other organs	2.08×10^{-6} $(MPC)^{-1}$ rem per Ci s m^{-3}
for bone, long-lived materials	$6{,}960\ f_a\ (MPBBf_2)^{-1}$ rem per Ci s m^{-3}

where MPC = maximum permissible concentration in air for occupational exposure, 40 hours per week, for the organ under consideration, in μCi cm^{-3}

MPBB = maximum permissible body burden with bone as the critical organ, in μCi

f_a = fraction reaching bone by inhalation

f_2 = fraction in bone to that in total body

Table 4 lists doses to critical organs for children and adults cited by other authors for some particular isotopes.

Comparison of the respective figures given in Tables 3 and 4 shows that the adult doses for ruthenium-106 and caesium-137 are essentially the same, but that there are differences for strontium and, to a lesser extent, iodine. The iodine figures from Table 4 and the strontium figures from Table 3 are used in this report as they are based on more recent data.

Reference to the original literature for child dose in bone and lung shows that it differs from adult dose because of differences in organ weights and breathing rates rather than metabolism. The ratios of 4.5 for child/adult bone dose and 2.8 for child/adult lung dose may therefore be applied to other isotopes for which bone and lung are critical organs. Beattie and Bryant (1970) give reasons for taking the child/adult gut dose ratio as unity. No information relevant to other critical organs and isotopes has been found in the literature; in such cases also the ratio is taken as unity.

6. EXTERNAL RADIATION

External radiation dose from airborne and deposited beta-gamma activity is listed in Table 5. The dose from airborne activity is given by the expression:

$0.25\ E\gamma$ rad s^{-1}

where C = Ci m^{-3}

and $E\gamma$ = MeV per disintegration emitted as X- or gamma rays.

For cloud gamma dose, except at very large distances from a release, this expression will overestimate dose rate as lateral dimensions of the airborne plume will be generally less than the mean free path in air of the gamma rays.

For gamma activity deposited on the ground the expression 4.5×10^{-3} $E\gamma$ rad s^{-1} per Ci m^{-2} is used (Beattie and Bryant 1970) to give the dose rate at 1 metre above a uniformly contaminated plane. A deposition velocity of 3×10^{-3} m s^{-1} is assumed (Beattie and Bryant 1970) which gives a dose rate of 4.85×10^{-2} $E\gamma$ rad h^{-1} per Ci s m^{-3}.

The beta dose rate from activity deposited on the ground will be less than that from activity deposited on skin. For the approximate relationship for mean energies above 0.1 MeV, the skin dose rate from beta activity on skin is about 8 rad h^{-1} per μCi cm^{-2} (Osarov, Tissen and Radzievsky 1969) which gives a dose rate of 2.4 rad h^{-1} per Ci s m^{-3}, assuming a deposition velocity of 3×10^{-3} m s^{-1}.

In this report, the exposure time for deposited activity is taken as 6 hours on the assumption that, within this time, measurements of actual dose rates will be made and a more realistic assessment of the situation will be possible. Total doses per unit exposure in Table 5 are therefore based on this assumption.

7. INGESTION VIA MILK, OTHER FOODSTUFFS AND RAINWATER

Dose from the ingestion of activity deposited in the environment is given in Table 6, assuming a deposition velocity of 3×10^{-3} m s^{-1}. The derivation of these figures is given in Appendix B. Those for strontium-89 and -90, iodine-131, caesium-137, ruthenium-103 and -106 are taken from Beattie and Bryant (1970).

The table has not been extended to other isotopes in the absence of any indication that milk could be a significant exposure route, and as ingestion via other routes is generally less restrictive than inhalation (compare figures in Table 3 with those of Table B2 in Appendix B).

Tables 3 and 4 show that doses from milk contaminated by phosphorus-32, sulphur-35, strontium-89 and -90, iodine-131, caesium-137 and radium-226 are significantly greater than doses from direct inhalation at the same locality, and that doses from ingestion of other foodstuffs are about the same as those via inhalation. For other isotopes, ingestion via other foodstuffs is not as restrictive as inhalation. Ingestion via roof-collected rainwater is indicated as more restrictive than inhalation or uptake of milk for ruthenium-103 and -106, and radium-226.

8. CHEMICAL TOXICITY

Chemical toxicity is a limiting factor for soluble uranium (although in the event of release by fire or other high temperature event uranium is much more likely to be rendered airborne as an insoluble oxide). Table 7 lists exposure limits for soluble uranium and also for beryllium and fluorine.

The limits expressed as time integrals of airborne exposure enable limits to be set on the total quantity which may be discharged at any one time. It is to be noted that these limits cannot be associated with any particular value of risk because of lack of knowledge of the relationship between exposure and the biological effects of toxic materials at these levels.

9. METEOROLOGICAL FACTORS

Airborne material released to atmosphere is dispersed by atmospheric turbulence. The degree of dispersion varies widely and is dependent on the stability of the atmosphere, wind speed and the roughness of the local terrain. Predictions are possible for reasonably level ground as a function of stability and wind speed (Pasquill 1961). Pasquill's predictions have been summarised graphically by Bryant (1964). Pasquill does not give figures for dispersion under strong inversion conditions. Such conditions however occur frequently at night at Lucas Heights and E. Charash (AAEC unpublished report) has provided appropriate dispersion data. Table 8 shows predictions for selected distances and weather conditions, taken from Charash (AAEC unpublished report). The distances of 0.1, 1 and 5 km are chosen as they represent, respectively, the shortest distance for which reliable predictions may be made, the approximate distance of the housing at Engadine from the eastern edge of the Research Establishment site, and the distance from site to the nearest milk producing cows. The conditions chosen illustrate the strong dependence on stability of downwind concentrations. The most restrictive condition (clear night, low wind speed) gives downwind concentrations on site of the order of 100 times greater than those predicted for a fine sunny day.

10. EXPOSURE LIMITS

Table 9 lists exposure (time integrals of airborne concentration) to give doses associated with long term risks of 10^{-4} via inhalation for adults and children, Table 10 lists exposures associated with risks of 10^{-4} via external radiation, applicable at any age, and Table 11 exposures associated with risks of 10^{-4} via ingestion, for adults or children, depending on which is the more restrictive. For beta emitters and uptake into bone, dose to bone marrow and risk of leukaemia is taken to be more critical than dose to bone and risk of bone cancer, except for the low energy beta emitter plutonium-241. For alpha emitters of decay series involving both alpha and beta emitters, dose to bone and risk of bone cancer is taken to be more critical than dose to bone marrow and risk of leukaemia.

11. SITE EMERGENCY RELEASES

In the event of an accident releasing hazardous material to atmosphere, the effective height of the release will depend on such factors as point(s) of release from a building, effects of building induced turbulence, and thermal rise. The worst case is that where the effective height of release is zero. Site emergency releases are defined, therefore, in terms of ground level releases under adverse meteorological conditions such that the risk of subsequently developing some major adverse somatic effect is 10^{-4} for a person exposed for the period of the release at 100 metres downwind. The figure 100 metres is derived from the meteorological difficulty of predicting exposures at shorter distances but is considered not inappropriate for defining site emergencies, since exposure above the appropriate emergency reference levels at distances of not more than 100 metres can be considered as only a local and not as a site emergency. It is assumed that only adults will be exposed at this distance from any building on site.

Off-site emergency releases are defined in a similar way except that the reference distance is taken as 1 kilometre. This is approximately the closest distance between the 1 mile exclusion boundary around HIFAR and the nearest buildings on site. In this case both children and adults may be exposed. The nearest known milk producing cows are at 5 km, in Menai, but it is possible that the odd cow or goat may be kept at Engadine, so all exposure routes (airborne, milk and contamination from other sources) are considered at the 1 km distance.

Assuming the most adverse weather condition in Table 8 (inversion at night as described by Charash's stability Category F1, at a wind speed 1.0 metres per second), those quantities of the various materials of interest which could give rise to the emergency reference levels of airborne exposure applicable to adults at 100 metres downwind (Tables 9, 10) and those quantities which could give rise to the emergency reference levels applicable to children or adults - whichever are the more restrictive - at 1 kilometre downwind (Tables 9, 10, 11) were derived and are given in Tables 12 and 13. These values have been rounded down to the nearest 1 or 3 in magnitude and are recommended as site and off-site emergency releases.

Thus, if the quantity of material released to atmosphere in an accident cannot exceed the quantities given in Table 12, the accident cannot give rise to an emergency. Conversely, if the quantities could exceed the site emergency release figure the circumstances must be investigated and appropriate emergency action taken.

12. SITE EMERGENCY STOCKS

Apart from the meteorological variables which determine the magnitude of the consequences of a given release, the nature of the accident, the physical and chemical form of the material involved, and its containment at the time of the accident combine to determine what fraction of a given stock is released to amosphere. No reliable general figures for the effect of containment can be given, although the method used by Flew and Lister (1969) is of value in attempting to evaluate the relative hazard potential of various stocks of material (see Appendix C). However, some reasonably reliable figures are available for the fractions of various materials which can become airborne when involved in an accident without containment. These values are given in Table 14.

The figures are considered to be conservative. Those for beryllium are derived from the data of Warren and Copland (1968), Blumenthal and Santy

(1965), and Stuart and Price (1964). The figure for uranium metal is taken from Megaw, Chadwick, Wells and Bridges (1961) and those for uranium in combustible waste and plutonium, from Mishima and Schwendiman (1970). The figure of 3 per cent for uranium metal is assumed to apply to thorium metal and the figure of 1 per cent for dry plutonium compounds is assumed to apply to uranium, thorium and americium compounds. The data for fission product releases are taken from Parker, Martin, Creek and Lorenz (1963), except for the figure of 1 per cent for other unspecified products. The latter figure is adopted on the assumption that absence of data for these materials is due to their low volatility. For all other materials involved in fires a 10 per cent release is assumed, except for gases and vapours, for which a 100 per cent release is used. If the accident is an explosion directly involving the hazardous material, it is recommended that it be assumed that 100 per cent becomes airborne.

It is to be noted that these figures refer to the fraction converted to aerosol form within the immediate environment. Where some form of containment exists between this environment and the atmosphere, the actual release to atmosphere will be reduced. In the absence of specific figures for specific situations, it is recommended that it be assumed that 10 per cent of the material rendered airborne within a building is released within the first few hours following an accident which does not significantly damage the structure. There are two exceptions: in the case of unreactive gases, or where a building is significantly damaged by fire or explosion, a 100 per cent release is assumed.

Combination of the fractional release figures with the site emergency release figures of Tables 12 and 13 gives figures for site emergency stocks. An accident involving less than a site emergency stock is most unlikely to give rise to an emergency situation. An accident involving more than a site emergency stock may give rise to an emergency situation, depending on circumstances. Tables 15 and 16 give recommended figures for site emergency stocks.

13. CONCLUSION

Consideration has been given to available information on the long term risks of carcinogenesis associated with radiation exposure, the possible routes whereby radioactive material released to atmosphere at the AAEC Research Establishment, Lucas Heights, could give rise to radiation exposure of members of the public, the possible degrees of dispersion in the atmosphere at the Research Establishment and the possible fractions of stocks of such materials likely to be released to atmosphere as a result of a major fire or explosion. These considerations make it possible to set lower limits on the releases and stocks which could give rise to exposure of members of the public in excess of the recommended emergency reference levels.

These numbers may be used to provide an initial assessment of the of the possible radiological significance of an accident involving a stock of radioactive material.

Such limits have been derived for exposure with associated risks of carcinogenesis of 10^{-4} (a level put forward by the National Health and Medical Research Council to distinguish an accident situation not specifically requiring further investigation from one which does). The limits have been derived for exposure at 100 metres downwind and at 1 km downwind. The former are called site emergency releases and stocks, the latter off-site emergency releases and stocks.

It is recommended that these numbers be used by the site emergency organisation at the Research Establishment as a guide to the necessity for emergency action in the event of accidents on the site.

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TABLE 1

EMERGENCY REFERENCE LEVELS FOR RISK

Exposure Route	Emergency Reference Level for Associated Individual Risk	Recommended Action
Not specified	10^{-4}	Consider the application of possible counter-measures, i.e. alert the Site Emergency Organisation
Contaminated foodstuffs	3×10^{-4}	Control consumption
Airborne contamination	3×10^{-3}	Consider the evacuation of potentially exposed persons
Not specified	10^{-2}	Countermeasures must be taken unless agreed otherwise by responsible authorities

TABLE 2

RISK-DOSE RELATIONSHIPS

Population	Risk-Dose Relationship - Cases per 10^6 rem for the Following Tissues and Consequences				
	Whole Body	Bone Marrow	Thyroid	Bone	Other Organs
	All Forms of Cancer	Leukaemia	Thyroid Cancer	Bone Cancer	Cancer of Organ
In utero	400	200	-	-	-
0-9 years	150	60	60	-	-
10 or more years	200	30	30	-	-
All ages including those in utero	200	40	40	10	40

(a) rem is defined as in ICRP 2 (1959).

(b) Mortality from thyroid cancer is significantly less than from other forms of cancer. Dolphin and Marley (1969) recommend for assessment purposes a ratio of deaths to incidence of 0.1.

(c) Irradiation of the thyroid in childhood also produces non-malignant thyroid nodules. Conard et al., quoted in UNSCEAR (1972), give a risk rate for nodularity of about 50 cases per year per 10^6 thyroid rem, or 1000 cases total per 10^6 rem.

(d) Internal irradiation of the thyroid (e.g. by iodine-131) is frequently considered to be less hazardous than external irradiation (e.g. Dolphin and Marley 1969), on the basis of observations in animals and the absence of observed adverse effects following the diagnostic and therapeutic use of radioiodines. These latter data are inconclusive however, particularly with reference to children. In consequence it is conservatively assumed that internal irradiation of the thyroid is as hazardous as external irradiation.

(e) The age grouping is that used in BEIR (1972).

(f) The coefficients for all ages are derived assuming a population with 0.15 per cent in utero, 20 per cent under 10 years of age and 80 per cent over 10 years of age.

TABLE 3

DOSE OR DOSE-RATE PER UNIT EXPOSURE TO CRITICAL ORGAN

FOR ADULTS BY INHALATION

(After ICRP 1959, 1964)

Isotope	Rem per Ci s m^{-3}			
	Soluble		Insoluble	
^{3}H (HTO)	0.14	whole body	-	
^{14}C	0.14	whole body	-	
^{18}F	0.42	gut	0.7	gut
^{24}Na	2.1	gut	21.0	gut
^{32}P	60.0	bone	26.0	lung
^{35}S	6.9	testes	7.0	lung
^{46}Sc	10.0	liver	104.0	lung
^{54}Mn	5.2	liver	52.0	lung
^{60}Co	7.0	gut	230.0	lung
^{89}Sr	140.0	bone	52.0	lung
^{90}Sr	140.0	rem y^{-1}, bone (a)	830.0	lung
^{95}Zr	7.0	whole body	70.0	lung
^{99m}Tc	0.052	gut	0.21	gut
^{99}Mo	3.0	kidney	10.4	gut
^{103}Ru	4.2	gut	26.0	lung
^{106}Ru	26.0	gut	350.0	lung
^{110m}Ag	10.0	gut	210.0	lung
^{131}I	460.0	thyroid	7.0	lung
^{137}Cs	11.0	whole body	210.0	lung
^{226}Ra	2,100	rem y^{-1}, bone	42,000	lung
Th_{nat}	14,000	rem y^{-1}, bone	2.1 x 10^{6}	lung
^{233}U	8,300	bone	21,000	lung
^{234}U	7,000	bone	21,000	lung
^{235}U	7,000	bone	21,000	lung
^{238}U	30,000	kidney	21,000	lung
U_{nat}	30,000	kidney	35,000	lung
^{239}Pu	39,000	rem y^{-1}, bone	52,000	lung
^{240}Pu	39,000	rem y^{-1}, bone	52,000	lung
^{241}Pu	46,000	bone	52.0	lung
^{241}Am	12,000	rem y^{-1}, bone	21,000	lung

(a) *ICRP 2 (1959) gives a value of 420 rem y^{-1}, but ICRP 6 (1964) reduces dose by a factor of 3 for the same exposure. This figure is therefore consistent with ICRP 6.*

TABLE 4

DOSE OR DOSE-RATE PER UNIT EXPOSURE TO CRITICAL ORGAN FOR ADULTS AND CHILDREN BY INHALATION

(After Beattie and Bryant 1970)

Isotope		Rem per Ci s m^{-3}	
		Soluble	Insoluble
^{89}Sr	child	190.0 bone	
	adult	42.0 bone	
^{90}Sr	child	1,800.0 rem y^{-1}, bone	
	adult	420.0 rem y^{-1}, bone	
^{106}Ru	child		1,150.0 lung
	adult		420.0 lung
^{131}I	child	810.0 thyroid	
	adult	280.0 thyroid	
^{137}Cs	child	3.4 whole body	
	adult	10.8 whole body	

TABLE 5

EXTERNAL RADIATION DOSE FROM AIRBORNE OR DEPOSITED ACTIVITY

Isotope	MeV per Disintegration[(a)]		Dose per unit exposure (rem per Ci s m^{-3})					
			Whole Body			Skin		
	beta	gamma	Airborne (gamma) (rem)	Deposited on Ground (rem per 6 h)	Total (rem per 6 h)	Airborne (gamma plus beta) (rem)	Deposited on Skin (beta) (rem per 6 h)	Total (rem per 6 h)
^{3}H	0.006	-	-	-	-	- (b)	-	-
^{14}C	0.045	-	-	-	-	0.011	14.4	14.4
^{18}F	0.32	0.99	0.25	0.29	0.54	0.33	14.4	14.7
^{24}Na	0.46	4.12	1.03	1.19	2.2	1.15	14.4	15.6
^{32}P	0.69	-	-	-	-	0.17	14.4	14.6
^{35}S	0.049	-	-	-	-	0.012	14.4	14.4
^{46}Sc	0.12	2.01	0.50	0.58	1.1	0.53	14.4	14.9
^{54}Mn	-	0.84	0.21	0.24	0.45	0.21	-	0.21
^{60}Co	0.10	2.50	0.62	0.72	1.35	0.65	14.4	15.0
^{85}Kr	0.22	0.0021	0.0005	- (c)	0.0005	0.055	- (c)	0.055
^{89}Sr	0.47	-	-	-	-	0.12	14.4	14.5
^{90}Sr	1.0	-	-	-	-	0.25	28.8	29.0
^{95}Zr	0.18	1.49	0.38	0.43	0.80	0.42	28.8	29.2
^{99m}Tc	-	0.125	0.031	0.037	0.068	0.031	-	0.031
^{99}Mo	0.41	0.26	0.065	0.075	0.14	0.16	14.4	14.6
^{103}Ru	0.07	0.48	0.12	0.14	0.26	0.14	14.4	14.5
^{106}Ru	1.2	0.20	0.05	0.06	0.11	0.35	14.4	14.8
^{110m}Ag	0.07	2.54	0.63	0.74	1.4	0.65	14.4	15.0
^{131}I	0.19	0.76	0.19	0.22	0.41	0.24	14.4	14.6
^{133m}Xe	0.11	0.063	0.016	- (c)	0.016	0.043	- (c)	0.043
^{133}Xe	0.11	0.030	0.008	- (c)	0.008	0.035	- (c)	0.035
^{137}Cs	0.17	0.56	0.14	0.16	0.30	0.18	14.4	14.6

(a) Lederer, Hollander and Perlman (1967).

(b) Beta energy too low to give skin dose.

(c) Noble gases - no deposition.

TABLE 6

ESTIMATES OF DOSE OR DOSE-RATE FOLLOWING THE INGESTION OF CONTAMINATED MILK AND FROM THE INGESTION OF OTHER CONTAMINATED FOODS FOLLOWING DEPOSITION FROM UNIT AIRBORNE EXPOSURE

Isotope	Critical Organ and Age Group	Dose (or Dose Rate) per Unit Exposure (rem per Ci s m^{-3})		
		Milk	Other Foodstuffs	Roof-collected Rain Water
^{32}P	Bone, child	5×10^4	21.0	220.0
^{35}S	Whole body, all ages	500.0	0.08	240.0
^{89}Sr	Bone, child	4,500.0	225.0	1,250.0
^{90}Sr	Bone, child	4.5×10^4 rem y^{-1}	2,250 rem y^{-1}	10^4 rem y^{-1}
^{103}Ru	Gut, all ages	*(a)*	1.3	60.0
^{106}Ru	Gut, all ages	*(a)*	9.2	1,100.0
^{131}I	Thyroid, child	5×10^4	240.0	10^4
^{137}Cs	Whole body, adult	1,400.0	2.7	220.0
^{226}Ra	Bone, child	8,000 rem y^{-1}	400 rem y^{-1}	8×10^4 rem y^{-1}
^{232}Th	Bone, child	*(a)*	7.6 rem y^{-1}	1,700 rem y^{-1}
U_{nat}	Kidney, all ages	*(a)*	13.5	2.2×10^4
^{239}Pu	Bone, child	*(a)*	0.65 rem y^{-1}	140 rem y^{-1}

(a) For these isotopes, uptake into milk is not significant.

TABLE 7

EXPOSURE LIMITS BASED ON CHEMICAL TOXICITY

Material	Exposure Limit
Beryllium	2 μg m^{-3} occupational exposure[a] 0.01 μg m^{-3} non-occupational exposure, averaged over one month (equivalent to 7.5 μg h m^{-3})
Fluorine	0.2 mg m^{-3} occupational exposure[a] (NSW Department of Health use one thirtieth of this for non-occupational exposure) 3 ppm for 10 minutes 2 ppm for 30 minutes or 1 ppm for 60 minutes[b] (1 ppm is 2 mg m^{-3})
Uranium (soluble)	Limit inhalation to not more than 2.5 mg per day[c] i.e. at a breathing rate of 1 m^3 h^{-1}, 2.5 mg h m^{-3}

(a) NH and MRC (1970).

(b) Siegmund (1967).

(c) ICRP (1964).

TABLE 8

PREDICTED TIME INTEGRALS OF AIRBORNE CONCENTRATION AT GROUND LEVEL DOWNWIND OF A UNIT RELEASE OF ACTIVITY OVER A FEW MINUTES[a]

Conditions, Stability Category and Wind Speed[b] (m s^{-1})	Time Integral of Concentration (Ci s m^{-3}) per Ci released at Distances (km) of		
	0.1	1	5
Day, sunny, B,2	8 x 10^{-4}	7 x 10^{-6}	3 x 10^{-7}
Day or night, cloudy, D,2	4 x 10^{-3}	7 x 10^{-5}	6 x 10^{-6}
Night, clear (inversion), F1,1	5 x 10^{-2}	3 x 10^{-3}	4 x 10^{-4}

(a) if the release is prolonged, say over half an hour or more, these figures would be reduced by at least a factor of three.

(b) concentrations are inversely proportional to wind speed.

TABLE 9

EXPOSURES ASSOCIATED WITH LONG TERM RISKS OF 10^{-4}

VIA INHALATION

Isotope	Age	Exposure for Risk of 10^{-4} ($Ci\ s\ m^{-3}$)			
		Soluble		Insoluble	
^{3}H (HTO)	child	4.8	0.7 rem whole body	-	
	adult	3.6	0.5 rem whole body	-	
^{14}C	child	4.8	0.7 rem whole body	-	
	adult	3.6	0.5 rem whole body	-	
^{18}F	child	6.0	2.5 rem gut	3.6	2.5 rem gut
	adult	6.0	2.5 rem gut	3.6	2.5 rem gut
^{24}Na	child	1.2	2.5 rem gut	0.12	2.5 rem gut
	adult	1.2	2.5 rem gut	0.12	2.5 rem gut
^{32}P	child	0.0062	1.7 rem bone marrow	0.034	2.5 rem lung
	adult	0.056	3.3 rem bone marrow	0.096	2.5 rem lung
^{35}S	child	0.18	1.7 rem bone marrow	0.13	2.5 rem lung
	adult	1.1	2.5 rem testes	0.36	2.5 rem lung
^{46}Sc	child	0.09	1.7 rem bone marrow	0.009	2.5 rem lung
	adult	0.24	2.5 rem liver	0.024	2.5 rem lung
^{54}Mn	child	0.48	2.5 rem liver	0.017	2.5 rem lung
	adult	0.48	2.5 rem liver	0.048	2.5 rem lung
^{60}Co	child	0.36	2.5 rem gut	0.004	2.5 rem lung
	adult	0.36	2.5 rem gut	0.011	2.5 rem lung
^{89}Sr	child	0.0027	1.7 rem bone marrow	0.017	2.5 rem lung
	adult	0.024	3.3 rem bone marrow	0.048	2.5 rem lung
^{90}Sr	child	0.00013	1.7 rem bone marrow	0.002	2.5 rem lung
	adult	0.0012	3.3 rem bone marrow	0.006	2.5 rem lung
^{95}Zr	child	0.018	1.7 rem bone marrow	0.013	2.5 rem lung
	adult	0.072	0.5 rem whole body	0.036	2.5 rem lung
^{99m}Tc	child	48	2.5 rem gut	12	2.5 rem gut
	adult	48	2.5 rem gut	12	2.5 rem gut
^{99}Mo	child	0.84	2.5 rem kidney	0.24	2.5 rem gut
	adult	0.84	2.5 rem kidney	0.24	2.5 rem gut
^{103}Ru	child	0.6	2.5 rem gut	0.034	2.5 rem lung
	adult	0.6	2.5 rem gut	0.096	2.5 rem lung
^{106}Ru	child	0.044	1.7 rem bone	0.0021	2.5 rem lung
	adult	0.096	2.5 rem gut	0.0060	2.5 rem lung
^{110m}Ag	child	0.24	2.5 rem gut	0.0043	2.5 rem lung
	adult	0.24	2.5 rem gut	0.012	2.5 rem lung
^{131}I	child	0.0041	1.7 rem thyroid	-	
	adult	0.012	3.3 rem thyroid	-	

TABLE 9 (Cont'd.)

Isotope	Age	Exposure for Risk of 10^{-4} (Ci s m^{-3})			
		Soluble		Insoluble	
^{137}Cs	child	0.2	0.7 rem whole body	-	
	adult	0.046	0.5 rem whole body	-	
^{226}Ra	child	5.4×10^{-5}	10 rem bone	2.1×10^{-5}	2.5 rem lung
	adult	2.4×10^{-4}	10 rem bone	6.0×10^{-5}	2.5 rem lung
Th_{nat}	child	8.0×10^{-6}	10 rem bone	1.7×10^{-6}	2.5 rem lung
	adult	3.6×10^{-5}	10 rem bone	4.8×10^{-6}	2.5 rem lung
^{233}U	child	2.7×10^{-4}	10 rem bone	4.3×10^{-5}	2.5 rem lung
	adult	1.2×10^{-3}	10 rem bone	1.2×10^{-4}	2.5 rem lung
^{234}U	child	3.2×10^{-4}	10 rem bone	4.3×10^{-5}	2.5 rem lung
	adult	1.4×10^{-3}	10 rem bone	1.2×10^{-4}	2.5 rem lung
^{235}U	child	3.2×10^{-4}	10 rem bone	4.3×10^{-5}	2.5 rem lung
	adult	1.4×10^{-3}	10 rem bone	1.2×10^{-4}	2.5 rem lung
^{238}U	child	8.4×10^{-5}	2.5 rem kidney	4.3×10^{-5}	2.5 rem lung
	adult	8.4×10^{-5}	2.5 rem kidney	1.2×10^{-4}	2.5 rem lung
U_{nat}	child	8.4×10^{-5}	2.5 rem kidney	2.6×10^{-5}	2.5 rem lung
	adult	8.4×10^{-5}	2.5 rem kidney	7.2×10^{-5}	2.5 rem lung
^{239}Pu	child	2.8×10^{-6}	10 rem bone	1.7×10^{-5}	2.5 rem lung
	adult	1.3×10^{-5}	10 rem bone	4.8×10^{-5}	2.5 rem lung
^{240}Pu	child	2.8×10^{-6}	10 rem bone	1.7×10^{-5}	2.5 rem lung
	adult	1.3×10^{-5}	10 rem bone	4.8×10^{-5}	2.5 rem lung
^{241}Pu	child	4.7×10^{-5}	10 rem bone	1.7×10^{-2}	2.5 rem lung
	adult	2.1×10^{-4}	10 rem bone	4.8×10^{-2}	2.5 rem lung
^{241}Am	child	7.2×10^{-6}	2.5 rem kidney	4.3×10^{-5}	2.5 rem lung
	adult	4.2×10^{-5}	10 rem bone	1.2×10^{-4}	2.5 rem lung

TABLE 10

EXPOSURES ASSOCIATED WITH LONG TERM RISK OF 10^{-4}

VIA EXTERNAL RADIATION FROM BETA-GAMMA EMITTERS

Isotope	Exposure for Risk of 10^{-4} ($Ci\ s\ m^{-3}$)		
	Whole body		Skin
	0.5 rem (Adult)	0.7 rem (Child)	2.5 rem (Child and Adult)
^{14}C	-	-	0.17
^{18}F	0.9	1.2	0.17
^{24}Na	0.22	0.3	0.16
^{32}P	-	-	0.17
^{35}S	-	-	0.17
^{46}Sc	0.45	0.6	0.17
^{54}Mn	1.1	1.5	12.0
^{60}Co	0.37	0.49	0.17
^{85}Kr	1,000	1,400	45.0
^{89}Sr	-	-	0.17
^{90}Sr	-	-	0.08
^{95}Zr	0.62	1.12	0.08
^{99m}Tc	7.5	13.0	80.0
^{99}Mo	6.5	8.7	0.17
^{103}Ru	1.9	2.5	0.17
^{106}Ru	4.5	6.0	0.17
^{110m}Ag	0.35	0.47	0.17
^{131}I	1.2	1.6	0.17
^{133m}Xe	31.0	41.0	58.0
^{133}Xe	62.0	83.0	72.0
^{137}Cs	1.6	22.0	0.17

TABLE 11

EXPOSURES ASSOCIATED WITH LONG TERM RISKS OF 10^{-4} VIA INGESTION

Isotope	Critical Organ, Dose and Age Group	Exposure for Risk of 10^{-4} ($Ci\ s\ m^{-3}$)		
		Milk	Other Foodstuffs	Roof-Collected Rainwater
^{32}P	Bone marrow: 1.7 rem - child	3.4×10^{-5}	0.08	1.7×10^{-3}
^{35}S	Whole body: 0.7 rem - child	1.4×10^{-3}	88.0	2.8×10^{-3}
^{89}Sr	Bone marrow: 1.7 rem - child	3.7×10^{-4}	7.5×10^{-3}	1.4×10^{-3}
^{90}Sr	Bone marrow: 1.7 rem - child	1.9×10^{-6}	3.6×10^{-5}	8.5×10^{-6}
^{103}Ru	Gut: 2.5 rem	*(a)*	1.9	0.04
^{106}Ru	Gut: 2.5 rem	*(a)*	0.3	2.3×10^{-3}
^{131}I	Thyroid: 1.7 rem - child	3.3×10^{-5}	7.0×10^{-3}	1.6×10^{-4}
^{137}Cs	Whole body: 0.5 rem - adult	3.6×10^{-4}	0.18	2.2×10^{-3}
^{226}Ra	Bone: 10 rem - child	6.0×10^{-5}	1.2×10^{-3}	6.2×10^{-6}
^{232}Th	Bone: 10 rem - child	*(a)*	6.6×10^{-2}	2.9×10^{-5}
U_{nat}	Kidney: 10 rem	*(a)*	0.74*(b)*	4.5×10^{-4}*(c)*
^{239}Pu	Bone: 10 rem - child	*(a)*	0.74	2.6×10^{-3}

(a) Uptake into milk known to be small.

(b) Limit based on chemical toxicity is 2,500 g s m^{-3}*, which for natural uranium is 1.7 x* 10^{-3} *Ci s* m^{-3}*.*

(c) Limit based on chemical toxicity is 11 g s m^{-3} *which for natural uranium is 7.4 x* 10^{-6} *Ci s* m^{-3}*.*

TABLE 12

RECOMMENDED FIGURES FOR SITE AND OFF-SITE EMERGENCY RELEASES

(Activity in curies)

Isotope	Site Emergency Release (Curies)		Off-site Emergency Release (Curies)		
	Direct Exposure		Direct Exposure		Milk, Crops or Rainwater
	Soluble	Insoluble	Soluble	Insoluble	
^{3}H	30	-	3×10^{2}	-	
^{14}C	3	3	30	30	
^{18}F	3	3	30	30	
^{24}Na	3	1	30	30	
^{32}P	1	1	1	10	10^{-2}
^{35}S	3	3	30	30	3×10^{-1}
^{46}Sc	3	3×10^{-1}	30	3	
^{54}Mn	10	1	10^{2}	3	
^{60}Co	10	10^{-1}	30	1	
^{85}Kr	3×10^{2}	-	10^{4}	-	
^{89}Sr	3×10^{-1}	1	1	3	10^{-1}
^{90}Sr	10^{-2}	10^{-1}	3×10^{-2}	3×10^{-1}	10^{-3}
^{95}Zr	1	3×10^{-1}	3	3	
^{99m}Tc	10^{2}	10^{2}	10^{3}	10^{3}	
^{99}Mo	3	3	30	30	
^{103}Ru	3	1	30	10	10
^{106}Ru	1	10^{-1}	10	3×10^{-1}	3×10^{-1}
^{110m}Ag	3	10^{-1}	30	1	
^{131}I	10^{-1}	-	1	-	10^{-2}
^{133m}Xe	3×10^{2}	-	3×10^{3}	-	
^{133}Xe	10^{3}	-	10^{4}	-	
^{137}Cs	3×10^{-1}	-	10	-	10^{-1}
^{226}Ra	3×10^{-3}	10^{-3}	10^{-2}	10^{-2}	10^{-3}
Th_{nat}	3×10^{-4}	10^{-4}	10^{-3}	3×10^{-4}	10^{-2}
^{233}U	10^{-2}	10^{-3}	3×10^{-2}	10^{-2}	
^{234}U	10^{-2}	10^{-3}	10^{-1}	10^{-2}	
^{235}U	3×10^{-4}	10^{-3}	3×10^{-3}	10^{-2}	
^{238}U	3×10^{-5}	10^{-3}	10^{-3}	10^{-2}	
U_{nat}	3×10^{-5}	10^{-3}	10^{-3}	10^{-2}	10^{-1}
^{239}Pu	10^{-4}	10^{-3}	3×10^{-4}	3×10^{-3}	1
^{240}Pu	10^{-4}	10^{-3}	3×10^{-4}	3×10^{-3}	
^{241}Pu	3×10^{-3}	1	10^{-2}	3	
^{241}Am	3×10^{-4}	10^{-3}	10^{-3}	10^{-2}	

TABLE 13

RECOMMENDED FIGURES FOR SITE AND OFF-SITE EMERGENCY RELEASES

(Mass in grams)

Isotope	Site Emergency Release (grams)		Off-site Emergency Release (grams)		
	Direct Exposure		Direct Exposure		Milk, Crops or Rainwater
	Soluble	Insoluble	Soluble	Insoluble	
Th_{nat}	3×10^{3}	3×10^{2}	10^{4}	3×10^{3}	10^{5}
^{233}U	1	0.1	3	1	
^{234}	3	0.3	10	1	
^{235}U	10^{2}	10^{3}	3×10^{3}	3×10^{3}	
^{238}U	10^{2}	3×10^{4}	3×10^{3}	3×10^{4}	
U_{nat}	10^{2}	3×10^{3}	3×10^{3}	3×10^{4}	3×10^{5}
^{239}Pu	3×10^{-3}	10^{-2}	10^{-2}	3×10^{-2}	10
^{240}Pu	10^{-3}	3×10^{-3}	3×10^{-3}	10^{-1}	
^{241}Pu	3×10^{-5}	10^{-2}	10^{-4}	3×10^{-2}	
^{241}Am	10^{-4}	3×10^{-4}	3×10^{-4}	3×10^{-3}	
Beryllium	-	3×10^{-1}	-	10	
Fluorine	30*(a)*	-	1,000*(a)*		

(a) Based on limiting exposure integral of 3 ppm for 10 minutes (see Table 7).

TABLE 14

CONSERVATIVE UPPER LIMITS FOR FRACTIONAL CONVERSION OF VARIOUS MATERIALS TO AEROSOL FORM WHEN INVOLVED IN FIRES OR EXPLOSIONS

Material	Cause of Release	Per Cent Conversion to Aerosol
BeO powder	Fire	1
BeO, sintered	Fire	10^{-4}
Be metal, massive	Fire	10^{-6}
Be metal powder	Fire	10^{-2}
U metal	Fire	3
Pu metal	Fire	0.1
Pu salts in solution	Fire	0.1
Dry Pu compounds as powders	Fire	1
Pu or U compound powders in combustible waste	Fire	50
Gases and vapours	Fire, explosion	100
Other materials	Fire, explosion	10
Fission products in HIFAR fuel	Fuel melting	
Kr, Xe		100
Br, I		100
Te		25
Cs		11
Ru		5
Others		1

TABLE 15

RECOMMENDED FIGURES FOR SITE EMERGENCY STOCKS - QUANTITIES OF MATERIALS WHICH COULD GIVE RISE TO EMERGENCY RELEASES IN THE EVENT OF FIRE

(Activity in curies)

Material (assumed solid unless otherwise stated)	Site Emergency Stock (curies)		Off-site Emergency Stock (curies)		
	Direct Exposure		Direct Exposure		Milk, Crops or Rainwater
	Soluble	Insoluble	Soluble	Insoluble	
^{3}H (as water)	30	-	3×10^{2}	-	
^{14}C (gas)	3	-	30	-	
(solid)	30	30	3×10^{2}	3×10^{2}	
^{18}F (gas)	3	-	30	-	
(solid)	30	30	3×10^{2}	3×10^{2}	
^{24}Na	30	10	3×10^{2}	3×10^{2}	
^{32}P	10	10	10	10^{2}	10^{-1}
^{35}S	30	30	3×10^{2}	3×10^{2}	3
^{46}Sc	30	3	3×10^{2}	30	
^{54}Mn	10^{2}	10	10^{3}	10^{2}	
^{60}Co	30	1	3×10^{2}	10	
^{85}Kr	3×10^{2}	-	10^{4}	-	
^{89}Sr	3	10	10	10^{2}	3
^{90}Sr	10^{-1}	1	3×10^{-1}	3	10^{-2}
^{95}Zr	10	3	30	30	
^{99m}Tc	10^{3}	10^{3}	10^{4}	10^{4}	
^{99}Mo	30	30	3×10^{2}	3×10^{2}	
^{103}Ru	30	10	3×10^{2}	10^{2}	10^{2}
^{106}Ru	10	1	10^{2}	3	3
^{110m}Ag	30	1	3×10^{2}	10	
^{131}I	10^{-1}	-	1	-	10^{-2}
^{133m}Xe	3×10^{2}	-	3×10^{3}	-	
^{133}Xe	10^{3}	-	10^{4}	-	
^{137}Cs	3	10	10^{2}	-	1
^{226}Ra	3×10^{-2}	10^{-2}	10^{-1}	10^{-1}	10^{-2}
Th_{nat} compounds	3×10^{-2}	10^{-2}	10^{-1}	3×10^{-2}	1
metal	10^{-2}	3×10^{-2}	3×10^{-2}	10^{-2}	3×10^{-1}
^{233}U compounds	1	10^{-1}	3	1	
metal	3×10^{-1}	3×10^{-2}	1	3×10^{-1}	

TABLE 15 (Cont'd.)

Material (assumed solid unless otherwise stated)		Site Emergency Stock (curies)		Off-site Emergency Stock (curies)		
		Direct Exposure		Direct Exposure		Milk, Crops or Rainwater
		Soluble	Insoluble	Soluble	Insoluble	
^{234}U	compounds	1	10^{-1}	10	1	
	metal	3×10^{-1}	3×10^{-2}	3	3×10^{-1}	
^{235}U	compounds	3×10^{-2}	10^{-1}	3×10^{-1}	1	
	metal	10^{-2}	3×10^{-2}	10^{-1}	3×10^{-1}	
^{93}V U(a)	compounds	1	3×10^{-1}	10	1	
	metal	3×10^{-1}	10^{-1}	3	3×10^{-1}	
U_{nat}	compounds	3×10^{-3}	10^{-1}	10^{-1}	1	10
	metal	10^{-3}	3×10^{-2}	3×10^{-2}	3×10^{-1}	3
^{239}Pu	compounds (dry)	10^{-2}	10^{-1}	3×10^{-2}	3×10^{-1}	10^{2}
(Includes up to 10% ^{240}Pu)	compounds (solutions)	10^{-1}	1	3×10^{-1}	3	10^{3}
	metal	10^{-1}	1	3×10^{-1}	3	10^{3}
^{241}Am	compounds	3×10^{-2}	10^{-1}	3×10^{-1}	1	
U, Pu in combustible waste		use the emergency release figures given in Table 12 as a large fraction can become airborne				

(a) ^{93}V uranium is, by mass, mainly ^{235}U (93%) but, by activity, mainly ^{234}U (61 μCi g^{-1} out of total activity 63 μCi g^{-1}). The activity figure is that used by Flew and Lister (1969).

TABLE 16

RECOMMENDED FIGURES FOR SITE EMERGENCY STOCKS - QUANTITIES OF MATERIALS WHICH COULD GIVE RISE TO EMERGENCY RELEASES IN THE EVENT OF FIRE

(Mass in grams)

Material (assumed solid unless otherwise stated)		Site Emergency Stock (grams)		Off-site Emergency Stock (grams)		
		Direct Exposure		Direct Exposure		Milk, Crops or Rainwater
		Soluble	Insoluble	Soluble	Insoluble	
Th_{nat}	compounds[a]	3×10^5	3×10^4	10^6	3×10^5	10^7
	metal	10^5	10^4	3×10^5	10^5	3×10^6
^{233}U	compounds	10^2	10	3×10^2	3×10^2	-
	metal	30	3	10^2	30	-
^{234}U	compounds	3×10^2	30	10^3	10^2	-
	metal	10^2	10	3×10^2	30	-
^{235}U	compounds	10^4	10^5	3×10^5	3×10^5	-
	metal	3×10^3	3×10^4	10^5	10^5	-
^{93}V U	compounds	10^4	3×10^3	10^5	10^4	-
	metal	3×10^3	10^3	3×10^4	3×10^3	-
U_{nat}	compounds	10^4	3×10^5	3×10^5	3×10^6	3×10^7
	metal	3×10^3	10^5	10^5	10^6	10^7
^{239}Pu	compounds	3×10^{-1}	1	1	3	10^3
(Includes	solutions	3	10	10	30	10^4
up to 10% ^{240}Pu)	metal	3	10	10	30	10^4
^{241}Am	compounds	10^{-2}	3×10^{-2}	3×10^{-2}	3×10^{-1}	-
Beryllium	metal	-	3×10^7	-	10^9	-
	metal powder	-	3×10^3	-	10^5	-
BeO	powder	-	30	-	10^3	-
	sintered	-	3×10^5	-	10^7	-
Fluorine		30	-	10^3	-	-
U, Pu in combustible waste		use the emergency release figures given in Table 13 as a large fraction can become airborne				

(a) *Compounds include both dry and wet materials except where solutions are specified.*

APPENDIX A

RISK-DOSE RELATIONSHIPS FOR INTERNAL ALPHA EMITTERS

A1. SOURCES OF DATA

Information on the long term adverse effects of internal alpha emitters in man is derived from occupational exposure to radium and plutonium, from the therapeutic use of radium and from the exposure of uranium miners to radon and its short-lived daughter products. Adverse effects observed are the production of bone sarcomas (from radium-224, -226 and -228) paranasal and mastoid carcinomas (radium-226 only, almost certainly due to buildup of radon-222 daughter products in these areas) and lung cancers (from the inhalation of radon and daughter products). No adverse effects have been observed so far in persons occupationally exposed to plutonium.

A2. BONE TUMORS

The US data on radium-226 and radium-228 (BEIR 1972, Evans et al. 1969, Finkel, Miller and Hasterlick 1969) show no tumors at average skeletal doses less than 500 rad; there appears to be a non-linear dose response relationship (Rowland and Farnham 1969), although the probability of such is in dispute (Goss 1970, Goffman and Tamplin 1971). Using the Evans data and assuming a linear non-threshold response gives a risk-dose coefficient for bone sarcomas of 33 per 10^6 average skeletal rad (Evans et al. 1969). The frequency of occurrence of paranasal and mastoid carcinomas is about half that of the bone sarcomas. The Finkel data are consistent with those of Evans. The BEIR committee combine the two sets of data to give a risk rate of 1.1 cases per year per 10^6 average skeletal rad (BEIR 1972).

German data on radium-224 (ThX) do not show a threshold and the risk-dose coefficient is quoted as 140 sarcomas per 10^6 average skeletal rad for juveniles and 70 per 10^6 for adults (Spiess and Mays 1970).

The cumulative average skeletal dose of 37 individuals occupationally exposed to plutonium and showing no adverse effects is estimated at 1,800 rad. Langham (1969) suggests a risk of less than 1 tumor per 1,800 rad or less than 550 cases per 10^6 skeletal rad.

A3. LUNG CANCERS

The mortality of US uranium miners from lung cancer as a function of radon and daughter product exposure is reported by Lundin et al. (1969). The figures give a risk-exposure coefficient 4.4×10^{-3} cases per 100 working level months (assuming 20 years at risk). The dose-exposure relationship is uncertain, an exposure of 1 WLM giving a dose to the sensitive volume of the bronchial epithelium (assumed to be the region at risk) of between 2 and 20 rad (Parker 1969). Hence the risk-coefficient is in the range 2 to 20 cases per 10^6 rad to the bronchial epithelium. If the dose is averaged over the whole lung, as is done in the case of bone, the risk coefficient is of the order of 200 cases per 10^6 average lung rad, assuming 50 per cent retention of radon daughters in the lung.

The cumulative average lung dose of the 37 individuals occupationally exposed to plutonium and showing no adverse effects is estimated at 3,850 rad (Langham 1969), suggesting a risk of less than 1 tumor per 3,850 rad, or less than 260 cases per 10^6 average lung rad.

A4. OTHER TISSUES

No tumors from radium or radon have been observed in other tissues. Amongst the plutonium group, again without tumors, the estimated cumulative average liver dose was 1,560 rad, suggesting a risk of less than 1 tumor per 1,560 rad or less than 640 cases per 10^6 average liver rad.

A5. RECOMMENDED VALUES

On the basis of the above figures the following values will be used for risk coefficients for internal dose from alpha emitters:

bone tumors = 10 cases per 10^6 average skeletal rem

soft tissue tumors = 40 cases per 10^6 average tissue rem.

Rem are defined according to ICRP 2 (1959), i.e. for radium in any tissue and for other alpha emitters in any tissue but bone, 1 rad equals 10 rem, for other alpha emitters in bone 1 rad equals 50 rem.

APPENDIX B

DOSES FROM CONTAMINATED MILK, OTHER FOODSTUFFS AND CONSUMPTION OF RAINWATER COLLECTED FROM ROOFS CONTAMINATED BY DEPOSITION

B1. MILK CONTAMINATION

B1.1 Phosphorus-32 and Sulphur-35

A derivation of maximum permissible release rates of phosphorus-32 and sulphur-35 to atmosphere in a milk producing area has been given by Bryant (1963). The parameters used are listed in Table B1.

These same parameters can be used to derive integrated dose for a single deposition. Bryant uses the expression $Q = C/\bar{d}VgtA$ to derive the maximum permissible release rate Q, where $\bar{d}$ is the long term average air concentration per unit release rate at the location of interest and Vg is the deposition velocity of the material. The integral of air concentration at the release rate Q over a period of one year gives the annual dose limit (ADL). Hence, the dose given by unit exposure is $(ADL)/Q\bar{d}$. Substituting $Q\bar{d}$ from the above expression:

dose per unit exposure = (ADL)VgtA/C

Putting $Vg = 3 \times 10^{-3}$ m s^{-1} and using appropriate units

phosphorus-32 = 5×10^{4} rem, (child, bone) per Ci s m^{-3}

sulphur-35 = 500 rem, (whole body) per Ci s m^{-3}

B1.2 Strontium-89, Strontium-90, Iodine-131 and Caesium-137

Beattie and Bryant (1970) give figures relating deposition over pasture and subsequent dose from contaminated milk. Assuming a deposition velocity of 3×10^{-3} m s^{-1} in each case:

strontium-89 = 4,500 rem (child, bone) per Ci s m^{-3}

strontium-90 = 45,000 rem per y (child, bone) per Ci s m^{-3}

iodine-131 = 50,000 rem (child, thyroid) per Ci s m^{-3}

caesium-137 = 1,400 rem (adult, whole body) per Ci s m^{-3}

B1.3 Radium-226

In the absence of immediately relevant information for radium-226, the assumption will be made that the ratio of dose from milk and from other foodstuffs is the same as that for strontium in milk and other foodstuffs, i.e. a factor of 20 (see Table 6). This assumption is pessimistic, as there will be greater discrimination against radium than strontium in the cow's calcium metabolism.

B2. OTHER FOODSTUFFS

Beattie and Bryant (1970) assess the daily intake of activity ingested by routes other than milk as equivalent to that deposited on 10 cm^2, using a physical half-life in the environment of 10 days to determine the total intake. They quote ground depositions for specific doses from iodine-131, caesium-137, strontium-89, strontium-90, ruthenium-103 and ruthenium-106. Dose per unit exposure has been derived assuming a deposition velocity of 3×10^{-3} m s^{-1}. The following expressions incorporate the above assumptions to give total intake, ICRP models to give dose for adults and a further factor of 4.5 to give dose to child (as in the inhalation case):

for long lived bone seekers: 43.2 (ADL) fw/(MPBB)f_2 rem y^{-1} per Ci s m^{-3} where (ADL) is the annual dose limit in rem per year, fw is the fraction of the intake reaching the critical organ, f_2 is the fraction of the body burden in the critical organ and (MPBB) is the maximum permissible body burden, in μCi, with bone as the critical organ.

for other materials: 4.32×10^{-5} (ADL)T/(MPC) (T+10) rem per Ci s m^{-3} where (ADL) is the annual dose limit in rem, T is the radioactive half-life in days, and (MPC) is the maximum permissible concentration for water, in μCi cm^{-3}, by continuous ingestion.

For soluble uranium, chemical toxicity limits intake to 150 mg over any two day period, leading to a limiting ground deposition of 7.5 g m^{-2}. With a deposition velocity of 3×10^{-3} m s^{-1} this gives a limiting exposure of 2,500 g s m^{-3}.

B3. POSSIBLE DOSES FROM THE CONSUMPTION OF RAINWATER COLLECTED FROM ROOFS CONTAMINATED BY DEPOSITION

Where rainwater is collected from roofs for drinking or cooking, deposition of radioactivity from a passing cloud of airborne material will result in contamination of the collected water. Although the use of roof-collected rainwater is uncommon in the area around Lucas Heights there are older properties having tanks for rainwater collection and also people who prefer a water supply for drinking and cooking other than that provided by the Water Board.

The following model for estimating doses from the consumption of contaminated rainwater does not cover all possibilities, particularly those associated with the vagaries of rainfall, but is used, with conservative values for uncertain parameters, to give some estimate of the possible magnitude of doses from this route to ensure that in the event of accidental releases it is not overlooked.

It is assumed that rain falls immediately after deposition and that there is sufficient room in the collecting tank to take all the collected rain and activity. For short-lived activities the effective half-life in the drinking water will be the radioactive half-life, but for long-lived activities further rain will dilute the original concentration and the effective half-life will be less than the radioactive half-life. It will be assumed conservatively that the average rainfall over the period following deposition is only one third of the normal rainfall (the consequences of variations in rainfall pattern are not considered).

B3.1 Parameters and Assumptions

The following parameters and assumptions are now considered:

Roof area	A m^2	(assume 100 m^2)
Fraction washed off of that deposited	f	(assume f = 1.0)
Normal rainfall	D $m\ y^{-1}$	(at LH, D = 1.0 $m\ y^{-1}$)
Tank volume	V m^3	(assume V = 10 m^3)
Deposition velocity	v $m\ s^{-1}$	(assume v = 3×10^{-3})
Fraction in solution of that washed into tank	g	(assume g = 1.0)
Radioactive half-life	T_r	days

For a tank system, the average rate of collection must exceed the average rate of consumption if the tank is to provide a guaranteed supply. The above figures give an annual collection rate of 100 m^3y^{-1}, providing an average daily supply of 60 gallons which is more than sufficient to provide drinking and cooking facilities for the average family. The annual collection rate of 100 m^3y^{-1} in a 10 m^3 tank gives a mean life for water in the tank of 0.1y or a turnover half-life of 36.5 x 0.693 = 25 days. As stated above, it will be assumed conservatively that rainfall is only one third of the normal, giving a water half-life of 75 days. Removal of water from the tank for consumption will affect the total activity present but not its concentration in the water. The effective half-life for the concentration is the combined radioactive and turnover half-life, i.e. $T_{eff} = 75\ T_r / (75 + T_r)$.

The initial concentration in the tank for unit exposure to airborne material (1 Ci s m^{-3}) is Afgv/V Ci m^{-3} (assuming the tank is just filled by the rain washing the activity off the roof). For these values this is 3×10^{-2} Ci m^{-3} per Ci s m^{-3}.

To estimate total intake it is assumed that the ICRP standard man daily water consumption figure is 2,200 cm^3 per day. Thus, the total adult intake is:

$$\int_{0}^{\infty} 2.2 \times 10^{-3} \times 3 \times 10^{-2} e^{-\lambda t} dt = 6.6 \times 10^{-5}/\lambda$$

where $\lambda = 0.693/T_{eff}$.

Therefore the total adult intake is

$$6.6 \times 10^{-5} \times 75\ T_r/(75 + T_r) \times 0.693$$

$$= 7.2 \times 10^{-3}\ T_r/(75 + T_r). \quad \text{Ci per Ci s m}^{-3}$$

The same figure will be assumed to apply conservatively to children.

Using ICRP (1959, 1964) data, the dose per unit intake, and hence the dose via contaminated drinking water per unit airborne exposure for adults and the above model can be derived, as was done for inhalation. The incorporation of the above intakes into the ICRP data gives the following expressions:

whole body	=	$0.045\ T_r/(75 + T_r)$ MPC	rem per Ci s m^{-3}
skin, thyroid, bone	=	$0.27\ T_r/(75 + T_r)$ MPC	rem per Ci s m^{-3}
all other organs	=	$0.135\ T_r/(75 + T_r)$ MPC	rem per Ci s m^{-3}
bone, long lived materials	=	$2.16 \times 10^5\ f_w/f_2$ MPBB	rem y^{-1} per Ci s m^{-3}

where MPC = maximum permissible concentration in water for occupational exposure, 168 hours per week, for the organ under consideration, in μCi cm^{-3}.

MPBB = maximum permissible body burden with bone as the critical organ, in μCi.

f_w = fraction reaching bone by ingestion.

f_2 = fraction in bone to that in total body.

Doses to children from ingestion of some of the major fission products (iodines, strontiums, caesium-137 and rutheniums) have been considered by Beattie and Bryant (1970) who show that only for radioiodines is there a significantly larger dose per unit intake for children than for adults; they give a factor of 8 for iodine-131. Therefore, it is assumed that the water consumption is the same for children as for adults and that doses for children are the same as those fo adults except for iodine-131, in which case the child thyroid dose is taken to be 8 times the adult thyroid dose.

Table B2 lists the radioisotopes of interest and the estimates of possible doses per unit airborne exposure arising from the consumption of rainwater collected from contaminated roofs, derived using the expressions cited above.

Chemical toxicity of uranium requires consideration. The limit on ingestion of soluble uranium up to 150 mg over two days indicates an initial concentration limit in drinking water of $75 \times 10^{-3}/2{,}200 = 3.4 \times 10^{-5}$ g mℓ$^{-1}$. For the model discussed, the initial concentration per unit airborne exposure is A fgv/V units m^{-3} which, for the numerical values adopted, is 3×10^{-2} g m^{-3} per g s m^{-3}. Hence, for a concentration limit of 3.4×10^{-1} g m^{-3}, airborne exposure is limited to $3.4 \times 10^{-1}/3 \times 10^{-2} = 11$ g s m^{-3}. This is essentially the same as the limit for inhalation of airborne uranium of 2.5 mg h m^{-3} or 9 g s m^{-3} (see Table 7).

TABLE B.1

PARAMETERS USED FOR DERIVATION OF CONTINUOUS RELEASE RATES OF PHOSPHORUS-32 AND SULPHUR-35

Parameter	Numerical Value	
	^{32}P	^{35}S
Maximum permissible concentration in milk, C (nCi litre^{-1})	4	90
Mean life on pasture, t (day)	10	18
Ratio of concentration in milk to level on ground, A (unit litre^{-1}) per (unit m^{-2})	0.8	0.6

TABLE B.2

ESTIMATES OF POSSIBLE DOSE PER UNIT AIRBORNE EXPOSURE ARISING FROM THE CONSUMPTION OF RAINWATER COLLECTED FROM CONTAMINATED ROOFS

Radioisotope	Rem per Ci s m^{-3} and Critical Organ		Radioisotope	Rem per Ci s m^{-3} and Critical Organ	
^{14}C	45	whole body	^{110m}Ag	350	gut
^{18}F	0.02	gut	^{131}I	10^4	thyroid$^{(a)}$
^{24}Na	0.1	whole body	^{144}Ce	1,100	gut
^{32}P	220	bone	^{137}Cs	220	whole body
^{35}S	240	testis	^{226}Ra	8×10^4 rem y^{-1}	bone$^{(b)}$
^{46}Sc	180	gut	Th_{nat}	1,700 rem y^{-1}	bone
^{54}Mn	110	gut	^{233}U	450	whole body
^{60}Co	43	whole body	^{234}U	450	whole body
^{89}Sr	1,250	bone	^{235}U	450	whole body
^{90}Sr	10^4 rem y^{-1}	bone$^{(b)}$	^{238}U	22,000	kidney
^{95}Zr	100	gut	U_{nat}	22,000	kidney
^{99m}Tc	0.01	gut	^{239}Pu	140 rem y^{-1}	bone
^{99}Mo	2.4	kidney, gut	^{240}Pu	140 rem y^{-1}	bone
^{103}Ru	60	gut	^{241}Pu	135	bone
^{106}Ru	1,100	gut	^{241}Am	2,200 rem y^{-1}	bone

(a) Child thyroid dose. Adult thyroid dose = 1,300 rem.

(b) Here, and elsewhere, where half-life in bone is long, dose rate rather than dose is quoted.

APPENDIX C

FURTHER MODIFYING FACTORS

The following material is taken almost in its entirety from Appendix II of Flew and Lister (1969) and lists factors which could be taken into account when attempting to assess the release of activity from a given stock in the event of an accident. The numerical values given are purely notional and should therefore be used with some reserve.

(a) Fraction of aerosol produced which is released from primary containment into building

Gases and Vapours	
Elemental iodine released under water	0.01
All other cases	1.0
All other forms	
Fibre drums, glove boxes, cells, reactor structures, etc., which are so seriously damaged that containment is virtually nil	1.0
Storage blocks and pits, seriously damaged glove boxes, cells, flasks, reactor structures, etc.	0.1
Safes, undamaged or slightly damaged glove boxes, cells, flasks, reactor structures etc.,under water storage, particulate release into building via filtered extract, single metal containment	0.01
Concrete steel drums, double metal containment	0.001
Fraction of airborne material released from building	
Gases in damaged or undamaged buildings, volatile and particulate aerosols in buildings so seriously damaged that containment is virtually nil	1.0
Volatile and particulate aerosols in building containments undamaged or slightly damaged	0.1
Particulate release from building via filtered extract	0.01

(b) Effective release height

In a major fire thermal lift will give an effective height of release above ground level. This will significantly reduce on site exposures, particularly during inversion conditions. In such cases a reduction by a factor of 0.1 is recommended.

This factor should not be applied to off-site exposure estimates, nor in cases where the release occurs in the relatively lower parts of the Research Establishment.