DOWNGRADED TO SECRET

Copy No. 11

UNITED KINGDOM ATOMIC ENERGY AUTHORITY

DEFE 16/198

000971

ATOMIC WEAPONS RESEARCH ESTABLISHMENT

OR. 096. 261/85

Radiological health hazards at Emu

RADIATION HAZARDS AT EMU - 1st FEBRUARY 1955

Prepared by. G. A. Dale . W. E. Saxby ....

Approved by. .... Superintendent, Health Physics

Health Physics Branch,
A.W.R.E.
Aldermaston,
Berks.

January, 1955.

1. Calculations have been made (see Appendix) to obtain the hazards from radioactive "fall-out" at EMU at 1st February, 1955. The results of these calculations are summarised below, and recommendations are made relating to the safeguarding of personnel in the future.

2. EMU is a restricted area within the Rocket Range and will normally be visited only by authorised personnel, who should before entry be familiarised with the radiological hazards existing there. We have assumed however that unauthorised personnel might spend some 14 days in the EMU area, and that they might spend some 8 hours per day in the "fall-out" areas. It is also assumed that such an exposure would not occur more often than once in any period of 10 weeks.

3. At 1st February 1955 (D + 15 months) the main hazard is that due to the Beta and Gamma radiations from the external "fall-out" field. Two levels have been defined.

(a) Limit of Zero Risk

(b) Limit of Slight Risk

4. Zero Risk

The upper limit of Zero Risk is given by the gamma dose rate contour which would give an integrated dose to the body amounting to 6 rep over the 112 hours of exposure. The gamma dose portion of this must not exceed 3 rontgens.

5. Slight Risk

The upper limit of Slight Risk is given by the gamma dose rate contour which would give an integrated dose to the body amounting to 50 rep over the 112 hours of exposure. The gamma dose portion of this must not exceed 10 rontgens and the exposure should not be repeated within a year.

6. External Hazard

(a) Zero Risk

The ratio of beta dose rate to gamma dose rate at 1st February 1955 will be 21.2/1. The total allowable gamma dose will be $6 \times 10^3/22.2$ = 270 mr and the actual dose rate giving this in 112 hours will be 2.41 mr/hr, which is equivalent to 420 r/hr at H + 1 hour. This is shown on the accompanying map (Fig 1) as a YELLOW line.

(b) Slight Risk

For slight risk the total integrated dose is 50 rep. The gamma dose rate to give this will be 20.1 mr/hr. which is equivalent to 3500 r/hr at H + 1 hour. This is marked on the accompanying map (Fig 1) as a RED line.

7 Associated Hazards

At the levels given above the associated hazards due to inhalation and ingestion do not present comparable hazards provided normal care is taken to avoid dust, and personnel maintain reasonable fastidiousness with regard to food and personal cleanliness. Injection is not likely to present a comparable hazard particularly in view of the physical nature of the fall out. Deposition on the skin is also not likely to present a significant hazard.

8. It should be remembered that the "fall-out" traces from T_1 and T_2 still give significant activity at many miles from the ground zeros. Personnel should not be exposed unnecessarily in such areas. The GREEN line on the map (Fig 1) shows the extent of the contaminated area and this may be taken to extend over the Range Centre Line (see also Fig. 2).

9. Kittens Area

The existing Kittens Area which was closed in 1953 should remain a closed area. (Fig 2). Except in the vicinity of the firing sites the activity levels in the area are lower than those permitted for continuous breathing, and the area as a whole is one of Zero Risk. In the immediate vicinity of the firing sites small areas of Slight Risk may exist. These could be reduced to Zero risk by covering with a thin layer of earth. There may also be some widespread debris of fairly high activity, such as pieces of Asbestos Wool, but it is felt that this may be neglected.

10. Necessary Work in Active Areas

If the IRWE find it necessary to carry out very prolonged work in the Active Areas, the advice of SH/PR, A.W.R.E. should be sought. In an emergency advice could be obtained from the Scientific Advisor to the Air Board, Melbourne or from the Commonwealth X-Ray Laboratory. Work lasting up to 24 hours in any area could be carried out with only slight risk.

11. A prolonged period in the Central Area

A period of about 50 hours spent continuously in the centres of the craters would result in exposure up to the limit of slight risk, provided heavy boots are worn and direct contact of parts of the body with the ground is avoided.

12. Future Decay

(a) Because of the long half lives of the more dangerous isotopes present, there will not be much change in the situation in the main craters over the next decade.

(b) The Kittens area activity will decay by a factor of 100 in 30 months. After which all the Kittens Area may be considered one of Zero Risk, although there will be small quantities of contamination present.

RECOMMENDATIONS

It is suggested that the following action should be taken to safeguard personnel.

(a) <u>Fencing:-</u> The central areas, out to a radius of 75 yards should be clearly indicated. This could be done either by notices or by a very simple fence such as a circular single strand mine wire fence. These areas are marked in RED on the Map (Fig. 1).

(b) <u>Roads:-</u>

(i) All roads closed at 1st February, 1954 (Fig. 2) should remain closed, with the exception of the direct road from Dingo to EMU via "R" and "1", and the track from "M2" via "M1" to the western end of the "F" Lane.

(ii) A "no loitering" restriction should be placed on the re-opened direct road to Dingo between M2 and a point 1½ miles East of Dingo.

All "no loitering" restrictions imposed at 1st February, 1954 should remain in force.

(c) <u>Notices and Road Blocks</u>

(i) All existing notices and road blocks in existence at 1st February, 1954 including those on the Range Centre Line, (Fig 2) should be retained, except on roads cleared in (b) (i) above.

(ii) "No loitering" notices should be erected on the direct route to Dingo, (see para (b) (ii)), at the point where the M2 M1 road crosses it.

(iii) Notices giving warning of the danger should be erected on all roads and tracks leading towards the craters at a distance of about 800 yds from them. These notices should be repeated at 300 yds (the <u>Zero Risk</u> limit) and again at the 75 yds. radius.

(iv) Notices should be prominently displayed at "C", warning personnel not to remove equipment and not to loiter in the area. Similar notices should be displayed on Active buildings, Areas and equipment at "A(RH)".

(d) <u>Kittens Area</u>

A layer of earth some 2 to three inches thick should be spread over each firing site to a radius of about 30 yds. This could be done by bulldozing providing care is taken that the existing surface is not brought up.

(e) <u>Promulgation of Active Areas</u>

All personnel authorised to have access to the Range should be provided with both the attached maps. They should be instructed not to loiter unnecessarily within the contaminated areas not to pick debris and to avoid the areas numbered in Yellow and Red. Material and equipment remaining in the contaminated areas should not be handled except under

 Reviewed 17/12/84. GD 1.9(b) refers.

APPENDIX. BASIS FOR EVALUATING HAZARDS REMAINING AT EMU

1. External Dose

The Y dose rates at 1 hour at G.Z. as measured at 1 metre were

T_2 7,750 r/hr

T_1 4,400 r/hr

Considering the re-entry time as 1st February 1955 from decay curves the Y dose rates at G.Z. will be

T_2 45.6 mr/hr

T_1 25.9 mr/hr

The average total body β dose to a man clothed with 30 mgns/cm² will be

T_2 966 mrep/hr

T_1 548 mrep/hr

The local β dose in actual contact will be many times higher than this. We define the zero risk level as ⊁ 6 rep. β dose in 10 weeks and the slight risk level as ⊁ 50 rep. β dose in 10 weeks

As the β/Y ratio is over 20/1 at this time the Y dose cannot approach the levels of 3r. and 25r. if we limit the exposure on considerations of β dose.

We now assume that a man may be exposed for a maximum of 112 hours in any period of 10 weeks.

For zero risk maximum dose rate must be $\frac{6000}{112}$ = 53.5 mrep/hr

With β/Y ratio of 21.2/1 this will be accompanied by a Y dose rate of 2.53 mr/hr, the corresponding dose rate at 1 hour would have been 429 r/hr

This occured at a distance of 300 yds. from G.Z. for T_2 and the distance from T_1 is the same within the limits of accuracy.

For slight risk maximum dose rate must be $\frac{50,000}{112}$ = 447 mrep/hr

This will be accompanied by a Y dose rate of 21.1 mr/hr

At 1 hour the dose rate would have been 3,580 r/hr

This occurs at a distance of 75 yds. from G.Z. for T_2

and as before the same distance may be applied to T_1

2. Inhalation

Consider the slight risk Y dose rate of 21.1 mr/hr on 1/2/55 From H7/53 the ground activity at such a point would be 0.64 μc/cm² If we assume a K factor* of 2 x 10^{-6} which for an open space is certainly pessimistic for stirred up dust, there may be an air concentration of 1.3 x 10^{-8} μc/cm³.

The Internation Regulations quote figures of 10^{-9} μc/cm³ for any mixture of β/Y emitters except Sr^{90} and a figure of 2 x 10^{-10} for $Sr^{90} + Y^{90}$. These figures are for continuous exposure. In this case about 1% is Sr^{90} and a figure of 10^{-9} may be used. With a maximum exposure to any individual of two 112 hour periods per annum for 40 years the ratio of the breathing times possible at EMU to occupational ... of air concentration in μc/m³ to ground concentration in μc/m² breathing is $\frac{1}{40}$. Thus an air hazard up to 4×10^{-8} μc/cm^3 will be safe. Thus the possible air concentration is considered quite safe especially with the large K factor used.

3. Injection

Of the fission products present at 460 days after D day about 40% are potentially dangerous and they are bone seekers.

Hence in 0.64 μc/cm^2 of fission products 0.26 μc/cm^2 would cause trouble if access to the blood stream were obtained. On the average about 45% of these elements would be deposited in the bone structure from the blood stream and so with a permissible body burden of 1 μc which coveres the most dangerous isotope Sr^{90} an injection of 2.2 μc could be permitted.

This would cover an area of about 10 cm^2. For all the activity from 10 cm^2 to be completely absorbed through an injured skin seems unlikely even if bleeding and subsequent washing did not occur. It should be remembered that the residue of 460 day fission products must be fairly if not wholly insoluble and in the crater area are tightly held on the fused surface.

4. Ingestion

The average fraction of ingested fission products reaching the critical organ is down by an order of magnitude on the above figures and it would require a large volume of soil to be eaten to take in the activity from the order of 10 cm^2. Common hygiene would preclude this.

5. Alpha contamination

The maximum ground contamination at the old Kittens site measured shortly after detonation was 5 mc/cm^2.

This would be 0.48 mc/m^2 on 1/2/55.

If we again use the pessimistic K factor 2×10^{-6} an air concentration of 10^{-9} μc/cm^3 may result which is less than 40 times the recommended continuous breathing concentration of 10^{-10} μc/m^3. Assuming as before that the activity from 10 cm^2 gains access to the body a body burden of 0.5 μc would result which would give 40 rep in 10 weeks.

UNITED KINGDOM ATOMIC ENERGY AUTHORITY

DOWNGRADED TO UK UNCLASSIFIED

UNCLASSIFIED

Reviewed 12/12/84. SCO 4956 refer.

000969

OK. 25/1/85

06.12

02 FEB 1985 S.W.1

ATOMIC WEAPONS RESEARCH ESTABLISHMENT - ALDERMASTON

Radiological Health Hazards at Trials 0144 I.

MAXIMUM PERMISSIBLE DOSES FOR WEAPONS TRIALS

by

D. E. BARNES
Superintendent Health Physics

In view of the change over from M of S to the Authority and to take account of any recent changes in maximum permissible levels it is necessary to review and re-state the levels to be used in weapons trials.

Special levels have to be laid down for these Trials because the nature of the work is such that high dose-rates are encountered and moderately high integrated doses received over a period of a few weeks. The number of personnel engaged on a trial is quite large and of those only a small proportion receive high doses. In many cases it is possible to distribute the work in such a way that total doses are kept well below limiting values and where non-specialist personnel are concerned this is done. However, for certain tasks a dose in excess of 0.3r is received in one sortie and for others the degree of skill or knowledge required is such that only a few persons are available to do the work and they have to make repeated sorties. In both these cases it is necessary to define maximum permissible levels of integrated dose.

The conditions of a Trial are such that the number of personnel and the amount of time available are limited. There are great difficulties in increasing either and to do so, even to the very limited extent possible, would involve the Authority in considerable extra expense. Because of these limitations the scope of the measurements which are made is carefully restricted to those which are regarded as essential and any further restriction due to radiological considerations would be a serious loss. This means that the levels must be as high as can safely be allowed and we cannot choose a value merely because we are sure that it is safe without also being sure that it leaves no unnecessary margin of safety. However, it must not be thought that the Authority would seek to justify on grounds of expendiancy, doses which would be harmful nor that it would be prepared to allow personnel under its control knowingly to be exposed to such doses.

The levels used at the Hurricane and Totem trials were defined and agreed by the Minister of Supply in August 1952 after consultation with Medical and Health Physics authorities. These levels, which are reproduced below, are suggested as a basis for discussion.

Three dosage levels were applied under various conditions, viz:-

(i) Normal Working Rate

An intermittent or continuous dosage up to 0.3 rep per day of which the Y-ray component is not to exceed 0.1 r/day.

This is the normal working limit which will be applied generally and it is estimated that it will be possible to carry out the greater part of the operation under these conditions.

(ii) Lower Integrated Dose

An integrated dose, received in one or a few exposures, of up to 15 rep of which the Y-ray component is not to exceed 5r. This dose will be applied only with the express permission of the Radiation Safety Officer, which will be given only where he regards it as necessary for the smooth running of the operation. Except as provided for under (iii) below personnel who have received this dose will not be subjected to further exposure during the remainder of the operation.

(iii) High Integrated Dose

An integrated dose of up to 50 rep. of which the Y-ray component is not to exceed 10r.

This dose will be applied only in cases of extreme urgency in order to recover vital records which might otherwise be lost, and will require the express personal permission of the Commander of the Operation who will have expert medical and radiological advice at hand. Personnel receiving this dose will not be subjected to further exposure for a minimum period of 12 months.

CONFIDENTIAL

(g) On return they are undressed, dosimeters collected, they are checked for contamination, showered and re-checked and report to the Control - Dosimeters are read immediately and films developed and read the same day so that full records of each days doses are available to Control each morning.

It may be relevant to consider U.S. practice in their Weapon Trials, so far as information is available. The only statement which I have been able to find which refers directly to the staff employed on Trials is in the 8th Semi-Annual Report of the A.E.C. (July 1950) where they say. "Operating limits for radiation exposure as fixed for the weapons tests paralleled those in use in the atomic energy program in 1948: one-tenth of one roentgen a day. In special cases, exposure might be allowed up to 3 roentgens in one day, provided the exposure was approved by the top radiological officers and that the person so exposed was then allowed no further radiation exposure for 30 days. No exposure in excess of this amount was allowed except at the express permission of the task force commander."

In the 14th Semi-annual Report (July 1953) a further reference is made which by its context would seem to apply to the general public:"....it has been determined that a dose of 0.3 roentgens per week may be delivered to the whole body for an indefinite period without hazard. Though much larger rates of exposure are harmless if not continued for too long, the Commission has adopted a policy of limiting exposures whenever possible to a total of not more than 3.9 roentgens over a period of 13 weeks, approximately the length of the 1953 test period. (A limit of 3 roentgens per 10 weeks was used for the 1952 test period, which was shorter)."

It can be seen that in 1950 their permissible dose system was very similar to ours, except that no upper limit to the highest doses is set down. In 1953 the wording suggests that the limit corresponding to our Lower Integrated Dose was raised from 3r to 3.9r. This change, which would be in line with the M.R.C. Recommendations for emergencies, would relieve the commander of the need to consider the question of dosage in a certain number of cases, but it is not proposed to make the modification in our regulations since the number of cases is quite small and it is thought advisable to give the same consideration as any other Higher Integrated Dose.

~~CONFIDENTIAL~~ DOWNGRADED TO UNCLASSIFIED

UK U/C 25/1/85

UNITED KINGDOM ATOMIC ENERGY AUTHORITY

Radiological Health Hazards of Tests ... I

ATOMIC WEAPONS RESEARCH ESTABLISHMENT - ALDERMASTON

HEALTH PHYSICS BRANCH

HP Memo 4/56

Safety Criteria for Po^{210} mixed with Fission Products

by

G. C. Dale

Summary:

Levels of contamination with Po^{210} are derived and by comparison with levels of fission product contamination for zero hazard a total production figure/nominal bomb is calculated.

Building A6.1
A.W.R.E., Aldermaston.
July 1956

CONFIDENTIAL

TABLE OF CONTENTS

CONFIDENTIAL

Introduction

It is common knowledge that the fission products from an atomic explosion which fall to earth may constitute a hazard to life according to the concentration level of the surface contamination resulting. The unfissioned material, generally Pu^{239} or U^{235} can add to the hazard. These two materials although present initially in small quantities by comparison do persist by virtue of their long half-lives and may eventually outweigh the effect of the residual fission products. It is the purpose of this memorandum to consider what quantity of Po^{210} can accompany fission products without this material becoming the overriding hazard.

1. Hazards which may arise

In a previous paper (1), the hazards from fission products and unfissioned material were listed as:-

1. External dose from material deposited on the ground.
2. External dose from material deposited on the skin.
3. Internal dose from material deposited in local water supplies.
4. Internal dose from material deposited over catchment areas.
5. Internal dose from material deposited on human food.
6. Internal dose from material inhaled from settling dust.
7. Internal dose from material inhaled from stirred-up dust.
8. Internal dose from material absorbed through a broken skin.
9. Internal dose to grazing animals.

In the case of Po^{210} which is an alpha particle hazard, effects 1 and 2 need not be considered.

2. Maximum permissible levels of exposure to Po^{210}

Levels of exposure to Po^{210} are laid down by I.C.R.P.(2) which deals with occupational hazards to workers exposed over a working lifetime to radioactivity. The levels derived below are based on these recommendations which are themselves derived from the fact that a body burden of 0.04 μc of Po^{210} will not cause a dose of greater than 0.3 rem/week to be delivered to the critical organ in the body, which in this case is the spleen. A second criterion is that in the case of highly insoluble material inhaled, the amount in the lungs must not exceed 0.02 μc. In the case of non-occupational workers it is recommended that body burdens of one tenth of the occupational levels shall not be exceeded.

However, in view of the fact that Po^{210} has a half-life of 138 days it may be argued that a much larger temporary body burden may be equated biologically to this permissible maintained one. Following the practice established for trials and supported by procedure in the U.S.A. it is not desirable to carry this process further than giving a dose equal to ten times the weekly permissible value in a period of ten weeks. The increase in initial body burden which this would permit is not significant by comparison with the uncertainty of the assumptions used here and so will be neglected.

3. Direct deposition in drinking water

The long term maximum permissible concentration of Po^{210} in drinking water for non-occupational workers is 3×10^{-6} μc/cc.

As an example of an exposed domestic water supply consider a small tank of area one square metre and depth two metres. Larger tanks are likely to have a smaller ratio of surface area to volume and so the example chosen is considered to be pessimistic. A concentration of 3×10^{-6} μc/cc is produced by a surface contamination of 6 μc/m^2 on to the tank area (1m^2).

4. Indirect deposition in drinking water

In a large volume of water being replenished as it is consumed we will consider that three years is a maximum time of consumption. After this, decay will have been such as to render the water innocuous anyway. We further assume an average rainfall of 5" which is applicable to arid

~~CONFIDENTIAL~~

regions and consider 25% loss of this surface water by direct evaporation. Experiments have shown that the ground is a very efficient filter but perhaps 1% of the deposited activity could find its way into a drinking water supply.

The volume draining from one square metre over 3 years is 2.86×10^{5} cc so with a long term drinking level of 3×10^{-6} μc/cc we obtain maximum permissible contamination of <u>86 μc/m²</u>.

5. <u>Deposition on human food</u>

The quantity of unwashed food eaten is very variable from locality to locality but following previous work (1) a maximum surface area of 1.25 m² will be considered to be the subtended area of food eaten before rain washes it or it is discarded in favour of new season's produce. This is about equivalent to 500 apples or 1000 tomatoes. The maximum permissible body burden of polonium is 0.004 μc, for non-occupational workers, of which 0.00024μc is in the critical organ. With an uptake factor of 6×10^{-4} into the critical organ from ingestion the maximum permissible contamination is <u>0.32 μc/m²</u>.

6. <u>Dust before settling</u>

In the case of the material inhaled into the lung, if it is soluble, the fraction reaching the spleen is 0.004 whereas if it is insoluble 0.12 is retained in the lung which is then eliminated with a half-life of 40 days neglecting decay. The maximum permissible lung burden is 0.002 μc indefinitely and because of decay this can safely be increased to 0.004 for a single incident. In reference (1) it has been shown that during settling of a cloud the ratio of air concentration (μc/m³) to final ground contamination (μc/m²) is $1 : 8.7 \times 10^{2}$. The maximum permissible air concentration which can be breathed for 24 hours is 1.67×10^{-3} μc/m³ giving a maximum permissible ground contamination of <u>1.45 μc/m²</u>.

7. <u>Dust raised after initial deposition</u>

It has been found by experiment (3) that the dust raised by working amongst debris gives an air concentration in μc/m³ of 2×10^{-5} the ground contamination in μc/m². On a weapons trial (4) figures differing from this by orders of magnitude have been found. The variation due to different dust creating conditions was considerable but it may be concluded that the figure quoted above will lead to safe maximum deposition levels.

It is assumed that the dust hazard would not exist on the average for more than 40 hours weekly. For Po^{210} the long term maximum permissible level in air is 10^{-11} μc/cm³. Neglecting the fact that it would take longer than 10 weeks for the lung burden to reach 0.002 μc during which time the level of 10^{-11} μc/m³ will have decayed, the maximum deposition is <u>5 μc/m²</u>.

8. <u>Absorption through a broken skin</u>

This hazard is difficult to assess but, as an example consider all the activity from 10 cm² of surface being taken into the bloodstream through a damaged skin. Two percent of this will find its way into the spleen. Since six percent of the permissible body burden of 0.004 μc is in the spleen a total quantity of 0.012 μc may be deposited over 10 cm² and hence the maximum deposition level may be <u>12 μc/m²</u>.

9. <u>Hazard to grazing animals</u>

We will first consider sheep. Following reference (1) para 3.4 et seq., we assume a daily intake of 5 Kg. of herbage covering approximately 12 m². As data for sheep are not obtainable yet, we assume that the metabolism of Po^{210} is similar in sheep to humans. Calculations from I.C.R.P. (2) show an allowable daily intake of 0.045 μc for occupational workers. It has been suggested and largely agreed that no economic damage will occur in either cattle or sheep which are allowed to accumulate ten times the human body burden.

It is probable that animals will graze over an area and remove the activity gradually and half of the activity will fall between the leaves.

~~CONFIDENTIAL~~

CONFIDENTIAL

regions and consider 25% loss of this surface water by direct evaporation. Experiments have shown that the ground is a very efficient filter but perhaps 1% of the deposited activity could find its way into a drinking water supply.

The volume draining from one square metre over 3 years is 2.36×10^5 cc so with a long term drinking level of 3×10^{-6} μc/cc we obtain maximum permissible contamination of <u>86 μc/m²</u>.

5. <u>Deposition on human food</u>

The quantity of unwashed food eaten is very variable from locality to locality but following previous work (1) a maximum surface area of 1.25 m² will be considered to be the subtended area of food eaten before rain washes it or it is discarded in favour of new season's produce. This is about equivalent to 500 apples or 1000 tomatoes. The maximum permissible body burden of polonium is 0.004 μc, for non-occupational workers, of which 0.00024μc is in the critical organ. With an uptake factor of 6×10^{-4} into the critical organ from ingestion the maximum permissible contamination is <u>0.32 μc/m²</u>.

6. <u>Dust before settling</u>

In the case of the material inhaled into the lung, if it is soluble, the fraction reaching the spleen is 0.004 whereas if it is insoluble 0.12 is retained in the lung which is then eliminated with a half-life of 40 days neglecting decay. The maximum permissible lung burden is 0.002 μc indefinitely and because of decay this can safely be increased to 0.004 for a single incident. In reference (1) it has been shown that during settling of a cloud the ratio of air concentration (μc/m³) to final ground contamination (μc/m²) is $1 : 8.7 \times 10^2$. The maximum permissible air concentration which can be breathed for 24 hours is 1.67×10^{-3} μc/m³ giving a maximum permissible ground contamination of <u>1.45 μc/m²</u>.

7. <u>Dust raised after initial deposition</u>

It has been found by experiment (3) that the dust raised by working amongst debris gives an air concentration in μc/m³ of 2×10^{-5} the ground contamination in μc/m². On a weapons trial (4) figures differing from this by orders of magnitude have been found. The variation due to different dust creating conditions was considerable but it may be concluded that the figure quoted above will lead to safe maximum deposition levels.

It is assumed that the dust hazard would not exist on the average for more than 40 hours weekly. For Po^{210} the long term maximum permissible level in air is 10^{-11} μc/cm³. Neglecting the fact that it would take longer than 10 weeks for the lung burden to reach 0.002 μc during which time the level of 10^{-11} μc/m³ will have decayed, the maximum deposition is <u>5 μc/m²</u>.

8. <u>Absorption through a broken skin</u>

This hazard is difficult to assess but, as an example consider all the activity from 10 cm² of surface being taken into the bloodstream through a damaged skin. Two percent of this will find its way into the spleen. Since six percent of the permissible body burden of 0.004 μc is in the spleen a total quantity of 0.012 μc may be deposited over 10 cm² and hence the maximum deposition level may be <u>12 μc/m²</u>.

9. <u>Hazard to grazing animals</u>

We will first consider sheep. Following reference (1) para 3.4 et seq., we assume a daily intake of 5 Kg. of herbage covering approximately 12 m². As data for sheep are not obtainable yet, we assume that the metabolism of Po^{210} is similar in sheep to humans. Calculations from I.C.R.P. (2) show an allowable daily intake of 0.045 μc for occupational workers. It has been suggested and largely agreed that no economic damage will occur in either cattle or sheep which are allowed to accumulate ten times the human body burden.

It is probable that animals will graze over an area and remove the activity gradually and half of the activity will fall between the leaves.

CONFIDENTIAL

CONFIDENTIAL

regions and consider 25% loss of this surface water by direct evaporation. Experiments have shown that the ground is a very efficient filter but perhaps 1% of the deposited activity could find its way into a drinking water supply.

The volume draining from one square metre over 3 years is 2.85×10^5 cc so with a long term drinking level of 3×10^{-6} μc/cc we obtain maximum permissible contamination of 86 μc/m².

5. **Deposition on human food**

The quantity of unwashed food eaten is very variable from locality to locality but following previous work (1) a maximum surface area of 1.25 m² will be considered to be the subtended area of food eaten before rain washes it or it is discarded in favour of new season's produce. This is about equivalent to 500 apples or 1000 tomatoes. The maximum permissible body burden of polonium is 0.004 μc, for non-occupational workers of which 0.00024μc is in the critical organ. With an uptake factor of 6×10^{-4} into the critical organ from ingestion the maximum permissible contamination is 0.32 μc/m².

6. **Dust before settling**

In the case of the material inhaled into the lung, if it is soluble, the fraction reaching the spleen is 0.004 whereas if it is insoluble 0.12 is retained in the lung which is then eliminated with a half-life of 40 days neglecting decay. The maximum permissible lung burden is 0.002 μc indefinitely and because of decay this can safely be increased to 0.004 for a single incident. In reference (1) it has been shown that during settling of a cloud the ratio of air concentration (μc/m³) to final ground contamination (μc/m²) is 1 : 8.7×10^2. The maximum permissible air concentration which can be breathed for 24 hours is 1.67×10^{-3} μc/m³ giving a maximum permissible ground contamination of 1.45 μc/m².

7. **Dust raised after initial deposition**

It has been found by experiment (3) that the dust raised by working amongst debris gives an air concentration in μc/m³ of 2×10^{-5} the ground contamination in μc/m². On a weapons trial (4) figures differing from this by orders of magnitude have been found. The variation due to different dust creating conditions was considerable but it may be concluded that the figure quoted above will lead to safe maximum deposition levels.

It is assumed that the dust hazard would not exist on the average for more than 40 hours weekly. For Po^{210} the long term maximum permissible level in air is 10^{-11} μc/cm³. Neglecting the fact that it would take longer than 10 weeks for the lung burden to reach 0.002 μc during which time the level of 10^{-11} μc/m³ will have decayed, the maximum deposition is 5 μc/m².

8. **Absorption through a broken skin**

This hazard is difficult to assess but, as an example consider all the activity from 10 cm² of surface being taken into the bloodstream through a damaged skin. Two percent of this will find its way into the spleen. Since six percent of the permissible body burden of 0.004 μc is in the spleen a total quantity of 0.012 μc may be deposited over 10 cm² and hence the maximum deposition level may be 12 μc/m².

9. **Hazard to grazing animals**

We will first consider sheep. Following reference (1) para 3.4 et.seq., we assume a daily intake of 5 Kg. of herbage covering approximately 12 m². As data for sheep are not obtainable yet, we assume that the metabolism of Po^{210} is similar in sheep to humans. Calculations from I.C.R.P. (2) show an allowable daily intake of 0.045 μc for occupational workers. It has been suggested and largely agreed that no economic damage will occur in either cattle or sheep which are allowed to accumulate ten times the human body burden.

It is probable that animals will graze over an area and remove the activity gradually and half of the activity will fall between the leaves.

CONFIDENTIAL

However it makes no difference if for the purposes of this paper we assume that the sheep remove half the activity from their grazing ground and return to the same area after the clean herbage has regrown. This period of return varies considerably according to climate and may be as short as 2 weeks in England and New Zealand or as long as six months in arid regions. Consider 10 weeks as an average. The fraction taken orally which arrives at the critical organ is 6×10^{-4} and the maximum permissible level in the critical organ i.e. the spleen is 0.024 μc. Then if all the fall-out is in a soluble form the maximum permissible level of deposition is 0.1 μc/m². Cattle are approximately ten times the weight of sheep and consume ten times the quantity of herbage spread over ten times the area and thus, levels of contamination which result in an allowable body burden for sheep, will not result in a body burden in excess of that permissible for cattle.

10. Addition of hazards

Any individual may be exposed simultaneously to hazards 3 - 8 and so a limiting deposition taking into account all these factors has been derived. This is 0.23 μc/m². This is near enough to the figure for sheep to regard it as safe for animals.

11. Maximum quantity of polonium mixed with fission products

The limiting deposition (level A of reference 1) of fission products for exposure commencing at about 9 hours to reasonably civilized people is 3.3×10^{4} μc/m² of fission products measured at 1 hour (1). The ratio of the two limiting values of polonium and fission products is 7×10^{-6}.

A nominal bomb produces about 10^{10} curies of fission products at one hour from 2.5×10^{24} fissions, and thus for production of Po^{210} to remain the minor hazard not more than 7×10^{4} curies of this material per 20KT of fission yield should be produced. Another way of expressing this is that no more than 4.4×10^{22} atoms of Po^{210} should be produced per kilogram of material fissioned.

If higher fission product levels (e.g. level B 1.3×10^{5} μc/m²) were considered acceptable it is felt that the resulting Po^{210} level would be no less acceptable.

~~CONFIDENTIAL~~

References

1. Safety levels for Contamination from Fall Out from Atomic Weapons Trials. AWRE O-41/55 G. C. Dale.

2. Recommendations of the International Commission on Radiological Protection 1955.

3. Atomic Warfare in Relation to Civil Defence A.E.R.E. [illegible]/R 698.

4. The Dust Hazard during Operation Totem AWRE T 1/55 P.A. Carter.

~~CONFIDENTIAL~~

United Kingdom Atomic Energy Authority

ATOMIC WEAPONS RESEARCH ESTABLISHMENT - ALDERMASTON

Health Physics Branch

Branch Memo No. HP.6/56

SOME NOTES ON BIOLOGICAL EFFECTS OF BETA AND GAMMA RADIATION

By

D. E. BARNES

Absract

The effects on man of doses of ionizing radiations are briefly described and an attempt made to collect the best estimates of various workers of the dose required to produce various overall effects.

Building 16.1,
A.W.R.E.
Aldermaston

December, 1956

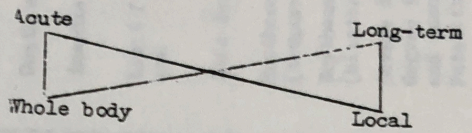
1. Introduction

The effects of ionising radiations on a biological system, such as man, can be divided into two groups:-

(i) Acute effects, that is those which result from a single massive dose, or a few somewhat smaller doses received within a few days of one another, and which manifest themselves within a period up to a few weeks of exposure.

(ii) Long-term effects which may result from the integrated effect of any number of doses spread over any period of time and which may not show themselves as noticeable effects for a long period, in some cases as long as 40 years.

Each of these groups can be further sub-divided according to whether the irradiation has been whole-body (i.e. involving the greater part of the volume of the body) or local. Diagrammatically:-



Whole-body exposure may be due either to wide-field penetrating radiation from outside or to absorption of some radio-isotope which spreads widely throughout the body tissues (e.g. Tritium or Sodium).

Local exposure may come from a collimated beam of penetrating radiation, from a wide field of radiation such as β-rays or soft γ-rays which affect only a shallow layer or from absorbed isotopes which migrate to some specific part or organ of the body.

In general much larger doses are required to produce an effect when the dose is localised. Thus the highest doses are those producing acute effects from local irradiation and these may be many thousands of rads.* The smallest doses affecting an individual are those giving long-term effects from whole body irradiation and are of the order of a few rads/year. The average dose to a population which will lead to observable genetic effects is much lower than this and is considered to be of the same order as natural background, about a tenth of a rad per year.

2. The mechanism of radiation damage is not fully understood, but in general it may be said that it results in cell destruction. Where a single massive dose is received this destruction will produce serious illness and, if the dose is large enough, death. With doses not quite large enough to be a direct cause of death, fatalities will still result because of destruction of the body's ability to combat infections. With moderately large doses acute effects, such as generalised illness and reduced blood-count, will still arise but complete recovery from these symptoms can be expected. There is, however, an irrecoverable effect which is estimated to be equivalent to some 10-20% of the dose. With moderate or small doses no immediate observable effect is to be expected but there may be a long-term effect due to this irrecoverable fraction or to the addition over years of a number of such fractions. From this it follows that fractionation of the dose (i.e. delivery of the same total dose in a number of fractions separated by intervals of several days or more) will reduce acute effects but will not significantly alter the long-term effects.

Long-term effects generally seem to be in the nature of an overstimulation of the repair mechanism. Examples of this are leukaemia, which is a non-limiting overproduction of white blood-corpuscles, and the production of tumours.

---

* The rad is the unit of absorbed dose and is defined as an energy absorption of 100 ergs/gm. For practical purposes it can be taken as numerically equal to the roentgen and the rep.

3. There is no very precise knowledge of the doses required to produce the different levels of effect, nor is this situation likely to improve except in a very gradual way. The main reason for this is that experiments cannot be made on healthy human beings; data is obtained from accidental exposure, often not well measured, from therapeutic exposure, difficult to interpret because of the underlying illness, and from animal experiments with a difficult and sometimes dubious extrapolation to man.

Alpen[x] has done a large number of animal experiments, particularly with dogs, and as a result of these has suggested certain levels for acute effects.

Mitchell[†] has suggested levels for long-term effects due to β and soft γ irradiation of the skin and the M.R.C. have given data on whole-body long-term effects. The attached table combines these various pieces of information.

---

[x] U.S. Naval Radiological Defence Laboratory, San Fransisco.

[†] Department of Therapeutics, University, Cambridge

~~CONFIDENTIAL~~ - [redacted]

Degree of Exposure	Dose in rads	Delivery	Effects
Whole body exposed to penetrating radiation	200	Single or fractionated	Limit for non-significant increase in incidence of Leukaemia.
	200	Single	Vomiting in < 24 hours. Incapacitation in 2 weeks
	400	Single	Death within 30 days
	600	Single	Immediate vomiting. Death in one week
Small area exposed to superficial radiation (skin due to β or soft γ)	1200	Single or fractionated	Limit for threshold of tumour production
Large area superficial	250	Single or fractionated	Safe level for no effect.
Small or large area superficial	600	Single	Erythema (akin to sunburn) and epilation (temporary loss of hair)
	1400	Single	Erythema followed by wet desquamation (blistering) within 2 weeks.
	3-5000	Single	Severe damage (similar to 2nd and 3rd degree thermal burns) with prolonged and incomplete recovery. Fatalities may arise from infection.
Gonad dose	50	Single or fractionated	Safe level to be received by an individual up to age 30 without fear of genetic effects.
	~ 0.1 per year	-	Average over whole population to give not more than double normal mutation rate

~~CONFIDENTIAL~~ - [redacted]

RESTRICTED Downgraded to UNCLASSIFIED OK. 25/1/85

02 FEB 1985 LONDON S.W.1

ATOMIC WEAPONS RESEARCH ESTABLISHMENT - ALDERMASTON

Radiological Health Hazards at trials C144 I

HEALTH PHYSICS DIVISION

H.P. Memo 2/57

Hazards to Civil Aircraft from Atomic Clouds

by

E.W. Fuller

Abstract

The radiological doses to which the crew and passengers of a civil aircraft flying through an atomic cloud would be exposed have been evaluated and expressed in terms of the cloud concentration which would result in a dose equal to one tenth level A. It is concluded that, if the biological factors given by the I.C.R.P. are appropriate to this case, the most serious sources of dose are ingestion and inhalation.

Building A6.1,
A.W.R.E.,
Aldermaston.

February, 1957.

RESTRICTED

Table of Contents

Hazards to Civil Aircraft from Atomic Clouds

1. Introduction

At times between a few hours and a few days after an air burst atomic explosion the fission product cloud may spread over a large volume of the sky so the chance of an aircraft intercepting it accidentally will not be negligible. On the other hand, the cloud may not be so diffuse that it represents no hazard. Further, unless the aircraft is equipped with radiation detection instruments the crew will not realise they are in a radioactive cloud and no precautions will be taken. The purpose of this memo is to assess the hazard to the passengers and crew of a civil aircraft flying through an atomic cloud under these conditions.

As a basis for calculation it is assumed that the aircraft spends 15 minutes in the cloud, that the aircraft height is 25,000', so the air density is 37% of the density at sea level, and the interior is pressurised to 75% of the density at sea level (equivalent height, 8000'). The fission product concentration, expressed as 1 hr $\mu c/cc$, which will result in a dose equal to 1/10th of the Level A dose under these conditions is tabulated in the following sections for various sources of irradiation as a function of time of entry into the cloud.

2. Gamma dose due to immersion in the cloud

If the activity in the cloud is C $\mu c/cc$, the air density is ρ g/cc, and the average gamma energy per disintegration is E MeV, the dose rate due to immersion in the cloud is

$$I = 2.3 \frac{CE}{\rho} \text{ r/hr} \qquad (1)$$

When the acitvity is expressed in terms of 1 hr $\mu c/cc$ (C_1) the dose due to a 15 min flight through the cloud at time t (hrs) is approximately

$$R = 2.3\, C_1 \;\; E\, t^{-1.2}/4\, \rho \text{ r} \qquad (2)$$

The following table of cloud contamination resulting in a dose of 0.3r for various times of entry into the cloud has been obtained from this equation assuming

$$E = 0.7 \text{ MeV and } \rho = 4.8 \times 10^{-4} \text{ g/cc}$$

Table I Concentration in the cloud producing 0.3 r in 15 mins

Time of entry	1	5	10	15	20	30	40	50	60	hrs
Fission Product Density	.035	0.24	0.57	0.92	1.28	2.1	2.9	3.9	4.8	$\times 10^{-2}$ 1hr $\mu c/cc$

3. Beta dose due to immersion in the cloud

The radius of the fuselage will probably be about 2 m. which is at least twice the mean range of fission product β particles. Hence, the interior of the aircraft may be regarded as an infinite sphere for the purpose of calculating the β ray dose. Then the energy flux at the centre will be n $\bar{E}\, \rho/\mu$ Mev/cm^2/sec where n is the number of β particles of average energy $\bar{E}$ emitted per gram per sec, ρ is the density and μ is the energy linear absorption coefficient (cm^{-1}). However, no part of the body will have a flux greater than half this passing through it as it will be shielded from the radiation from at least half the sphere. The density of air inside the aircraft will be 10^{-3} grm/cc so, as the rate of energy loss for electrons of energy greater than 0.2 Mev is about 4 Mev per gram/cm^2 in light elements and 1 rep is 6×10^7 Mev/grm, the β dose rate to tissue in an atmosphere containing 1 $\mu c/cc$ is

$$\frac{4 \times 3.7 \times 10^7}{2 \times 6 \times 10^7} \; \frac{\rho}{\mu} \text{ rep/sec}$$

The effective energy of the β particles varies by about a factor of t during the first few days after the explosion and so ρ/μ varies also. value of 0.1 gm/cm^2 corresponding to $\bar{E}$ = 0.6 Mev, is used, the concentr in the cloud (half that in the aircraft) giving rise to 1.5 rep in 15 mins at time t (hrs) is

$$\frac{t^{1.2}}{150} \quad 1 \text{ hr } \mu c/cc$$

Table II has been calculated from this relation.

Table II Concentration in the cloud producing 1.5 rep β in 15 mins

Time of entry	1	5	10	15	20	30	40	50	60	hrs
Fission Product Density	0.17	1.2	2.6	4.4	6.0	10	14	18	22	$\times 10^{-2}$ 1 hr $\mu c/cc$

4. Gamma dose due to contamination on the exterior of the aircraft

After the aircraft has passed through the cloud the passengers will continue to be irradiated by the radioactive material from the cloud which adheres to the aircraft. To assess the hazard from this source it is assumed that the amount of material adhering to the plane is proportional to the mass of material which it has intercepted. This assumption is supported by observations on some of the aircraft used for cloud sampling in Operation Buffalo. These showed that the dose rate from the fuselage was approximately proportional to the dose rate from the engines which almost certainly integrate the activity intercepted. If the assumption is correct, and the time to pass through the cloud is so short that the decay of contamination activity during transit may be neglected, the dose rate from contamination on the aircraft on leaving the cloud will be proportional to the dose received from the cloud itself and inversely proportional to the air density in the cloud. The data available from Buffalo indicate that at 25,000' the dose rate associated with a transit dose of 1 r will not be greater than 0.7 r/hr. In estimating the total dose due to contamination it is assumed that the passengers remain in the aircraft for 10 hours after passing through the cloud. According to the $t^{-1.2}$ law the following 1 hr dose rates would result in a dose of 0.3r in the next 10 hours.

Time of entry	1	5	10	15	20	30	40	50	60	hrs
Dose rate at H + 1	.16	.42	.74	1.1	1.4	2.2	2.8	3.7	4.6	r/hr at H + 1

This dose rate was converted into contamination concentration in the cloud at 1 hr producing it using the factor 1r gives 0.7r/hr and equation (2). The results are given in table III

Table III Concentration in the cloud producing 0.3r from contamination on exterior

Time of entry	1	5	10	15	20	30	40	50	60	hrs
Fission Product Density	0.26	0.69	1.25	1.9	2.4	3.6	4.9	6.2	7.8	$\times 10^{-3}$ 1 hr $\mu c/cc$

5. Beta dose due to contamination of the interior of the Aircraft

It is considered that, in view of the fact that the ratio of doses from β and γ rays from an infinite plane contaminated with fission products is about 10 to 1 at early times, and that dimensions of the fuselage are small compared with the γ ray range in air, the γ ray dose from interior contamination can be neglected. The β ray dose was calculated using the data given by Dale et al. (1) and assuming that the contaminated area could be regarded as infinite for β rays. Then the surface contamination producing 1.5 rep in 10 hours is as follows.

Time Exposure Starts	1	5	10	15	20	30	40	50	60	hrs
Surface Contamination	0.69	2.0	3.8	6.2	8.8	15.4	23.0	34	42	1 hr $\mu c/cm^2$

To relate these values to the corresponding fission product density in the cloud the factor given by Chamberlain (2) that a cloud of concentration 1 $\mu c/cc$ deposits at the rate of 1 $\mu c/cm^2/sec$ has been used. As civil aircraft may not be efficiently filtered and the pressure inside is twice that outside we must consider that the fission product density inside the plane may be as high as twice that in the cloud. Then, assuming that the interchange of air is sufficiently rapid that depletion of the activity by deposition need not be considered, the following table of fission product density producing 1.5 rep in 10 hrs. after a 15 min flight through the cloud is obtained.

Table IV Concentration in the cloud producing 1.5 rep from deposition on interior

Time of entry	1	5	10	15	20	30	40	50	60	hrs
Fission Product Density	0.38	1.11	2.1	3.5	4.9	8.8	12.8	18.9	23	$\times 10^{-3}$ 1 hr $\mu c/cc$

6. Beta dose due to deposition of contamination on the skin

As only a comparatively small area of skin will be exposed it is considered that a β dose of 3 rep to this area will correspond to the same hazard as 1.5 rep to the whole body surface. According to Chamberlain (3) a deposition of 1 $\mu c/cm^2$ of a β emitter of average energy 0.6 MeV on the skin results in a dose rate to the surface tissues of 7 rep/hr. Hence the following depositions of 1 hour fission products will result in a dose of 3 rep if they remain on the skin for 10 hrs. The time is taken as 10 hrs again as the passengers will probably wash thoroughly shortly after the flight.

Time of Deposition	1	5	10	15	20	30	40	50	60	hrs
Surface Contamination	.23	.60	1.0	1.5	1.9	3.1	4.0	5.1	6.3	1 hr $\mu c/cm^2$

Under the same assumptions as used in 5 these levels correspond to the concentrations in the cloud given in Table V.

Table V Concentration in the cloud producing 3 rep from deposition on the skin

Time of entry	1	5	10	15	20	30	40	50	60	hrs
Fission Product Density	0.13	0.33	0.58	0.85	1.07	1.7	2.2	2.8	3.5	$\times 10^{-3}$ 1 hr $\mu c/cc$

7. Dose due to inhalation of Fission Products

As in the cases for deposition on the interior and on the skin it is assumed that the contamination will pass freely into the aircraft and that, owing to pressurisation, the concentration inside will be twice that outside. The hazard due to breathing this air has been evaluated on the basis of the distribution in the body given by I.C.R.P. (4) for insoluble particles, i.e. 25% is exhaled, 50% is swallowed, and 25% is retained in the lungs. Of the 25% retained in the lungs half is swallowed in the first 24 hrs and the remainder is retained in the lungs with a half life of 120 days. Hence inhalation results in irradiation of the lungs and of the gastro intestinal tract. Dale (5) has given the amount of 1 hr fission products delivering a dose of 3 rep to the G.I. tract for various ingestion times. The following table is based on these data, and on the assumptions that the exposure lasts for 15 mins, during which time 2.5 x 10[illegible] cc are inhaled, and that 50% of the inhaled activity is deposited in the G.I. tract.

Concentration in the cloud giving 0.3 rep to the G.I. tract from inhalation

Time of inhalation	1	5	10	15	20	30	40	50	60	hrs
Fission Product concentration	0.12	0.27	0.46	0.64	0.80	1.18	1.56	1.96	2.32	$\times 10^{-3}$ 1hr μ c/cc

The concentration required to give a dose of 0.3 rep to the lungs under the same conditions can also be calculated from data given by Dale (5) and is as follows.

Concentration in the cloud giving 0.3 rep to the lungs from inhalation

Time of inhalation	1	5	10	15	20	30	40	50	60	hrs
Fission Product concentration	0.48	0.70	0.90	1.05	1.15	1.25	1.32	1.38	1.45	$\times 10^{-3}$ 1hr μc/cc

Table VI is constructed from these two tables and gives the fission product concentration which would result in a dose of 0.3 rep from inhalation to the limiting organ.

Table VI Concentration in cloud producing 0.3 rep internally from inhalation

Time of entry	1	5	10	15	20	30	40	50	60	hrs
Fission Product Density	0.12	0.27	0.46	0.64	0.80	1.18	1.32	1.38	1.45	$\times 10^{-3}$ 1 hr. μc/cc

8. **Dose due to ingestion of Fission Products**

As the people in the aircraft will be unaware that they are in an atomic cloud we must consider the possibility that they may eat food which has been exposed to contaminated air during the whole time the aircraft is in the cloud and has not been subsequently washed. It is estimated that a reasonable maximum area of food to use in calculating the amount of activity which might be ingested in this way is 10^3 cm^2. According to Dale (5) the ingested activity which exposes the Gastro Intestinal tract to 0.3 rep is as follows:

Time of Ingestion	1	5	10	15	20	30	40	50	60	hrs
Ingested Activity	.03	.07	.13	.16	.20	.29	.39	.49	.58	1 hr mc

Hence the surface deposition on 10^3 cm^2 of food which would result in 0.3 rep is

0.3	0.7	1.3	1.6	2.0	2.9	3.9	4.9	5.8	$\times 10^{-1}$ 1 hr. μc/cm^2

at these times.

Using the same assumptions as before to relate this surface deposition to cloud density, Table VII, giving the cloud concentration which would result in 0.3 rep due to ingestion, is obtained.

Table VII Concentration in the cloud producing 0.3 rep from ingestion

Time of Entry	1	5	10	15	20	30	40	50	60	hrs
Fission Product Density	0.17	0.39	0.72	0.89	1.1	1.6	2.2	2.7	3.2	$\times 10^{-4}$ 1 hr $\mu c/cc$

9. Conclusion

It appears from the preceding table that if a meal is eaten during the flight the limiting hazard is from ingested activity. This restricts the cloud density to about 10^{-4} 1 hr $\mu c/cc$ at times likely to be of interest if the total dose is not to exceed 0.3 rep. If no food, or only food taken straight from sealed packages, is eaten this limit would be unnecessarily restrictive and the limit set by inhalation, i.e. about 10^{-3} 1 hr $\mu c/cc$, could be used. In either case the concentration is so much lower than that required to deliver 0.3 rep to the same organ from any other source that the additive effect of doses from all the sources considered need not be taken into account.