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CIVIL DEFENCE ASPECTS OF RADIOACTIVE CONTAMINATION IN AGRICULTURAL PRODUCE

R. Scott Russell and J.D. Burton

Agricultural Research Council Radiobiological Laboratory,
Letcombe Regis, WANTAGE, Berkshire

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1. INTRODUCTION

The object of this paper is to assemble information on the contamination of agricultural produce which may be of use to those who are responsible for Civil Defence policy. No attempt is, however, made to discuss the practical aspects of Civil Defence. This paper is concerned primarily with food chain transfer mechanisms and many other questions must be taken into account in deciding what plans should be made to minimise risks to the population.

Although many aspects of the effects of radiation on living organisms are incompletely understood it is well established that the effects of radiation from different sources to which a tissue may be simultaneously exposed are additive. This has important practical implications for Civil Defence. The risk from radiation to which populations will be exposed can be assessed adequately only in terms of the total dose received by any organ from internal as well as from external sources. Furthermore, no significant mitigation of radiation injury will be possible unless the major sources of exposure are susceptible to control; the elimination of a source which contributes but a trivial fraction of the total dose will confer little benefit. The practical implications of this are obvious. Firstly, the presence of radioactivity in foodstuffs will deserve consideration only when the resultant internal radiation dose is appreciable relative to that simultaneously experienced from external sources. Secondly, if on this basis internal radiation deserves consideration, it will be important to identify the nuclides which will deliver the major internal doses and the foods in which they are contained. The "critical nuclides" and "critical foods" must be identified; the word "critical" being used in a comparable manner to that adopted by ICRP(1) who apply it to the organ which is at greatest risk. Thirdly, in planning measures for the re-establishment of agriculture in the years following a nuclear attack, it is important to have knowledge of the relative extent to which foodstuffs are likely to be contaminated as a result of absorption from the heavy initial deposition on the soil as opposed to current world-wide fallout; if the latter should be the dominant source of dietary contamination, measures to reduce absorption from the soil would be of little avail.

The procedure here adopted to assess these questions is as follows. In Section 2 the critical nuclides in fallout and the critical foods are identified and quantitative relationships are considered between the deposition of finely-divided, freely-soluble fission products and the extent of dietary contamination. In Section 3, the tissue doses likely to result from dietary contamination are assessed, while in Section 4 the extent to which the critical nuclides may enter food chains in different fallout fields is considered. This makes it possible to compare internal and external doses in Section 5. General conclusions are suggested in Section 6.

It is assumed that the diet consumed by the population is of the type characteristic of the major part of Europe and North America; that is to say dairy produce is of considerable importance, especially to young children. Consideration is limited to the consequences of the contamination of growing crops either as a result of the direct lodgement of fission products on their foliage or through absorption from the soil. In some circumstances the contamination of stored or prepared food may also deserve consideration.

2. GENERAL NATURE OF FOOD CHAIN MECHANISMS

2.1 The critical nuclides

The extent to which fission products which have been deposited from the atmosphere can enter man's diet varies greatly, depending on many factors which are considered in Section 2.3. Notwithstanding these causes of variation, however, the highest internal radiation doses are likely always to be delivered by one or other of the four nuclides, iodine 131, strontium 89, strontium 90 and caesium 137. Except when the composition of diet and the method of food production are exceptional, caesium 137 is likely to be of minor concern relative to iodine 131, strontium 89 and strontium 90; these are the critical nuclides. It will be shown in subsequent discussion, in which these nuclides are considered individually, that in many circumstances the list of critical foods, especially in the early emergency period, is equally short. The evidence on which these conclusions are based is derived from many sources including biological investigations at weapons trials (2, 3) as well as wide scale surveys and experiments undertaken to elucidate the consequences of world-wide fallout and discharges of radioactivity in the environs of nuclear reactors; a comprehensive review on these peacetime problems has been provided by the United Nations Scientific Committee on the Effects of Atomic Radiation (4) as well as other publications (5, 6).

It must be understood that the critical nuclides are not responsible for the total internal dose. Shortly after fission products have been released, the dose from iodine 131 may be augmented by that of the shorter-lived iodine 133 and those to bone from strontium 89 and strontium 90 may be similarly augmented from that of short-lived barium 140. The tissue doses from these sources will, however, be small relative to those from the nuclides previously named.

2.2 Food chains and the critical foods

The relative extent to which different foodstuffs will be contaminated with different nuclides may vary greatly and the situation will change depending on the time which has passed since the deposition of fallout. Before discussing the identity of critical foods it is necessary, therefore, to note the general nature of food chain mechanisms, but because the contribution of aquatic produce will be small consideration can be confined to food chains on dry land (Figure 1).

Fission products which have been deposited from the atmosphere onto agricultural land may lodge either on growing plants (direct contamination) or enter the soil from which they may subsequently be absorbed (indirect contamination). The extent of direct contamination depends both on the physical form of the fallout and the morphology of plants. Finely-divided material (e.g. less than circa 40 μ) is retained to a considerably greater extent than larger particles (2, 7). The highest levels of dietary contamination, relative to the deposit are to be expected from finely-divided materials both for this reason and because particulate deposits of appreciable size are usually sparingly soluble and only soluble materials can enter food chains. The growth form of permanent pastures on which cattle graze in many regions is particularly favourable for direct entrapment of the deposit and it is estimated that some 25% of finely-divided deposits will initially lodge on herbage edible by cattle (8, 9). After deposition ceases the contamination of the exposed tissues will decrease not only because of the decay of radioactivity but also through the removal of

contamination from leaves by rain and other mechanisms or the "dilution" of the contaminated herbage by new growth. The extent of reduction in the contamination of herbage which occurs with time as a result of processes other than the decay of radioactivity is conveniently expressed in terms of a "Field Loss Factor". Experiments in the United Kingdom (10) and observations after the Windscale accident (11) suggest that after finely-divided materials have been deposited, the value of the Field Loss Factor in the early period will be about 2 every two weeks. It is assumed to become negligible after six to eight weeks.

Relative to direct contamination, the indirect contamination of herbage through absorption from the soil is a slow process, so that it is not important in the early period after fission products have been deposited; it need be considered, therefore, only in relation to nuclides of relatively long half-life.

Dairy cattle constitute a particularly important link in the transfer of radioactivity into human diet. Iodine, strontium and caesium are relatively readily transferred from the diet of cattle to milk (8) and during the grazing season animals may ingest fallout equivalent to the deposit on wide areas. Beyond this, milk is particularly important in the diet of infants who, because of their long expectation of life and rapid growth, may be particularly exposed to radiation injury. Moreover, the interval between the production of milk and its consumption is considerably shorter than that which occurs with many other foods, so that there is less opportunity for short-lived activities to decay.

Another obvious way in which fission products can reach man's body rapidly is by the consumption of leaf vegetables which have been directly contaminated by fallout. No consideration is given to this aspect here since, as these foods are not important sources of energy or protein they could be dispensed with in an emergency; moreover washing and the removal of outer leaves (which may be regarded as normal hygiene in such circumstances) would greatly reduce contamination.

Against the foregoing outline of food chain mechanisms specific points relative to the critical nuclides and the critical foods in which they can be present are noted below:

Iodine 131: Because of its 8 day half-life, iodine 131 is of concern for only a relatively short period after the deposition of mixed fission products. If deposition occurs during the summer months when cattle are grazing on pastures, milk is likely to be the sole critical food; if deposition occurs during the winter months the transfer of iodine 131 to diet will be relatively slight.

Strontium 89 and strontium 90: The activity of strontium 89 in fresh fission products is likely to be 150 to 200 times that of strontium 90 and the longer-lived nuclide is judged some 100 times more hazardous on account of its long half-life (1). Since the half-life of strontium 89 is 51 days, it follows that the radiation dose from it is likely to exceed that from strontium 90 only for about six weeks after fission. In this period milk will be the critical food for strontium 89 as for iodine 131, though it is transferred from the diet

of cattle to milk to a considerably smaller extent. Direct contamination with radioactive strontium may be particularly important also in cereal grain since fallout is relatively readily entrapped in developing ears and strontium absorbed by these tissues is not transferred to other parts of the plant; in practice the contamination of grain is important only with strontium 90, since the interval between the production of grain and its consumption is usually sufficient for strontium 89 to decay considerably.

Over still longer periods of time the absorption of strontium 90 from the soil will become the dominant route of dietary contamination; the relative extent to which strontium 90 enters different foodstuffs will then contrast greatly with that in the early period. This question is best considered in terms of ratios of strontium 90 to calcium. This ratio is lower by a factor of about 10 in milk than in the diet of cattle. However, in the early period, when direct contamination is important, the ratio in milk is likely to differ little from the average in other components of diet because the marked retention of strontium 90 on pastures offsets the discrimination against it in the metabolism of cattle. There are only relatively small differences in the ratio in which different plant species absorb strontium 90 and calcium from the soil. Thus, when the soil is the major source of radioactivity in diet the ratio of strontium 90 to calcium in milk is considerably below the average for other foods. The importance of cereals as a source of strontium 90 will similarly diminish as they too will have been subject to particularly marked direct contamination in the early period.

Caesium 137: Milk and meat are the critical foods for caesium 137. In the normal European diet caesium 137 delivers appreciably lower tissue doses than arise from strontium 90; this is because it is not concentrated in specific tissues and retained for considerable periods. In an exceptional diet which consists predominantly of meat or dairy produce caesium 137 may become of critical importance, especially when local conditions are particularly favourable for its ingestion by animals. There is, however, no reason to believe that it may be regarded as a critical food in more normal European conditions.

2.3 Quantitative relationships in the transfer of fission products through food chains

Whereas the critical nuclides and critical foods can usually be identified with certainty, quantitative estimates of the relationship between the amount of fission products deposited per unit area and the resultant levels in foodstuffs are open to considerable uncertainty. It is important that the reasons for this should be understood. The extent to which fission products are transferred to food chains after they have been deposited on the earth's surface may vary widely depending on the physical form of the deposit, the time of year at which contamination occurs, local agricultural conditions, and weather. Discussion of the first of these causes of variability, namely the physical form of the deposit, is deferred until Section 4. It is here assumed that fission products are deposited in a finely-divided, freely soluble form. This not only is

the worst situation from the viewpoint of dietary contamination, but also it has been most widely studied because world-wide fallout occurs in this form. Relationships derived for these conditions can be scaled to other situations by allowing for differences in the availability of fallout.

The effect of the time of year on the passage of fission products through food chains is most obvious in relation to the transfer of the recent deposit to milk and the contamination of cereal grain with long-lived nuclides. During the summer, when cattle are grazing, the quantity of recently deposited fission products which they ingest is considerably greater than that which will occur in winter when they are fed mainly on stored food. Since the grazing season occupies an appreciable part of the year, it is assumed in this discussion that the deposition of fission products takes place during the summer months. Similarly, since the extent to which long-lived nuclides, and especially strontium 90, enter cereal grain is considerably greater when deposition occurs after developing ears have emerged, it is assumed that fallout occurs at that time.

The local agricultural factors which influence the transfer of radioactivity comprise not only variations in agricultural practices but also variations in the nature of the soil; especially with strontium 90 this may exert a marked effect. Since the significance of the contamination of foodstuffs is usually judged in terms of the average exposure of large groups, it is reasonable to base assessments on the average conditions which are likely to occur in European countries, though the responsible authorities for any region may find it necessary to take note of local variability which may cause appreciable departure from the average.

The weather pattern when fallout descends and in the immediately ensuing period affects the transfer of fission products through food chains through influencing both the extent of deposition in any locality and also the extent to which fission products are retained by vegetation. Heavy rain will remove superficial contamination from plants on which it initially lodged. In contrast, under conditions of drought when herbage is growing slowly, the continuous deposition of fallout may contaminate herbage above the average level. Since the climatic conditions which will prevail during any emergency cannot be predicted, the prudent course, in considering situations which may arise in the early stages, is to consider the range of conditions which can reasonably be expected to occur. In assessing continuing situations such as would occur from strontium 90 in subsequent years it is reasonable, however, to assume that over an extended period the effects of weather will conform to the average observed hitherto.

It has been shown in Section 2.2 that in the early period after deposition of fission products the contamination of milk with iodine 131 or strontium 89 is likely to be the major source of concern; over longer periods, however, the contamination of total diet with strontium 90 may be the major cause of internal dose. Quantitative estimates of the relationship between the deposition per unit area (assumed to be soluble and finely-divided) and the levels of dietary contamination under these circumstances are shown in Tables 1 and 2.

Transfer of iodine 131 and strontium 89 to milk in the early period:

The levels of iodine 131 and strontium 89 which may occur in milk at varying times after the deposition of 1 mc of each nuclide per m^2 are shown in Table 1. It is assumed that contamination occurs during the grazing season when cattle are deriving their total diet from grazing and that 25% of the deposit initially lodged on edible herbage. Separate estimates have been made on the alternative assumptions that the radioactivity in herbage decreases only in consequence of physical decay or that a Field Loss Factor of 2 every two weeks is applicable; it was also.

shown earlier that the latter situation is to be expected.

The numerical values in Table 1 are based on extensive series of laboratory experiments in which the two nuclides were fed to cattle (8). Confidence in these estimates is encouraged by the fact that the relationship between levels of iodine 131 in milk and those on the ground surface, observed after the Windscale accident in 1957, agreed closely with that which would have been predicted from the values shown in Table 1 when allowance is made for grazing conditions at that time (11).

Transfer of strontium 90 to milk and other components of diet: Long-term relationships: In considering the transfer of strontium 90 to diet over extended periods, the contribution both of the recent deposit and of the cumulative total in the soil should be taken into account. This relationship can be expressed by an equation of the following type:

$$C = \underline{p_r}\, D_r + \underline{p_c}\, D_c$$

where C is the strontium 90 content of the foodstuff in question (normally expressed as the ratio of strontium 90 to calcium), D_r and D_c are the magnitude of the recent deposit (e.g. the annual rate) and the cumulative total respectively, and $\underline{p_r}$ and $\underline{p_c}$ are proportionality factors conveniently described as the "Rate" and "Soil" Factors respectively. This type of equation has been used in a number of studies; the values shown in Table 2 are those derived by the United Nations Scientific Committee (4). The Committee regard the figures on a conservative basis for prediction and independent estimates of those for the United Kingdom (12), the Netherlands (13) and the USA (14) support this view.

3. ASSESSMENT OF TISSUE DOSES

From the viewpoint of the present enquiry it is a primary requirement to estimate the tissue doses which will result from given levels of dietary contamination. In addition, however, it is desirable to consider the minimum tissue dose which it may be reasonable to take account of in any emergency. Guidance on both questions is provided by assessments made for peacetime emergencies. The figures given in Table 3 have been adopted in the United Kingdom (15) and are endorsed by ICRP (1); it was assumed that the emergency would affect appreciably less than one-fiftieth of the population of the country. Wartime emergencies must be expected to affect the entire population but since the doses specified in the Table are generally similar to current occupational "maximum permissible levels", it would seem probable that in any wartime emergency the risk associated with the exposure of the entire population to these levels would be so small relative to other risks that it could reasonably be ignored. This statement is made in the light of the pronouncement of ICRP that any severe somatic effects from exposure to occupational maximum permissible levels are likely to be so rare as to be detectable only by statistical methods applied to large groups.

Table 3 shows that infants under the age of one are subject to considerably higher dose rates from iodine 131 than adults. The milk intake of the two age groups may be comparble, and the extent to which iodine 131 is transferred to the thyroid appears to be relatively constant. However, the weight of the infant thyroid is about one-tenth of that of adults so that the radiation dose it receives is considerably higher.

Limits of dietary contamination for strontium 89 and strontium 90 are set as ratios to calcium because the two ions are transferred from diet to bone in a relatively constant ratio so that the concentration in bone and hence the radiation dose is best inferred from this ratio. The ratios cited refer to the total diet but since milk may be the sole food of infants the figures may also be applied to milk alone.

4. CHARACTERISTICS OF FALLOUT

The types of information on the chemical and physical characteristics of fallout which are relevant to Civil Defence assessments of dietary contamination depend on two considerations:-

Firstly, as shown in Section 1, the attention which it would be appropriate to give to the contamination of diet depends on the probable magnitude of the resultant internal radiation dose relative to external exposure.

Secondly, especially in the early period, the only information which would be available on the extent of fallout would be the gamma dose rate; measurements of individual nuclides and their physical state can only be made when relatively elaborate analytical facilities are available.

Both these considerations emphasise the importance of relating quantities of critical nuclides present on the ground surface to external gamma dose rate. To assess this question it is necessary to have knowledge both of the relationship between the quantity of individual nuclides present per unit area and the external gamma dose rate and also of the physical form of the deposit, since this influences the passage of nuclides through food chains. These two questions are conveniently considered separately. Before doing so, however, it may be noted that since the calculations on which this paper is based were completed, a comprehensive analysis of physical data, from United States sources, on this and other Civil Defence aspects has been prepared by Miller (16); differences between the two assessments appear to be small.

4.1 Relationship between deposition of fission products and the external gamma dose rate

A convenient starting point for this assessment is to consider the gamma dose rate which will result from a given deposition of fission products in fission yield. The fission yield of different nuclides varies depending on the nature of the fissile material. This effect is not large and it appears reasonable to use the information of Bolles and Ballou (17) for the fission of U^{235} as a general guide. The results of these workers show that the percentages of the total activity present after 24 hours due to the "critical" nuclides are as follows:-

Iodine 131	0.8%
Strontium 89	0.18%
Strontium 90	0.0012%*
Caesium 137	0.0010%

and that the decay factor for mixed fission products between 1 hour and 24 hours is 36. Accepting Dunning's conclusion (3) that 800 megacuries beta activity/mile^2 1 hour after fission gives a dose rate of 4000 r.p.h. above a theoretical flat plain and assuming that the dose may be reduced by a factor of 2 above a rough surface, the quantities of the critical nuclides which would be present on the ground surface if fission products were deposited in fission yield and the gamma dose rate were 1 r.p.h. at 1 hour can be calculated (Table 4, Column 2).

*The data of Bolles and Ballou for strontium 90 have been adjusted to allow for the currently accepted half-life of 28 years.

It is well established, however, that volatile nuclides, or those with volatile precursors, will be depleted in near-in fallout. Estimates of the magnitude of this effect vary widely and the fractionation factors (i.e. the factors by which the nuclides are depleted) shown in Table 4, Column 3 were selected as conservative estimates on the basis of numerous reports (2, 3, 16, 18, 19, 20). By dividing the values in Table 4, Column 2 by the fractionation factors (Column 3) the estimated deposit of each nuclide at day 1 corresponding to 1 r.p.h. at 1 hour is obtained (Column 4).

4.2 Physical properties of fallout

It is well established that in areas of high fallout the mean particle size of the deposit would be relatively large and its solubility correspondingly small. These relationships will, however, vary depending on the size of weapons, the altitude at which they are detonated, and, with low altitude detonations, by the nature of the terrain. The selection of estimates of physical characteristics for use in Civil Defence assessments is, therefore, subject to particular uncertainty; the only wise procedure is to select values which appear conservative in the light of existing data. In this way the values in Table 5 have been obtained.

Four fallout fields, where the dose rate at 1 hour is >100, 10, 1 and 0.1 r.p.h. respectively, have been considered. The values given in Table 5 for the particle size of the deposit are compatible with those given in other assessments (18, 21). The estimation of the initial retention on herbage, a matter of major importance in assessing the contamination of diet, especially milk, in the early period, is rendered difficult by the fact that nuclear weapons are necessarily tested at sites remote from productive grazing land and only at one series of nuclear trials has the study of retention of fallout on pastures been made a major objective (2). The limitations which beset such field estimates should be emphasised. Unless great care is exercised, a large part of the activity initially present on grass may be dislodged during sampling with the result that the intake of a grazing animal might be seriously underestimated. Estimates of retention in areas of heavy fallout are based on target response investigations in Australia (2). Other studies (7) show a generally similar variation of retention with distance from ground zero, although they indicate an appreciably lower retention of large particles than is assumed here. Thus, the present figures introduce a factor of caution. The retention assumed for long-range fallout is also supported by experimental investigations and other data referred to in Section 2.2.

Information on the initial solubility of fission products is subject to great variability depending on the analytical method employed and widely varying values have been reported (2, 7, 18, 22, 23). As with other parameters, the figures shown in Table 5 represent the upper range of solubility in these observations. The reported solubilities are for mixed fission products and, in the absence of other information, these have been taken to apply to the critical nuclides.

To facilitate the comparison of the relative extent to which the deposit in different fallout fields may enter food chains, values for the "relative availability %" have been calculated by multiplying the figures for initial retention by those for solubility. The availability is much lower in areas of high dose rate. From these estimates the relative extent to which diet will be contaminated in different areas may be computed by multiplying the predicted values for "relative availability %" by the dose rate at 1 hour, since this varies in direct proportion to the deposit when the extent of fractionation is constant.

These estimates, described as "relative contamination" in Table 5, show that levels of dietary contamination are likely to vary little between areas where the dose rate at 1 hour ranges from 0.1 to 10 r.p.h.; the lower deposition in the less contaminated areas is offset by its greater availability.

Apart from the physical characteristics of the deposit assumed in Table 5, it is necessary to take account of the Field Loss Factor discussed in Section 2.2. It was there shown that when finely-divided material is deposited on foliage with relatively high initial retention (circa 25%) the contamination of vegetation is likely to decrease by a factor of 2 every two weeks over and above that due to decay of radioactivity. While it is reasonable to assume that this factor can be operative in areas where the initial retention on herbage is appreciable, i.e. dose rates of 1 and 0.1 r.p.h. at 1 hour (Table 5) it is unjustified to assume a significant Field Loss Factor in areas where the initial retention on herbage is low due to large particle size. Not only are no observations available for such circumstances, but also the much larger fraction of the deposit which will initially reach the ground surface raises the possibility that loss from vegetative tissues may be compensated by upward movement. Accordingly, the Field Loss Factor is not taken into account when the gamma dose rate is 10 r.p.h. at 1 hour or greater.

5. RELATIONSHIP BETWEEN INTERNAL EXPOSURE FROM DIETARY CONTAMINATION AND EXTERNAL RADIATION

In Table 6 the data set out in Tables 1 to 5 have been used to estimate the tissue doses which would result from consuming the produce of an area where the external gamma dose rate was 100 r.p.h. at one hour. It is assumed that contamination occurs at a time of year when diet is most vulnerable to contamination, that is to say during the summer (see Section 2.2). As a further safeguard against underestimating the extent of dietary contamination it is assumed that the consumption of contaminated foods commences 24 hours after detonation of weapons, that it continues indefinitely, and that the solubility of fallout is the maximum suggested in Table 5.

Calculations have been made for the two limiting sources of radiation exposure in the early period, namely the contamination of milk with iodine 131 and strontium 89, and also for the contamination of the total mixed European diet with the latter nuclide. Food chain data on the contamination of milk with both nuclides come directly from Table 1. Because different components of the mixed diet are produced at different times of year, the extent to which the total mixed diet would be contaminated with strontium 89 could vary considerably depending on the season and also on the length of time for which food is stored before consumption. To indicate an upper limit to the dose from strontium 89 in the mixed diet it has been assumed that all foodstuffs are subject to contamination within 6 weeks of the deposition of fission products and the decay of strontium 89 has been ignored. The levels in diet which would result from direct contamination under these conditions have been calculated from the appropriate "Rate" Factor (Table 2) multiplied by 52/6; this factor is introduced because it is assumed in Table 2 that fallout is transferred to diet at a relatively steady rate throughout the year, whereas in the model here postulated the entire effect is assumed to occur in 6 weeks.

The long-term situation which would occur in the year following a nuclear attack has been considered for strontium 90; separate estimates have been made for milk and for the total mixed diet. In this case it is necessary to consider both the contribution of the deposit in the soil and of current worldwide fallout.

Taking into account the solubility of near-in fallout (Table 5) uptake from the soil can be estimated by applying the "Soil" Factors in Table 2 to the estimated deposit derived from Table 4. The extent of current world-wide fallout will depend on the total quantity of fission products released into the atmosphere and on the rate at which they are deposited. It is here assumed that 1000 MT of fission occurred in the previous year and that the relationship between the rate of fallout and the injection into the atmosphere in the previous year was the average observed in the United Kingdom in 1958 and 1959; the mean deposit in these two years was about 5.5 mc/km^2 (24) and the mean fission yield of weapon tests per year for the two previous years was 20 MT (4).

Since it has been shown in Table 6 that the highest internal dose rates are those delivered by iodine 131 to the thyroid glands of infants, separate calculations have been made in Table 7 for the dose rates they would receive from the consumption of milk produced in gamma fields of 100, 10 and 0.1 to 1 r.p.h. at 1 hour. Separate calculations are made for the consumption of milk starting at times from 1 to 42 days after detonation. Values for external doses are given for comparison, no allowance having been made for shielding.

6. CONCLUSIONS

Attention has already been directed to the considerable uncertainties which are inevitably associated with any assessment of future levels of dietary contamination. Even if considerably more reliable experimental information were available, much uncertainty would remain as to the nature of the weather immediately after a nuclear attack and this factor can exercise a considerable effect. For this reason assumptions of an intentionally conservative nature have been made and it is likely that the assessments in Tables 6 and 7 somewhat overestimate the probable extent of dietary contamination.

An obvious difficulty in comparing estimates of the internal doses resulting from dietary contamination with the external dose is that a large variation in the latter could result either from shielding or from the delay in the arrival of fallout. However, it is apparent from Table 6 that the entry of fission products other than iodine 131 into foods produced in a field of 100 r.p.h. at 1 hour will lead to internal radiation doses which are not only very small relative to the possible external gamma dose, but also considerably below the minimum judged to warrant remedial action in an emergency (see Table 3). The desirability of protecting infants from ingestion of excessive iodine 131 is, however, obvious; it may be considered the sole aspect of dietary contamination which will deserve serious attention in the early period. The substitution of dried for fresh milk would provide protection.

The assessment of the long-term contamination of diet with strontium 90 as shown in Table 6 indicates firstly, that the external gamma dose, in the early period, will exceed, by a considerable factor, the internal dose which may subsequently be received as a result of the passage of strontium 90 from the soil into foodstuffs and secondly, that, a year after a nuclear attack, current world-wide fallout may be the major source of strontium 90 in diet in areas where the initial gamma dose rate was about 100 r.p.h. at 1 hour or less.

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Table 1

Expected levels of iodine 131 and strontium 89 in milk after the deposition of 1 μc per m^2 in finely-divided freely-soluble form

Time after deposition days	If activity of herbage decreases only through radioactive decay		Assuming field loss factor of 2 every 14 days	
	I^{131}	Sr^{89}	I^{131}	Sr^{89}
	μc/litre		μc/litre	
1	0.12	0.006	0.11	0.006
2	0.16	0.014	0.14	0.013
3	0.16	0.020	0.14	0.017
7	0.13	0.027	0.09	0.019
14	0.07	0.026	0.03	0.013
21	0.04	0.023	0.01	0.008
28	0.02	0.021	0.005	0.005
42	0.006	0.018	0.001	0.002

Based on Garner (8)

Table 2

Proportionality factors for the transfer of strontium 90 to diet

	Rate Factor: Contribution of current fallout mμc/g.Ca per μc/m^2/year	Soil Factor: Contribution of cumulative deposit mμc/g.Ca per μc/m^2
Milk	0.8	0.3
Cereals unmilled	20	0.5
milled	7	0.5
Vegetables	1*	1
Mixed European diet**	1.5	0.4

*Leaf vegetables only; zero for root crops

**Assuming that half of the cereals are unmilled

Based on United Nations (4)

Table 3

Limits of dietary contamination for peacetime emergencies

Nuclide	Limit of dose	Limit of intake
Iodine 131	25 rads (thyroid)	Total Intake Infants (6 months) 0.65 μc Children (3 years) 1.2 μc Adults (over 20 years) 15 μc
Strontium 89	15 rads (new bone)	0.2 μc/day i.e. 0.2 μc/g.Ca
Strontium 90	1.5 rads/year (new bone)	2 mμc/day i.e. 2 mμc/g.Ca
Caesium 137	10 rads (whole body)	Total Intake Infants (6 months) 15 μc Adults (over 20 years) 115 μc

Medical Research Council (15)

Table 4

Estimated levels of fission products on ground surface if external dose rate is 1 r.p.h. at 1 hour after fission

Nuclide	Deposition of mixed fission products	Deposition of fractionated fission products	
	μc/m^2 at 1 day	Fractionation factor	μc/m^2 at 1 day
(1)	(2)	(3)	(4)
Iodine 131	34	3	11
Strontium 89	7.6	5	1.5
Strontium 90	5×10^{-2}	5	10^{-2}
Caesium 137	4×10^{-2}	10	4×10^{-3}

Table 5

Assumed physical properties of fallout

(1)	Degree of fallout contamination Dose rate r.p.h. at 1 hour	Heavy > 100	Medium 10	Light 1	Very long range 0.1
(2)	Particle size μ	100	40	25	small
(3)	Initial retention on herbage %	2.5	2.5	10-15	25
(4)	Initial solubility* %	5-10	5-10	10	50
(5)	"Relative availability" % (3) x (4)	0.125-0.25	0.125-0.25	1.0-1.5	12.5
(6)	Relative contamination (1) x (5)	12.5-25	1.25-2.5	1.0-1.5	1.25
(7)	Field loss Half-life (days)			14	14

*Refers to material at the time of deposition. In considering long-term relationships in the soil, 50% solubility is assumed.

Table 6

Expected levels of contamination in foodstuffs produced in a fallout field of 100 r.p.h. at 1 hour, and the resultant tissue doses

	Food	Maximum level of contamination	Maximum tissue dose
EARLY PERIOD			
Iodine 131	Fresh milk	2 μc/litre	530 rads to thyroid glands of infants* 25 rads to thyroid glands of adults*
Strontium 89	Fresh milk	0.04 μc/g.Ca	3 rads to new bone
Strontium 89	Total mixed diet	0.02 μc/g.Ca	2 rads to new bone
LONG-TERM SITUATION DUE TO STRONTIUM 90			
A. From deposit in soil			To new bone
	Milk	150 pc/g.Ca	0.1 rads/year
	Total mixed diet	200 pc/g.Ca	0.15 rads/year
B. From world-wide fallout (one year after attack)			
	Milk	250 pc/g.Ca	0.2 rads/year
	Total mixed diet	450 pc/g.Ca	0.35 rads/year

*The daily intake of milk is assumed to be 0.7 litre.

Table 7

Comparison of external gamma doses with doses delivered to thyroid of infants (6 months) from iodine 131 in milk

External dose rate, r.p.h. at 1 hour (no shielding)	100	10	0.1-1
Total external dose (rads)			
Assuming exposure starts at 1 hour	500	50	0.5-5
24 hours	260	26	0.26-2.6
Total dose (rads) from iodine 131 in milk to thyroid of infants (6 months)			
Assuming consumption starts at			
2 days	530	53	16-40
14 days	240	24	4-10
21 days	130	13	1.5-4
28 days	76	8	0.5-1.4
42 days	20	2	0.1-0.3

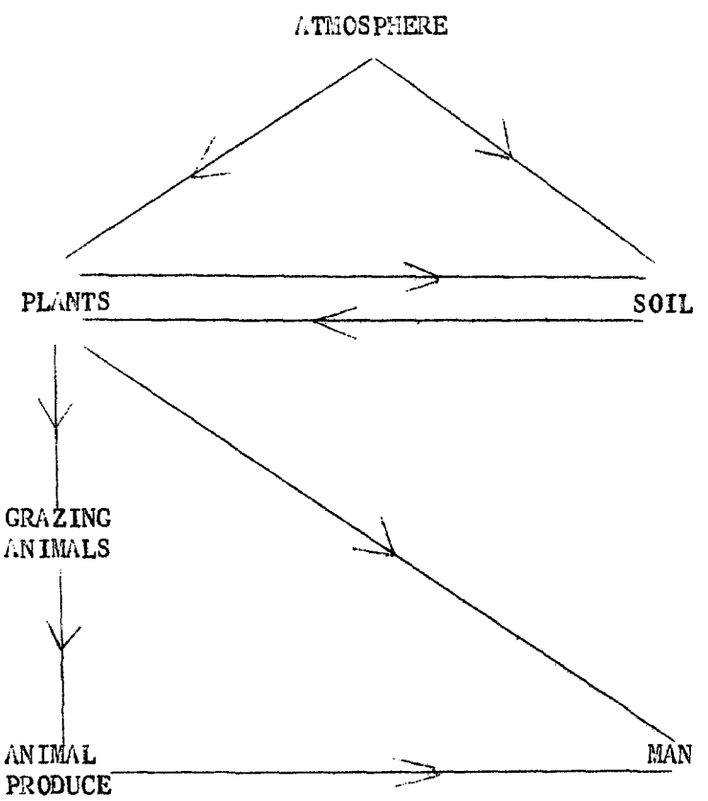

Figure 1. Principal food chains when fission products are deposited from the atmosphere onto agricultural land.