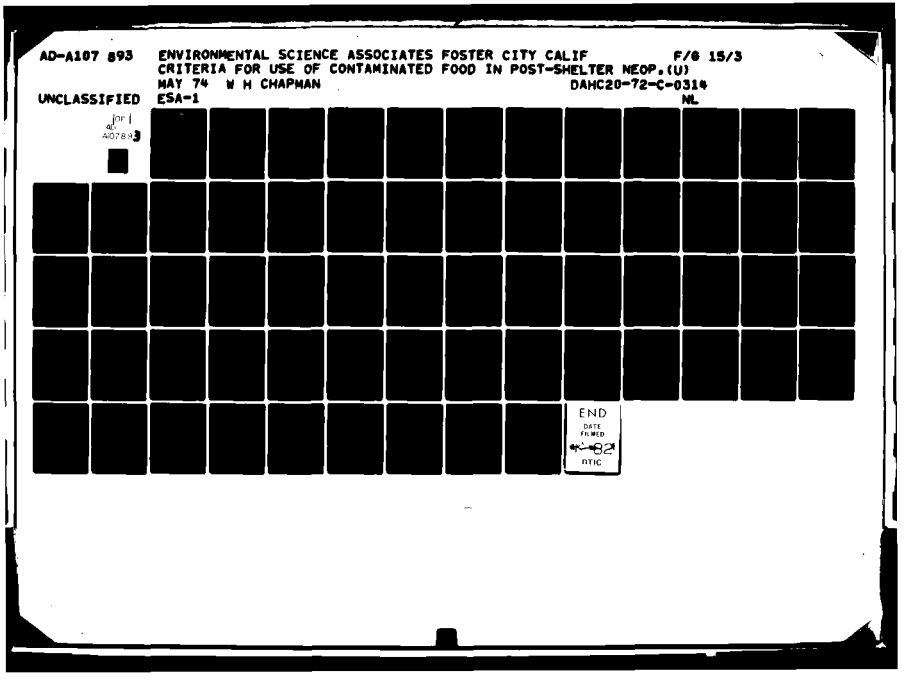
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Summaries are presented of selected reports bearing on the problem of fallout contamination of food in both early and long-term post-attack periods. Relevant factors affecting food contamination are discussed in eight appendices, including: fallout deposition; retention of small fallout particles on vegetation; half-life of fallout on plants; retention of large particles on vegetation; determination of radiation dose to man from small fallout particles on plants; comparison of dosage via milk and meat; dose from stratospheric fallout; and radiological hazard to man from long-lived fission products after a nuclear war.

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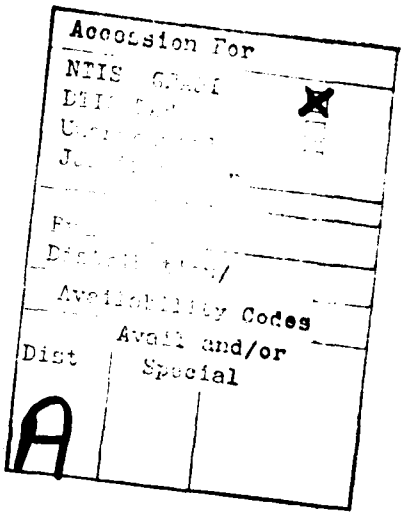
CRITERIA FOR USE OF CONTAMINATED FOOD IN POST-SHELTER NEOP

WORKING PAPER

William H. Chapman

Contract DAHC 20-72-C-0314



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INTRODUCTION

A review of the proceedings of Civil Defense Symposia reveals that a shift in emphasis and a change in philosophy has occurred regarding the relative importance of the components of the civil defense problem. Further, whereas in the past the vulnerability of the important elements of the United States have been studied individually, the more recent trend has been to consider the results of these analyses collectively in terms of national entity survival.

The participants of the earlier symposia were primarily concerned "with the tasks of keeping people alive during and immediately after an attack (unless the people survive, postattack problems would be academic)." This early doctrine was reinforced by the paucity or lack of postattack research data, which in turn usually resulted in "worst-case" estimates of attack damage. The need for postattack experimental results focused increasing attention upon postattack problems. In 1967 the most important of these and the accompanying philosophy were set forth as follows:

> "Three elements of a postattack society that are absolutely essential are sustenance (food and water), protection from the elements (housing and clothing), and avoidance of epidemic disease." "It is patently futile to save people from an attack, if it should occur, only to lose them afterward to starvation and disease."

The present report is addressed to the first of these, *i.e.*, the problem of food availability and utilization in the post-nuclear-attack environment. The dominant status of this element among the other absolute essentials for survival is substantiated by the following summary statements from the civil defense literature:

(a) protection from the elements
"... there seems little reason to expect that surviving supplies (housing and clothing) would be out of proportion to the surviving population."

(b) the avoidance of epidemic disease
"The state-of-the-art ... exists in sufficient magnitude at the present time for the control of communicable diseases." The limiting factor with regard to what can be done from the medical standpoint (regardless of the stockpile of medical supplies) is medical manpower, for "there are going to be more surviving casualties than we can care for with any system that can be realistically devised".

(c) sustenance

"Short term survival depends on the availability of food stockpiles and their early distribution, but the period over which short term survival applies depends on the level of preattack food stockpiles and the extent to which they are destroyed or unavailable as a result of the attack." "The ability of the nation to produce enough food in the postattack period to feed the surviving population is important to long term survival." This general summation of the food problem is self-evident; however, the total impact of the importance of food availability is not evident without consideration of the following: the degree of recovery of each of the elements that have been determined as necessary for national entity survival will be directly dependent upon the availability of food. In other words, the level of social order that will prevail, indeed the entire posture of social behavior in the postattack environment will be directly proportional to the availability of food.

The definition and scope of the problem of food availability and utilization in the postattack environment as well as the methods and degree of proficiency presently available for assessing this problem have, for the most part, evolved from the results of three events.

The first (in chronological order) was the exposure of Marshallese Islanders and American servicemen to the fallout from Shot Bravo of Operation Castle in 1954. The second was the subsequent appearance, almost 10 years later, of thyroid lesions in exposed Marshallese children. The third was the ensuing national awareness that similar results might occur among U. S. children who had been exposed to fallout from atmospheric nuclear tests at the Nevada test site.

The results of the first of these events disclosed which radionuclides would be the major contaminants of food in both early and long-term situations. The second event revealed the most critical human factor to be considered: *i.e.*, the most radiosensitive group in the population. The third provided sufficient impetus to necessitate the development of predictive capabilities for assessing the radiological hazard to man from the consumption of foods contaminated by radionuclides.

These and related events and their results* can now be described:

* only the results pertaining to radionuclide contamination of food in the civil defense context are emphasized.

1. The accidental exposure of the Marshallese inhabitants of Rongelap and the U.S. servicemen stationed on Rongerik to radioactive fallout from the BRAVO H-bomb detonation, March 1, 1954.

This was the first instance of internal deposition of mixed fission products in humans. Prior to this event, concern over the potentially greater radiological hazard to man from open-field external fallout sources had essentially precluded serious consideration of the contribution of internal emitters to the total radiation dosage in the early fallout situation. The preliminary estimates of the radiation dosages received by those involved in this episode were: (a) an average total-body dose of 78 rad and a radioiodine burden leading to a thyroid dose of 50 "rep" for the 28 American servicemen on Rongerik, and (b) an average total-body dose of 175 rad and a radioiodine burden leading to a thyroid dose of 150 "rep" for the 45 adult Marshallese on Rongelap.

RESULTS AND CONCLUSIONS:

(a) From Cronkite, *et al.*, (1954): "The results of radiochemical studies of urine (pooled urine samples from Rongelap group) indicate that Sr^{89}, Ba^{140}, and the rare earth group apparently constitute 77 per cent of the total beta activity at 46 days. Strontium - 89 contributes 40 per cent of the total beta activity, Ba^{140} - 11 per cent and the rare earth group - 25 per cent (of which 11 per cent is La^{140}, in equilibrium with Ba^{140} at this time). Fissionable material was not found in significant amounts in any of the urine samples analyzed. Iodine - 131 was found only in samples analyzed at early time intervals, due to its relatively short physical half-life."

(b) From Cohn, *et al.*, (1956): "Internal deposition of fission products resulted from inhalation and ingestion of the fallout material." "Ingestion appears to be the more important of the two routes of entry into the body." "Iodine was probably the most hazardous internal radio emitter at early times after this exposure." "The dose to the thyroid, while appreciable, was low compared to the partially or totally tissue - destroying dose of I^{131} used in treatment of hyperthyroidism or cancer." "On the basis of the short half-life of the most abundant fission products in this situation, the possibility that chronic irradiation effects will occur is quite small." "At 1 day post detonation Sr^{89} was calculated to be near the maximum permissible level for this nuclide. At later times following exposure of this group, this longer lived fission product presents the greatest potential internal hazard." "An evaluation of the data on

the internal contamination, including that of Sr^{90}, leads to the conclusion that the internal hazard to the contaminated inhabitants of the Marshall Islands is minimal both from the acute and the long-range point of view."

B. The report [illegible] of [illegible] and [illegible] that [illegible] was [illegible] as a late effect of [illegible] is [illegible] among the following groups:

(a) in individuals who had received x-ray therapy to the cervical area.

Perhaps no greater concern and research effort has occurred in the annals of medicine than that generated by the finding of thyroid carcinomas in individuals years after they had been treated with x-radiation in infancy or childhood for thymic enlargement or cervical adenitis. Medical attention was focused upon this problem following a 1955 report by Simpson, *et al.*, which was summarized in NAS-NRC Report No. 452 (1956) as follows: "The high sensitivity of the children's thyroid to ionizing radiation is indicated by the development of thyroid tumors in children who have been treated with x-rays for enlargement of thymus or lymphadenopathy with doses somewhat above 200r (Simpson, *et al.*,)." Extensive investigations were conducted on this subject. The majority of these studies were retrospective analyses of existing data at x-ray therapy centers, in which the authors sought to elicit a previous history of x-ray therapy to the cervical area in patients with thyroid carcinoma. The following statements from a review by Saenger, *et al.*, summarize this data accumulated by 1962:

(1) In adults with large x-ray doses (2000-6000r) delivered to the thyroid gland, carcinoma may develop rarely after a latent period of 10-35 years.

(2) "It is probable that doses of 100r or greater of external x-ray delivered to the thyroid of children will cause an increase in the incidence of carcinoma."

(3) "β,γ-irradiation with I^{131} in adults cannot as yet be indicted as causing carcinoma of the thyroid. At least 10-20 years of observation are needed."

(4) "An increased susceptibility to neoplastic changes of the thyroid following I^{131} in children has been demonstrated as compared to adults."

(b) in the Japanese A-bomb survivors of Hiroshima and Nagasaki

In 1963, Socolow, *et al.*, reported 19 thyroid carcinomas among these survivors, detected 12-16 years following exposure to radiation dosage estimated to have ranged from 50 to more than 200 rad. The occurrence of these carcinomas was attributed to whole- or partial-body gamma/neutron irradiation, since no internal contamination was found in any of the survivors.

(c) in the Marshallese

The discovery, in 1963, of an asymptomatic thyroid nodule in one of the Marshallese children was but the prelude to a succession of similar discoveries during subsequent annual medical surveys. By 1969, 15 of the 19 children who had been under 10 years of age at the time of exposure had developed thyroid nodules and 2 others were hypothyroid as a result of atrophic thyroid glands. These developments were almost totally unexpected. In 1954-56 the possibility of the occurrence of late effects was considered rather remote when the estimated radioiodine dosages of ~150 "rep" to the thyroid were compared with the ^{131}I dosage routinely administered in treating hyperthyroidism. Now, however, just a year before the first thyroid nodules had been discovered in the Marshallese, Sheline, *et al.*, (1962) had reported the occurrence of thyroid nodules in 6 of 18 patients under 20 years of age and in 2 of 238 adult patients treated with ^{131}I for hyperthyroidism. On the basis of these latter results, the occurrence rate of thyroid nodules in the Marshallese children was not in accord with their original thyroid dosage estimates. This discrepancy was partially resolved by James, who in 1964 recalculated the radiation thyroid dosages of the Marshallese and reported the most probable dose to the 2 gram child's thyroid to be in the range 700-1400 rad, average 1000 rad, or roughly three times the thyroid dose of the adult Marshallese (~160 rad from inhalation/ingestion plus 175 rad total body radiation, for a total thyroid dose of 335 rad).

Now, more than a decade since the first thyroid lesions were discovered in the Marshallese, the incidence of benign thyroid lesions in those over 10 years of age at the time of exposure is about a factor of 10 less than that in the children age 10 or less at the time of exposure.

3. The awareness of the possibility that similar results might occur among the children who had been exposed to radioactive fallout

from the Nevada Test Site, an airborne corollary to the Hanford type of thyroid dosage to the Marshallese.

This possibility was officially noted in testimony before the Joint Committee on Atomic Energy in 1963. In response to concern about this problem, intensive re-assessments of the ^{131}I - infant thyroid-dosage problem were begun and clinical surveys were initiated of the school children in areas of Nevada and Utah known to have been subjected to fallout from previous nuclear tests. These surveys spanned the period 1965-1968. Attempts to establish the thyroid dosages which these children might have received from earlier tests disclosed the inadequacies of the radiological monitoring programs conducted in conjunction with these tests, including the fact that no measurements of ^{131}I concentrations in milk were made in these areas prior to 1957. It was clear that more-comprehensive and more-precise post-shot documentation studies should be conducted at all future tests* and that every effort be made to insure that these children were not subjected to any additional radioactive fallout. Further, it was known from previous weapons testing experience that this latter objective could best be achieved by the integration of pre-shot prediction with post-shot documentation**, *i.e.*, the utilization of all available earlier post-shot dosimetry documentation data in pre-shot operations planning to forecast all eventualities within the realm of probability and eliminate or minimize in advance those which might result in a hazardous fallout situation. The predictive methods and models which were developed during this era reinforce earlier results that can be applied to civil defense planning.

In June 1968 there appeared a publication from each of the three individuals and/or organizations then (and now) generally recognized as having achieved the greatest degree of proficiency in the development of a predictive capability for estimating the postattack levels of food contamination and the internal radiation dosages to man that could result from consumption of these contaminated foods. These publications were:

* Note that atmospheric testing by the U.S. ceased with the implementation of the 1963 test-ban treaty. There was still a possibility of venting of underground shots, however.

** As recently as the July 1962 tests, pre-shot predictions had not been integrated with post-shot documentation and "surprises" occurred.

1. Russell, R.S. (1968). Dietary Contamination -- Its Significance in an Emergency. In [illegible] Nuclear War Situation, Proceedings of a Symposium held at Interlaken, Switzerland, 26 May - 1 June, 1968, pp 279-306.

   Earlier studies by Russell and associates which led to this capability included the following: Loutit, et al., (1960), Loutit and Russell (1961), Bartlett and Russell (1966), and Russell (1966).

2. Brown, S. L., H. Lee, and O.S. Yu. (1968): [illegible] - Foods and Food and Water Contamination, Final Report. Stanford Research Institute. Report SRI Project No. MY-6250-050.

   Starting with the original guidance of C. F. Miller, the staff of the Stanford Research Institute has produced an imposing list of authoritative reports on various aspects of this problem, including: Miller (1962); Miller (January, 1963); Miller & Brown (May, 1963); Miller (June, 1963); Miller (July, 1963); Miller (October, 1963); Billheimer and Dixon (1964); and Billheimer (1967).

3. Ng, Y.C. (1968): *Estimation of the Internal Dose to Man from the Radionuclides Produced in a Surface Explosion of a Nuclear Device.* Proceedings of a Symposium held at Interlaken, Switzerland - 26 May through 1 June 1968, pp 315-332. The staff of the Biomedical Division of the Lawrence Livermore Laboratory produced the following reports in developing their predictive capability: Tamplin (1965); Koranda (1965); Thompson (1965); Ng (1965); Burton (1966); Burton and Maxwell (1966); Tamplin (1966); Ng (1966); and Chapman (1968). The contents of these reports and the pertinent data for all isotopes with half-lives greater than 12 hours were incorporated into a handbook by Ng, *et al.* (1968), entitled: "Prediction of the Maximum Dosage to Man from the Fallout of Nuclear Devices".

It was hoped that the methodologies embodied in the three 1968 studies cited above would provide the basis for the determination here of food availability and utilization in the postattack environment. The predictive methods developed by Ng, *et al.* were used in detail as the guidelines for making the assessments, since the Livermore work was updated in 1971

(Ng and Tewes, 1971) to include the most recent data on the retention of small and large particles on plants and their subsequent rate of loss by weathering, on the uptake of nuclides into dietary constituents, and on the biological availability of nuclides in nuclear debris. As a first step, however, all three methodologies were intercompared for consistency, since earlier DCPA assessments had been based on the work of the other two groups, particularly the SRI effort.

APPENDIX A - 100R CONTOUR LINE (Local or early fallout)

The radiological hazard following attack is evaluated in terms of:

(a) the 100R/hr (at one hour) contour lines, and
(b) a 1-Mt-yield explosion.

The area within the designated contour can be scaled to other yields; doses on the contour can be scaled to other contour levels.

THE SIGNIFICANCE OF THE 100R/HR CONTOUR LINE

Ng and Tewes define a standard fallout field as one that would deliver an exposure rate of 100R/hr at one hour postdetonation, if all the fallout had deposited by H + 1. (Hypothetical R/hr at one hour is called the "reference" dose rate in DCPA publications.) The total radiation dose resulting from exposure from such a field, starting at H + 4 hour would be about 300R; the total dose resulting from exposure starting at H + 8 hour would be about 250R. [According to Glasstone (1962), the dosage would actually be about 0.7 as great because of terrain shielding. It would be further reduced by any sort of shielding protection.] Following a nuclear attack of 4000 MT, it has been determined that 50% or more of the land area of the nation would be outside the 100R/hr contour lines. Based on the information available concerning the effects of radiation on man, the unit-time dose rate not exceeding 100R/hr would be compatible with survival of a substantial segment of the population.

THE RELATIONSHIP BETWEEN WEAPON YIELD AND THE 100R/HR CONTOUR LINE

The next step in the procedure was to equate the 100R/hr contour lines with a unit of weapon yield. This relationship was taken from Glasstone (1962), Chapter IX, Section 9.183: "It has been calculated that, on the average, the total gamma-ray activity from the fission products produced by a 1-kiloton TNT equivalent fission explosion would be about 550 gamma-megacuries at one hour after the explosion. If this activity were spread uniformly over a smooth plane one square mile in area then, assuming a mean photon energy of 0.95 Mev, the radiation dose received at a point three feet above the plane can be estimated from Figure 9.179 as roughly 6.8 x 550, *i.e.*, approximately 3,700 R/hr."

From the above information, Ng and Tewes then determined the fractional kiloton deposition per square meter that would give a dose of 100R/hr. "If we accept a theoretical unit-time dose rate of 3700 R/hr in association with the uniform deposition of one kt of fission products per square mile of surface, a unit-time dose rate of 100R/hr from unfractionated fission products is equivalent to a deposition of 1.05×10^{-8} kt of fission products per square meter of surface."

$\frac{3.86 \times 10^{-7}}{37}$ square meter (fraction of square mile) reduce 37R/hr to 1R/hr

"We have assumed that the contributions of neutron-activation products to the gamma field are small and, conservatively, that a unit-time dose rate of 100R/hr is equivalent to a deposition of fission products totaling 10^{-3}kt/m^2."

PHYSICAL CHARACTER OF DEPOSITION IN RELATION TO THE 100R/HR CONTOUR LINES

The basic information utilized to show this relationship was that presented by Glasstone (1962, Chapter IX, Sections 9.186 and 9.187), who calculated, from aerodynamic equations of motion, the time at which particles of a given size and density will arrive at the ground from specified heights in the nuclear cloud. For these calculations, "the density of the fallout material is taken to be 2.5 grams per cubic centimeter, which is roughly that of dry sand; the falling particles are assumed to be spherical, their radii being given in microns (μ)." Glasstone's results are shown in his Figure 9.187.

The second source of information used in establishing this relationship was that reported by Peterson (1970), whose data showed that the cloud from a single 1-Mt surface burst in the latitude band 30 to 90°N can be expected to stabilize between altitudes of 26,000 and 55,000 ft., and the cloud from a single 10-Mt burst can be expected to stabilize between 50,000 and 100,000 ft.

Ng and Tewes used these two data sources for their estimations of the minimum size of particles that can be deposited from the elevations of the 1 Mt and 10 Mt clouds under the influence of gravity alone. To them, these data suggested that, if the 100R/hr contour represented the fallout deposited 4 to 12 hours after detonation, particles of diameter >200μ would deposit inside the contour and particles of diameter <50μ would deposit outside, while a dominant particle-diameter range of 50 to 200μ could be expected in the fallout deposited along the 100R/hr contour from a single surface burst. Accordingly, Ng and Tewes made two sets of predictions for the concentrations of nuclides in foods subsequent to the deposition of fallout. One set is based on data obtained from particles 50 to 200μ and greater in diameter; the other is based on data obtained from small particles (<30μ) and worldwide fallout.

APPENDIX B - RETENTION OF SMALL PARTICLES ON VEGETATION

This aspect of the analysis requires a value for the initial retention of small particles on vegetation and a value for the rate at which these particles are lost or removed by weathering (or the total retention time).

The initial retention factor for small particles (<50μ in diameter) on vegetation was assumed by Ng and Tewes to be two-thirds (67%). This value is at the upper limit of the range of results obtained by Chamberlain (1970) from studies of the experimental release of vapors and aerosols. In the relation

$$1 - P = \exp(-\mu w)$$

where

P = initial retention factor
μ = absorption coefficient in m^2/kg
w = herbage density in kg/m^2 (dry matter)

for μ values on grass of 2.3 to 3.3 m^2/kg and with w values ranging from 0.2 to 0.4 kg/m^2, Chamberlain found that the initial retention factor varied from 30 to 70%.

The value for the time small particles are retained on forage was that established by Thompson (1965) in a study of the half-residence time and effective half-life of fallout on plants in which he found that the half-residence time was independent of isotopes and in the majority of cases varied between 9 and 14 days with a mean half-residence time of 13 days. Since a realistic assessment of the radiological hazard to man from the consumption of fallout contaminated foods is directly dependent upon the behavior of fallout on plants, Thompson's study is reviewed in detail in Appendix C.

Thompson's value of 13 days for the mean half-residence time of fallout on forage was subsequently validated by Chamberlain (1970) who obtained a field-loss coefficient of 0.05 day^{-1} from studies of the loss of small particle activity from foliage. On the basis of these two studies, Ng and Tewes assumed a half-residence time of 14 days for small particles on forage, which is equivalent to a rate of loss by weathering of 0.05 day^{-1}.

APPENDIX C - EFFECTIVE HALF-LIFE OF FALLOUT ON PLANTS

Precise knowledge of the behavior of fallout on vegetation is essential for a meaningful assessment of the biological availability of radionuclides and the radiological hazard they pose to man subsequent to the initial deposition of fallout. This information was provided by Thompson (1965) in a review of the effective half-life of radionuclides on plants; a study which he initiated to characterize the retention of I^{131} on forage plants. The results of Thompson's survey of the literature regarding this subject are presented by him in a table which shows the times reported by various observers for the reduction of I^{131} to half its initial activity on plants and in milk.

In summarizing these data, Thompson emphasized these points:

(a) The dose correlation between the contamination level of forage and the I^{131} content of the milk produced from it. The literature demonstrates that milk measurements are superior to the usual grass sampling techniques because of the large quantity of forage consumed daily by the cow. Since the primary reason for the study of plant retention time for radioiodine is its application to prediction of milk burdens, it was considered appropriate to include milk data.

(b) In spite of the different deposition sources, climates, and plant types that are represented by the data in Thompson's table , the effective half-lives for I^{131} are remarkably similar and most of them fall within the range of 5 ± 1 days. The major factors that have been proposed to explain the reduction in plant half-life for radioiodine to a value less than its radiological half-life of 8 days include:

    (1) exchange or volatilization,
    (2) plant processes (growth, dying back, metabolism), and
    (3) weathering (wash-off by rain, removal by wind, and loss with particles of plant tissue, especially cuticular wax).

Although iodine is volatile at ordinary temperatures and pressures and requires meticulous care in handling during analytical chemical analyses to avoid losses and contamination of other laboratory equipment, the majority of the available data indicates that volatilization plays a minor role in the loss of fallout radioiodine from plants.

The only data referenced by Thompson in support of the occurrence of volatilization was that by Lane (1964) who concluded from his studies of the fallout debris from Project Sedan: "It was found that iodine fission products volatilize and are released from particulate fallout." No evidence of volatilization was noted in the other references cited by Thompson. Boni (1963) demonstrated that green vegetation can be heated to 150°C without loss of fallout iodine. No loss of radioiodine was noted in studies of the Windscale samples (Booker, 1958). In fact, a comparison of the rate of loss of iodine with that of the nonvolatile elements zirconium and cesium from the Seascale vegetation showed approximately equal retention times for these elements, and Middleton, *et al.* (1961) obtained similar results with seven elements on cabbage.

The most in-depth analysis of this subject is found in a recent review by Cole (1972) entitled "Inhalation of Radioiodine from Fallout: Hazards and Countermeasures." Cole's approach to this problem is embodied in his introductory statement: "If there is a radioiodine-inhalation problem in the civil-defense context, the source of the radioiodine vapor would have to be volatilization of radioiodine(s) from the fallout particles deposited outdoors, trapped in the conventional filters of shelter ventilation systems, or somehow entering the shelter proper." Since the entirety of Cole's analysis of the radioiodine inhalation problem was directly dependent upon the degree of volatilization that occurs in fallout radioiodine, his evaluation of this subject is reviewed in detail.

Cole (1972) cited several references which provided indirect measurements of iodine volatility, among which were the following:

> Norman and Winchell (1970) showed that the rate of evaporation of tracer I^{131}, surface-deposited on glass beads, is constant with time, averaging about 1% per week at room temperature with no air flow. In additional studies, these authors [Norman and Winchell (1970a)] measured the extent of evaporation of I^{131} volume-distributed throughout 10μ TeO_2 particles which were subjected to temperatures ranging upward from 110°C, and found a loss of about 0.1% in the first week (the loss rate was a decreasing function of time, indicating that diffusion in the solid was the controlling factor).

An additional reference reviewed by Cole, as indirect evidence for the volatilization of radioiodine, was by Martin (1963). Martin's stated objectives of this study were to estimate:

(a) the concentration of I^{131} on vegetation, in the stomach contents of rabbits, and in rabbit thyroids in relation to distance from ground zero and time after fallout,

(b) the rate of I^{131} loss from fallout-contaminated vegetation and hence from the diet of rabbits and

(c) the rate of I^{131} accumulation in and disappearance from the thyroids of rabbits living in the fallout field.

Martin utilized three experimental approaches in studying the loss of I^{131} from fallout-contaminated vegetation at Project SEDAN. In the first of these experiments, samples of desert vegetation from pre-selected areas of the fallout field were collected in paper bags (on D+5, 10, 15, 20, 25, and 30), air dried and then shipped to the laboratory where they were oven dried, ground in a Wiley mill and counted for I^{131}. A plot of the specific activity of I^{131} found at each station versus time post-detonation indicated that "the rate of I^{131} loss from vegetation was greater than would be expected on the basis of radioactive decay alone". The means of all vegetation samples collected at 5-day intervals approximated an effective half-life of 5.5 days, and the rate of I^{131} disappearance from the diets of rabbits was the same as the effective half-life on vegetation (*i.e.*, 5.5 days). From these results, Martin concluded: "The difference between the effective half-life on vegetation and the radioactive half-life of I^{131} was probably due, in this case, to:

(a) the removal of fallout particles (by wind, rain, or other mechanical disturbances) from contaminated plant surfaces and/or

(b) the removal of I^{131} by vaporization or leaching (or possibly by foliar absorption and translocation to other parts of the plant) from particles which were trapped and retained on plant surfaces."

This latter possibility was probably suggested by the condition of some of the collected samples, for he stated: "The wetter samples were sometimes placed in the sun for 8-10 hours before being shipped to the laboratory at Los Angeles." In any event, Martin's second and third experiments were performed to gain information concerning the possible significance of vaporization as a mechanism of I^{131} loss from fallout-contaminated vegetation.

Martin's second experiment consisted of five plant samples collected (in duplicate) on D+7 from the vicinity of SEDAN ground zero. Two aliquots from each sample were sealed in glass jars with sufficient 6N NaOH to convert any iodine present to a non-volatile form. Two additional aliquots from each sample were placed in metal boxes. For a period of ten days the jars remained sealed while the contents of the boxes were exposed to air at room-temperature. All samples were then analyzed to determine their I^{131} content. The average I^{131} content of the sealed samples containing NaOH was approximately twice that of the samples exposed to air. Martin's comment regarding the results of this experiment was: "This suggests that I^{131} may indeed be lost from fallout-contaminated plants as a result of vaporization."

The validity of this suggested explanation for the results of this experiment is subject to considerable speculation, including the following factors:

The number of samples was small.

The difference in I^{131} content of the replicates stored in NaOH was relatively large in three of the five cases.

Martin conceded that "a few of the higher levels encountered at some of the stations in our study areas could represent the combined effects of fallout following the underground test of June 13 and of fallout following the SEDAN test on July 6, 1962".

From one station, there was essentially no difference in the I^{131} content of the samples exposed to air and the samples sealed in NaOH. If vaporization of I^{131} did occur under the conditions of this experiment, it would not be surprising that it varied in degree among the various samples; however, it is difficult to explain essentially no difference in the I^{131} content of all four samples from one station (two of which were exposed to air and two sealed with NaOH).

Finally, it should be emphasized that these samples had been exposed to the indeterminate effects of the desert environment until collection on D+7.

Martin's third experiment involved the use of an additional four bags of samples which had been collected on D+7 and processed as in the preceding experiment. Beginning on D+33, two 5g sub-samples from each bag were analyzed for I^{131} at intervals of about 5 days, for a total of six determinations. For the first four of these the sub-samples to be analyzed were lifted from the top of the material in the bags with a minimum disturbance to the remaining contents of the bags. During this period the decline of the I^{131} concentration of the sample material was greater than could be accounted for on the basis of radioactive decay alone. At each time prior to removing the sub-samples for the last two analyses, the material in the bags was thoroughly mixed before the sub-samples were removed. There was a marked decrease in the loss rate of I^{131} during this latter period. In fact, it was found to be very close to the radioactive decay rate for I^{131}. Martin attributed the increased rate loss of I^{131}

during the first part of the experiment to the settling of fallout particles toward the bottoms of the sample bags and the decreased rate loss of I^{131} during the latter portion of the experiment to the thorough mixing of the contents of the bags before taking sub-samples for analyses. From this third study, Martin concluded: "These results provide no evidence of I^{131} loss attributable to vaporization."

From his review of these experiments, Cole conceded that there was an apparent loss of I^{131} from the dry samples of the second experiment; however, he could not accept the statistics as thoroughly convincing. Despite the equivocal results as to whether or not vaporization of I^{131} occurred, these experiments were reviewed in detail because of Martin's recognition of the possible significance of the decreased effective half-life of I^{131} fallout on vegetation which he stated as follows: "If the difference between the physical decay rate of I^{131} and its *effective half-life* on vegetation is due primarily to the removal of fallout particles from contaminated plant surfaces, the *effective half-lives* of other isotopes on fallout-contaminated vegetation might be similarly affected." "In regard to food-chain relationships under early post-fallout conditions, the major implication of these findings and speculations is that I^{131} (and perhaps other radioisotopes) can be expected to disappear from the diets of herbivores at a rate significantly greater than the radioactive decay rate.

Cole then sought for experimental data from weapons tests which might enable him to quantify the degree of volatility of iodine in fallout particles. He failed to find any information or discussion of this subject in the 5-volume DASA-1251 series, which is the definitive publication on fallout and fallout fields, and covers all nuclear weapons tests up through 1958. Of the tests conducted subsequent to the 1958-1961 test moratorium, the only surface or near-surface shots that could have produced the desired information were SMALL BOY, JOHNIE BOY, and DANNY BOY of the Sunbeam Series and the Ploughshare cratering shot SEDAN. Lane (1964) conducted experiments to determine radioiodine volatility in fallout particles from SEDAN and La Riviere, *et al.* (1963) and Freiling, *et al.* (1964) attempted similar determinations on fallout particles from SMALL BOY. Cole elected to re-analyze Lane's SEDAN experiments, since SEDAN was the more thoroughly documented test.

Lane employed two experimental approaches in his attempts to determine radioiodine volatility in fallout particles from SEDAN. The first of these was an Iodine-Gas-Sampling experiment, performed in the field, with equipment designed to collect iodine vapor in a thiosulfate absorber for subsequent radioanalysis. Lane's second approach to the problem was a Volatilization or Air-Exposure experiment for which his stated objective was the determination of the radioiodine that remained in fallout particles after varying periods of exposure to air, *i.e.*, the determination of the rate of release of radioiodine from fallout particles in the field. This latter experiment was performed by exposing ten 20 gram samples of fallout

in petri dishes to normal air currents and sunlight, at times, beginning at H+35 hours, for ten successive days one of the fallout samples was added to a test tube containing sodium thiosulfate to trap any iodine that would be released thereafter from the particles.

Cole (1972, Appendix B) analyzed Lane's experiments systematically, step-by-step, and made the following interpretations of the data:

(1) With regard to Lane's Iodine-Gas-Sampling experiment, Cole concluded that "the iodine volatilization rate for SEDAN fallout particles (*i. e.*, dry siliceous fallout particles) is of the order of 0.00025% per day.

(2) Cole demonstrated that the results of Lane's Volatility or Air-exposure experiments were due to leaching of the fallout particles in the thiosulfate solutions rather than a measure of volatility, *i.e.*, "the changes in iodine recovery in the thiosulfate solutions used to analyze the iodine content of the particles can be accounted for entirely on the basis of variation of extent of leach with duration of immersion of such particles in the thiosulfate solutions [Lane (December, 1971) concurred with this interpretation of the data].

In addition to the above interpretation of Lane's SEDAN experiments, Cole emphasized these aspects of the SEDAN data: "SEDAN fallout cannot be considered to represent true surface-burst fallout in all respects. In particular, material from a cratering burst may be as much as a factor of 10^5 lower in specific activity than that from a surface burst of the same yield, since in the former a much larger mass of rock or soil mixes with the same quantity of fission products before the particles become airborne (Crocker, *et al.*, 1966). Also, fractionation behavior and radial distribution of specific chains may not be the same as in surface-burst fallout." (See Cole, 1972, Appendix C for fundamental information on chains.)

NOTE: The only positive evidence cited by Thompson regarding volatilization of iodine was the work of Lane (1964) which Cole refuted and showed to be a minimal value.

EXCHANGE

Although the exchange of stable iodine with radioiodine deposited on reactor walls has been noted (Megaw and May, 1962), Thompson failed to find any evidence to indicate that there was any appreciable exchange of stable iodine with radioiodine deposited on plants. The references cited included Chamberlain (1953) who stated that iodine "is strongly

the loss of activity corrected for decay correlated with growth season and light intensity. In additional studies wax particles carrying radioactivity were collected with air samples, indicating that fallout radioactivity may be lost in this manner since the loss of wax particles from leaf surfaces is also correlated with growing season and light intensity. The maximum rate of loss of the wax particles corresponded to a 24-day half-residence time in midsummer, followed by no loss in fall and winter.

WEATHERING

Rain

Thompson presented evidence from three sources, including both laboratory-type experiments and field observations following fallout deposition, to document the rate of wash-off of fallout radioactivity by rain.

Middleton (1959) reported the results of an experiment in which wheat was sprayed with solutions of Sr^{89} and Cs^{137}, and the retention of these radionuclides by plants protected from weather was compared with the retention by plants exposed to weather. Plants protected from weather retained six times as much strontium and three times as much cesium as those exposed to weather.

Pierson and Keane (1962) analyzed the data for early fallout in England from the 1961 Russian nuclear tests and determined a rate of wash-off from grass of 2.0% per mm of rain for I^{131} and 0.9% per mm for Ba^{140}.

Mocken and Alderhout (1961) calculated that the mean fraction of Sr^{89} washed off wheat was 1.7% per mm of rain, and for mixed fission products they obtained a wash-off fraction of 2.4% per mm of rain.

Wind

Experimental data concerning the effects of wind *per se* on the behavior of particulate fallout on vegetation are meagre. Following the MET shot Romney, *et al.* (1963) observed the effect of gusty winds in removing particle-borne fallout from alfalfa plants and reported that the loss corresponded to the removal of the larger fallout particles.

[illegible]
when in carrier-free form", and Chamberlain and Wiffen ([illegible]) also quoted work of Hudswell demonstrating that thermal desorption of iodine does not usually occur below 400°C. From the Windscale data, [illegible] (1959) determined that the rate of loss of radioiodine from plant surfaces was too low for an exchange with stable iodine to have occurred.

[illegible]

Growth

Plant growth rates are cyclic, seasonal, and dependent upon a number of variables, including geographic location, weather, and farming practices. The effect of plant growth can be quantified by correlating the radioactivity per unit weight of plant material with the radioactivity per unit area for the same plants at various time intervals. Thompson cited data to illustrate opposite extremes of the effect of growth rate. Data published on a pasture at Seascale (Fowden, 1959) suggested a negative form of growth due to die-back, while the short apparent half-life of 3.5 days for I^{131} on grass as reported by Hawley, *et al.* (1964) is due to the rapid spring growth of the grass.

Metabolic Processes

Only minute quantities of iodine are normally found in terrestrial plants. Beeson reported an unusually high value of 94.9 ppm of iodine for turnips fertilized with KI, which contrasted with a value of 0.74 ppm for unfertilized turnips from the same area. Thompson (1965) stated that the iodine content of forage plants is usually less than 1 ppm, and Ng, *et al.* (1968) selected the value of 0.1 ppm as representative of the values reported in the literature for the iodine content of terrestrial plants.

The results of experiments concerning the behavior of radioiodine on the foliar surfaces of plants indicated that the radioiodine was fixed within or on the leaf [Fowden (1959), Hungate (1963), and Selders and Rediske (1954)], and experimental decontamination procedures with plants revealed that most of the fallout I^{131} was on the leaf surface and could be washed off or removed with the cuticular layer [Hungate (1963), Romney, *et al.* (1963), and Selders and Rediske (1954)].

The significance of plant leaf surface retention of radioactive fallout in relation to the metabolic processes of plants was provided by Moorby and Squire (1963), who studied the loss of radioactive isotopes from the leaves of plants under dry conditions. Cabbage, potato, and ryegrass were sprayed with Sr^{89} and grown under dry conditions. An appreciable loss of fission product activity occurred which could not be explained on the basis of radioactive decay alone. It was found that

The weight of the foregoing evidence reviewed in this appendix concerning fallout I^{131} indicates that volatilization and exchange are minor factors and that fallout I^{131} occurs in association with particles, from which one would expect the behavior of I^{131} on plants to be similar to that of the less volatile or refractory radionuclides which are known to be associated with particles. Thompson presented data to show that this is indeed the case.

Thompson stressed these points in his summation of the data presented:

(a) The remarkable similarity in the mean reduction times for I^{131} in milk and on plants from exceedingly diverse experimental and field conditions. Most of the effective half-lives for I^{131}, as shown in his tables, fall within the range of 5 ± 1 days. This suggested that wind, rain, or the combination of wind and rain have a similar quantitative effect on the removal of fallout iodine from plants.

(b) With regard to Thompson's other data, the half-residence time for a variety of radionuclides shows a similarity to that of iodine. Since the physical properties of the other nuclides are quite different from those of iodine, this suggested to Thompson that there is a common factor influencing the behavior of fallout radionuclides and, since the majority of fallout nuclides are associated with particles, this common factor is the behavior of particles on plants.

From this study Thompson concluded that the following inter-relationship exists between the effective half-life and the half-reduction time of radionuclides on plants:

(a) The effective half-life is defined as the apparent half-reduction time as observed on the plant, and reflects loss of the nuclide involved by all means including the radioactive decay.

"Since the behavior of fallout reflects the behavior of particles and the effect of any combination of weathering factors is quantitatively similar, the effective half-life on plants for *any* fallout radionuclide can be approximated by

$$T_3 = \frac{15\ T_2}{15 + T_2}$$

where T_3 = effective half-life on plants,

T_2 = radiological half-life, and

15 = mean half-residence time

(In the case of I^{131}, with a half-life of 8.04 days its effective half-life on plants would be 4.97 days (*i.e.*, 5 days).) The formula approximates the half-life on plants and does not apply to the uptake and retention of radioelements from the soil. The half-life as calculated by this equation could be applied directly to milk in the absence of plant growth. However, in the presence of growth the milk half-life would have to be corrected for the growth rate of the pasture."

(b) The half-residence time is defined as the effective half-life corrected for radioactive decay.

"The effective half-life of a radioisotope on a plant as contrasted with its radioactive half-life has been treated mathematically (Martin 1963, 1964) to determine the mean residence time of a stable isotope as follows:

Let T_1 represent half-residence time,

T_2 represent radioactive half-life,

T_3 represent effective half-life;

$$\text{then} \quad T_1 = \frac{(T_2) \times (T_3)}{T_2 - T_3}$$

For I^{131}, with T_2 = 8.04 days and T_3 = 5 days, T_1 = 13.2 days.

APPENDIX C - [illegible] OF [illegible] PARTICLES ON VEGETATION

Ng and Tewes assumed the initial retention of large particles on plants to be 12 to 15% and the half-residence time for large particles on plants to be 4 days. These values were based on data which are summarized below.

The data include not only the results obtained from field experiments by Witherspoon and Taylor and by Johnson and Lovaas, but Miller's data as well, from a study of the retention of volcanic particles on plants. In the table, whenever possible the initial retention was expressed both as the percentage of fallout that is initially intercepted and retained on foliage and as the plant contamination factor, which Miller defined as

$$a = \frac{\text{activity per unit mass dry matter on foliage}}{\text{activity per unit area of ground}}$$

The data of Witherspoon and Taylor and Johnson and Lovaas suggested to Ng and Tewes that 0.5 to 0.6 m^2/kg was a typical value for the plant contamination factor for 88 to 350μ particles on forage plants. Although this value is representative of the majority of the data presented, its acceptance should be evaluated in terms of the following qualifying information:

> In the first place, Ng and Tewes excluded initial retentions obtained when the relative humidity was greater than 90%. This included data by Johnson and Lovaas who reported that, with heavy dew, the retention on bromegrass of particles 88 to 350μ in diameter was as much as 100%, and Miller noted that the plant contamination factors of volcanic particles were enhanced by a factor of 2 under "damp" conditions.
>
> Further, Ng and Tewes did not include results obtained with winds in excess of 20 mph. An indication of the effect of this factor is provided by Romney, *et al.* (1963) (cited by Thompson in Appendix C), who observed the effect of gusty winds on removing particulate fallout from alfalfa plants following the Met shot and reported that this loss corresponded to removal of the large particles.

There are data which differ considerably from the value adopted by Ng and Tewes; however, in both instances, the results were obtained with particles averaging less than 88μ in diameter.

APPENDIX E - THE DETERMINATION OF THE ULTIMATE RADIATION DOSE TO MAN WHICH MAY RESULT FROM THE DEPOSITION OF SMALL RADIOACTIVE FALLOUT PARTICLES IN TERRESTRIAL FLORA

1. The Forage-to-Cow-to-Milk Pathway

The basic assumptions made in the model for the forage-to-cow-to-milk pathway were:

(a) unfractionated deposition of both fission and activation products
(b) the fallout deposited on pasture is continuously ingested by the grazing cow.

The initial daily rate of ingestion of a given nuclide by the cow, I_o (μCi/day) is given by:

$I = R \times UAF \times F_o$, where

R = initial retention factor, i.e., 0.67 for small particles

UAF = utilized area factor = 45 m^2/day (This is the median value reported by Koranda (1965) for the pasture area grazed by dairy cows in the United States).

F_o = the initial fallout deposition in μCi/m^2 (the derivation of the F_o value for I^{131} is shown below*).

I_o (for I^{131}) = $0.67 \times 45 \times 1.5 \times 10^3$

$I_o = 4.5 \times 10^4$ μCi/day

*In an earlier section of this report it was shown that "a unit-time dose rate of 100R/hr from unfractionated fission products is equivalent to a deposition of 1.05×10^{-8} kt of fission products per square meter of surface".

To find the F_o for I^{131} (the initial fallout deposition in μCi/m^2), convert 10^{-8} kt of fission products/m^2 to μCi/m^2.

From Appendix A, a 1 MT fission explosion produces 1.5×10^8 Curies I^{131}

1.5×10^8 Ci I^{131}/MT = 1.5×10^5 Ci I^{131}/kt

1.5×10^5 Ci I^{131}/kt $\times 10^{-8}$ kt/m^2 = 1.5×10^{-3} Ci/m^2

or

1.5×10^3 μCi/m^2

Concentrations of particles in milk

The estimated peak concentrations in milk from the deposition of small particles are based on f_M, the "transfer coefficient" to milk, the fraction of the element ingested daily by the cow that is secreted in milk per liter. Ng and Tewes list the f_M for I^{131} in milk as 5×10^{-3}*.

The peak concentrations in milk, C_M, are given both as the fraction of the initial daily rate of ingestion per liter (*i.e.*, fraction of I_o per liter) and in μCi/liter. The peak concentration for I^{131} in milk, expressed as a fraction of I_o per liter, is 2.5×10^{-3}. This value was reached in 2.93 days. The calculations and the methods employed for the determination of these values are included in Appendix G.

The peak concentration of I^{131} in milk, expressed in μCi/liter, is the product of the initial daily rate of ingestion by the cow, I_o, and the fraction of I_o per liter, *i.e.*,

$$C_M(\mu Ci/liter) = I_o \times I_o/liter$$

$$= 4.5 \times 10^4 \mu Ci/day \times 2.5 \times 10^{-3}$$

$$= 1.1 \times 10^2 \mu Ci/liter$$

Estimated Dosages via Milk

The total activity ingested and the radiation dosage estimates via milk from the deposition of small particles are shown in Table E-1. For I^{131}, the value for the total amount ingested is listed at 1.3×10^3 μCi. This value is based on the assumption that the individual consumed one liter of milk per day. The calculation for this value is shown on the following page.

*In an earlier report from the LLL Biomedical Division, Tamplin had set the f_M value for I^{131} in milk at 2×10^{-2}.

$$\int_0^\infty C_p^*(t)\,dt = \int_0^\infty \frac{AI_o}{\lambda_{ME}-\lambda_p}\left(e^{-\lambda_p t} - e^{-\lambda_{ME} t}\right) dt$$

$$= \frac{AI_o}{\lambda_{ME}-\lambda_p}\left[\frac{e^{-\lambda_p t}}{-\lambda_p} + \frac{e^{-\lambda_{ME} t}}{\lambda_{ME}}\right]$$

$$= \frac{AI_o}{\lambda_{ME}-\lambda_p}\left[\frac{1}{\lambda_{ME}} + \frac{1}{\lambda_p}\right]$$

$$= \frac{AI_o}{\lambda_{ME}-\lambda_p}\left[\frac{\lambda_{ME}-\lambda_p}{\lambda_{ME}\,\lambda_p}\right]$$

$$= \frac{AI_o}{\lambda_{ME}\,\lambda_p}$$

TABLE [illegible]

TOTAL ACTIVITY INGESTED IN pCi

$$\text{[illegible]} = \frac{A}{\lambda_{Sr} \lambda_p} \qquad A = \lambda_{Sr} \lambda_{[illegible]}$$

λ_{Sr} = [illegible]

$\lambda_{SrB} = 0.6072$

$A = 5 \times 10^{-1}$

$\lambda_{[illegible]} = 1.5 \times 10^{-1}$

$\lambda_{SrL} = 0.6931$

$\lambda_p = 0.1554$

$$= \frac{[illegible]}{0.6931 \times 0.1554}$$

$= 1.4 \times 10^{3}$ $\qquad$ λ_{Sr} has 1.5×10^{3}

(Basis and definitions follow)

(Table E-1 continued)

$$C_M^*(t) = \frac{\Lambda I_o}{\lambda_{ME} - \lambda_p} \left(e^{-\lambda_p t} - e^{-\lambda_{ME} t}\right) \qquad (1)$$

I_o = initial rate of ingestion by cow, μCi/day

$\Lambda = f_M \lambda_{MB} = f_M^* \lambda_{ME}$
(element) (isotope)

f_M, f_M^* = Transfer coefficient, *i.e.*, fraction of daily intake/liter

λ_{MB}, λ_{ME} = biological and effective turnover rate in milk (per day)

λ_p = effective removal rate from vegetation

t = time after deposition

(Table E-1 continued)

Determine from Equation (1) the maximum concentration of isotope in milk (C_M^* max)

$$\frac{dC_M^*(t)}{dt} \quad \frac{AI_o}{\lambda_{ME}-\lambda_p} \qquad \left[-\lambda_p e^{-\lambda_p t} + \lambda_{ME} e^{-\lambda_{ME} t}\right] = 0$$

Set = 0. Then,

$$\lambda_p e^{-\lambda_p t} = \lambda_{ME} e^{-\lambda_{ME} t}$$

$$\frac{e^{-\lambda_p t}}{e^{-\lambda_{ME} t}} = \frac{\lambda_{ME}}{\lambda_p} = e^{-(\lambda_p - \lambda_{ME})t} \qquad (2)$$

For I^{131}

T_{ME} = 1.0 day (experimentally determined)

T_R = 8.065 day

λ_{ME} = 0.693 day $^{-1}$

$\lambda_R = \frac{0.693}{8.065}$ = 0.0859 day $^{-1}$

$\lambda_p = \frac{0.693}{14} + 0.0859$ = 0.1354 day $^{-1}$

(Table E-1 continued)

Use Equation (2) to determine t_{MAX}

$$\frac{\lambda_{ME}}{\lambda_p} = \frac{0.0931}{0.1354} = 5.119 = e^{-(\lambda_p - \lambda_{ME})t_{MAX}}$$

$$e^{-(0.1354 - 0.6953)t_{MAX}} = 5.119$$

$$e^{+0.5577t_{MAX}} = 5.119$$

$$0.5577t_{MAX} = 1.633$$

$$t_{MAX} = 2.93 \text{ day}$$

(Table E-1 concluded)

Go back to Equation (1) to get $C_M^*{}_{MAX}$

$$C_M^*(t) = \frac{AI_o}{\lambda_{ME} - \lambda_p} \left(e^{-\lambda_p t} - e^{-\lambda_{ME} t}\right)$$

$$\lambda_{ME} = 0.6931 \text{ day}^{-1}$$

$$\lambda_R = 0.0859 \text{ day}^{-1}$$

$$\lambda_{MB} = 0.6072 \text{ day}^{-1}$$

$$A = f_M \lambda_{MB} = (5 \times 10^{-3})(0.6072)$$

$$\lambda_{ME} - \lambda_p = 0.6931 - 0.1354 = 0.5577 \text{ day}^{-1}$$

$$e^{-\lambda_p t_{MAX}} = e^{-0.1354 \times 2.93} = 0.6727$$

$$e^{-\lambda_{ME} t_{MAX}} = e^{-0.6931 \times 2.93} = e^{-2.031} = 0.1312$$

$$C_M^*{}_{MAX} = \frac{(5 \times 10^{-3})(0.6072) I_o}{0.5577} (0.6727 - 0.1312)$$

$$= 5.444 \times 10^{-3} I_o (0.5415)$$

$$= 2.95 \times 10^{-3} I_o$$

I^{131} Radiation Dose to Adult Thyroid Gland Via Milk and Via Meat

Dose - Equiv.

$$\frac{51\ EF\ f_B}{W\lambda E}$$

Let $T_B = 100$:

$$\frac{(100)(8.05)}{108.05} = 7.45 \text{ per } \beta$$

I^{131}: $$\frac{(51)(0.23)(0.3)(7.45)}{(20)(0.693)} = 1.89$$

$T_B = 100$:

$$\frac{(100)(0.875)}{100.875} = 0.868 \text{ per } \beta$$

I^{133}: $$\frac{(51)(0.54)(0.24)(0.868)}{(20)(0.693)} = 0.414$$

Milk I^{131}: $1.30(10^3)$ x 1.89 = 2460 rad

I^{133}: $1.60(10^3)$ x 0.414 = 662 rad

x .75 = 496 ≈ 500

Meat I^{131}: $1.08(10^2)$ x 1.89 = 204 rad

2. The Plant-Herbivore-Meat Pathway

Since the source of radionuclides for both the milk and meat pathways is radioactive fallout deposited on pasture vegetation, the well-established data for the forage-to-cow-to-milk model greatly facilitated the development of this model for assessing the radiological hazard to man which may occur from the ingestion of meat obtained from herbivores which have grazed on fallout-contaminated forage. Ng and Tewes stated that this model represents a preliminary attempt to assess the hazard of fallout-contaminated meat, with the limitations of its applicability set forth below.

In the model, the "standard herbivore" was assumed to weigh 500 kg, with a muscle mass of 200 kg. The following procedure was employed in estimating the concentration of the individual radionuclides in muscle:

(a) The concentration in muscle was estimated from the daily rate of ingestion of contaminated vegetation and the turnover rate in muscle.

(b) the value for the fractional uptake in muscle was estimated on the basis of experimental data from animal studies.

(c) the biological half-life in muscle was then estimated from these fractional uptakes and the stable element concentration in meat and forage (as reported in the LLL Handbook). [NOTE: The fractional uptakes and turnover rates of Sr^{90}, I^{131}, and Cs^{137} are comparable with previously assumed values (Miller and La Riviere (1966)]

As in the case of the milk model, the assessment of the hazard from small fallout particles was made first.

Estimated Radiation Dosages from Deposition of Small Particles

The input data common to both the milk and meat pathway models were these:

(a) The standard herbivore, like the cow, was assumed to utilize 45 m^2 of pasture daily.

(b) The initial retention factor for small particles on forage was assumed to be 67%.

(c) The half-residence time on forage was assumed to be 14 days.

Generally, both cattle and sheep destined to be marketed for meat products are kept on pasture throughout the year, with supplemental feed provided only when inclement weather denies them access to forage or during a fattening period just prior to slaughter. In the model, it was assumed that the fallout-contaminated pasture was continuously grazed by the livestock.

The estimated peak concentrations of nuclides in herbivore muscle have been calculated. These estimates are based on the hypothetical fallout deposition of 10^{-6} kt of fission per square meter.

These then led to the total activity ingested (in μCi), and in turn to the radiation dosages to the whole body and bone of man. In the calculation of these values it was assumed that the animal was slaughtered when the concentration in muscle was maximal, and that meat consumption began immediately and continued for a 6-month period at the rate of 300 g per day. The total radiation dosage to the whole body of man was estimated to be 11 rad and that to bone was estimated to be 14 rad. The nuclides which contributed most to these estimated radiation dosages in man were Sr^{89}, Sr^{90}, I^{131}, Cs^{136}, and Cs^{137}.* The radiation dosage to the thyroid gland of adult man was calculated to be 200 rad. This serves as a point of reference for comparing the total radiological hazard from the meat pathway with that of the milk pathway, since in both instances the thyroid dose from radioiodine(s) was the highest estimated dose.

Estimated Radiation Dosages from Deposition of Large Particles

The radiation dosages from the deposition of large particles have also been estimated. These estimates were made in the same manner and based upon the same assumptions as those for the deposition of small particles, except that the initial retention of large particles was assumed to be 13% and the half-residence time on forage was assumed to be 4 days. The total radiation dosage to the whole body of man was estimated to be 1.2 rad, with almost the entirety of the dosage contribution from Cs^{136} and Cs^{137}. The total radiation dosage to bone in man was estimated to be 1.6 rad. Here again the major contribution to the dosage was from Cs^{136} and Cs^{137}, with the slightly greater dosage

*Estimates were made also of the dosages from Ru^{103} and Ru^{106}; they suggest their contribution to the total radiation dosages may be appreciable. However, the estimates are subject to question since the input parameters for these isotopes of Ru have not been as well established as those of the other nuclides.

to bone due tothe additional dosage contribution of Sr^{89} and Sr^{90}. The radiation dosage to the thyroid gland of adult man was calculated to be 28 rad.

APPENDIX F - SUMMARY AND COMPARISON OF THE DOSAGE ESTIMATES VIA THE MILK AND MEAT PATHWAYS

A summary was made of the dosage estimates via milk and via meat, for both fission and neutron activation products.

The summary served to focus attention upon the fact that for both the milk and the meat pathways and for both small and large particle deposition, the radiation dosage to the thyroid from iodine isotopes is by far the highest of all the estimated doses.

The thyroid dose via milk exceeds the total doses to whole body and bone by two orders of magnitude.

The thyroid dose via meat exceeds the total doses to whole body and bone by one order of magnitude.

It must be emphasized that the thyroid dosages are the calculated doses to the thyroid gland of the adult; for the child, each of these dosages would be higher by a factor of 10.

The estimates of dosage from small particle deposition almost uniformly exceed those from large particles by an order of magnitude.

The total dosages to whole body and bone are about the same via milk and via meat (for small particles and large particles, respectively).

The dosages from fission products exceed the dosages from neutron activation products* by about an order of magnitude.

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*Ng and Tewes (1970) made a detailed assessment of the possible radiological hazard from neutron activation products and presented estimates of the radiation dosages from this source, including estimates for a number of activation products which had not been considered in previous analyses of this problem. Their assessment included dosage contributions from activation products of unreacted fissionable material, of device material, and of environmental material. Estimates of the dosage from activation products were made in terms of the same hypothetical weapon as that used for the fission products dosage estimates,

(Footnote continued)

(Footnote continued)
i.e., a 1 MT, half-fission, half-fusion device.

It was emphasized that "most of the [dose contribution from activation] products is attributable to nuclides derived from rock and soil". Consequently, the dosage contribution from these products could vary over a considerable range, the extent of which would primarily depend upon:

(a) the height of the detonation of the weapon (with the maximal dosage contribution from activation products occurring in the case of a ground surface detonation). ". . . the calculations of Lessler and Gray (1963) indicate that for air bursts at a height of 1000 m, only about 1% of the neutrons released to the environment are captured by soil at ground level." Conversely, on the basis of the available weapons data, Ng and Tewes determined that 1/6 of the neutrons produced are released to the environment, and "one-half of the neutrons escaping the device . . . are assumed to be captured in rock and soil following a surface detonation."

(b) weapon design and environmental factors. "Details of device construction and variations in soil composition could drastically affect the amounts that would be formed of almost every species."

It was also emphasized in this analysis that the biological availabilities have not been determined for most of the activation products for which the highest dosage estimates were made (this list includes ^{24}Na, ^{32}P, ^{45}Ca, ^{47}Ca, ^{84}Rb, and ^{86}Rb).

In general, the assumptions made by Ng and Tewes in their analysis of this problem tended to maximize the radiation dosage estimates which might arise from activation products. However, despite this, their dosage estimates for the individual nuclides were all in the millirad range.

Since for a given weapon detonation the dosage contribution from activation products would be a function of the composition of that particular device, the height of detonation, and the physical characteristics of the site of detonation, only the totals of the dosage estimates made by Ng and Tewes have been used here. These serve to illustrate the dosage commitment that could result from activation products (under maximized conditions) relative to those from fission products.

(Footnote concluded)

A CHRONIC-CONTAMINATION MODEL

A chronic-contamination model was developed to provide estimates of the internal radiation dosages which could result from the ingestion of foods contaminated by stratospheric fallout deposited during the first year following a nuclear attack. It is readily apparent that the reliability of the model for dosage estimates is largely dependent upon the accuracy of the determination of the rate of surface deposition from the radionuclides injected into the stratosphere.

The Amount of Radioactivity Injected Into the Stratosphere

Peterson (1970) has estimated that, for a land-surface detonation in the megaton range, about one-half of the radioactivity would be injected into the stratosphere. In the model it was assumed that 50% of the nuclides produced by enemy weapons and an equivalent amount from retaliatory action by allied forces would enter the stratosphere, thus leading to the assumption that all the activity produced by surface bursts would enter the stratosphere.

The Rate of Deposition of Radionuclides From the Stratosphere

The method of estimating the deposition rate of radionuclides from the stratosphere is derived from Peterson's (1970) empirical model for estimating world-wide deposition from atmospheric nuclear detonations (Peterson's model is based primarily on injection-deposition experience gained from the U.S. and U.S.S.R. nuclear tests in 1958. Use of the model in 1963 to estimate Sr^{90} deposition from the 1961-62 tests showed the predictions usually within a factor of two of the observed deposition.)

According to Peterson's model the maximum annual surface deposition of Sr^{90} in the 30 to 50° N latitude band for a 1 MCi injection into the lower polar stratosphere (9 to 17 km altitude) would be expected to vary between 250 and 400 kCi. For a 1 MCi injection into the upper polar stratosphere (17 to 50 km altitude), the maximum annual deposition could be expected to vary between 50 and 170 kCi.

For the model, an intermediate value of 200 kCi of Sr^{90} was used for the amount of this radionuclide deposited in the 30 to 50° N latitude band per MCi injected into the stratosphere.

For the determination of an average value for the annual surface-air concentration of fallout radionuclides, the first step in the calculation was to show that an annual deposition of 1 kCi in the 30 to 50° N latitude band is equivalent to a deposition rate of 1.7×10^{-3} μCi/m²-hr.

Convert mi^2 in 30-50° N latitude band to km^2

$$26{,}600{,}000\ (mi^2 \text{ in } 30 \text{ to } 50^\circ \text{ N latitude band}) \times 2.589\ (km^2/mi^2) = 68{,}867{,}400\ km^2$$

Find μCi/km²/kCi

$$\frac{68{,}867{,}400}{1 \times 10^9\ (\mu Ci/kCi)} = 14.5\ \mu Ci/km^2/kCi$$

Reduce to $\mu Ci/m^2/kCi$

$$\frac{14.5\ \mu Ci/km^2/kCi}{1 \times 10^6\ (m^2/km^2)} = 1.45 \times 10^{-5}\ \mu Ci/m^2/kCi$$

Express in terms of $\mu Ci/m^2$-hr.

$$\frac{1.45 \times 10^{-5}\ \mu Ci/m^2/kCi}{8760\ (hr/yr)} = 1.7 \times 10^{-9}\ \mu Ci/m^2\text{-hr}$$

Thus, an annual deposition of 1 kCi in the 30 to 50° N latitude band is equivalent to a deposition rate of $1.7 \times 10^{-9}\ \mu Ci/m^2$-hr.

Use of the above deposition rate in conjunction with the deposition velocity for Sr^{90} provides the desired average value for the surface-air concentration. A deposition velocity of 40 meter/hr has been determined empirically from monthly deposition rates and average surface air concentration of Sr^{90} in the Northern Hemisphere (Kleinman and Volchok, 1969).

deposition rate x deposition velocity = surface-air concentration

$$1.7 \times 10^{-9}\ \mu Ci/m^2\text{-hr} \times \frac{1\ hr}{40} = 4.25 \times 10^{-11}\ \mu Ci/m^3/kCi$$

However, since it was assumed that 200 kCi Sr^{90} would be deposited per year per MCi injected into the stratosphere,

$$4.25\times10^{-11}\,\mu Ci/m^3/kCi \times 200kCi = 8.5\times10^{-9}\,\mu Ci/m^3$$

or

$$1\times10^{-8}\,\mu Ci/m^3$$

This is the average surface-air concentration of Sr^{90} in the 30 to 50° N latitude band for any 12-month period following the injection of 1 MCi into the stratosphere. The validity of this value is substantiated by and falls within the range of 1963 measurements made by Thomas *et* (1970) in their study of the relation between ground level air concentrations and the stratospheric burden of various radionuclides of the 1961-62 series.

In this model, $1\times10^{-8}\,\mu Ci/m^3$ is the value assumed for the surface-air concentration for *all* the nuclides of interest.

Deposition of Nuclides on Vegetation

F_{eq}, the steady-state deposition of particles on forage is expressed by:

$$F_{eq} = Vg \frac{L}{\lambda_M}$$

Vg = deposition velocity = 40 meters/hr [express in terms of 1 day (*i.e.*, x 24) since λ_M is expressed in terms of days]

L = air concentration of the nuclide. Use unit air concentration, *i.e.*, $\frac{1\mu Ci}{m^3}$

λ_M = rate of loss of nuclide by weathering = 0.05 day^{-1}, which is equivalent to a half-residence time on forage of 14 days.

$$F_{eq} = \frac{40 \text{ meters/hr}(x24) \times \frac{1\mu Ci}{m^3}}{0.05 \text{ day}}$$

$$F_{eq} = \frac{960\mu Ci/m^2 \text{ day}}{0.05 \text{ day}} = 19200\ \mu Ci/m^2$$

The Concentrations of Nuclides in Milk

C_M, the concentrations of nuclides in milk, are determined by the expression:

$$C_M = (f_M)(UAF)(R)(F_{eq})$$

f_M = fraction of the element ingested daily by the cow that is secreted in milk per liter

UAF = "utilized area factor" = 45 m^2/day, the area grazed by the cow daily

R = 0.67, the retention factor for small particles on forage

Feq = the steady-state deposition of particles on forage = 19200 $\mu Ci/m^2$, when calculated in terms of the unit air concentration (1 $\mu Ci/m^3$)

Using this expression, the calculations for the concentration of Sr^{90} and Cs^{137} in milk are shown below.

$\underline{Sr^{90}}$

(The f_M value for Sr^{90} is 9×10^{-4})

$$C_M = (f_M)(UAF)(R)(F_{eq})$$

$$C_M = (9 \times 10^{-4})(45)(.67)(19200)$$

$$C_M = 920 \frac{\mu Ci/liter}{\mu Ci/m^3}$$

This value is the concentration of Sr^{90} in milk in terms of the unit air concentration (1$\mu Ci/m^3$), and is used below in determining the concentration of Sr^{90} in milk which would result following a nuclear attack with a fission yield of 2000 Mt.*

8.8×10^4Ci Sr^{90} produced/Mt fission

*Ng and Tewes postulated a nuclear attack involving a total yield of 4000 Mt from half-fission half-fusion devices with individual yields between 1 and 10 Mt.

$\frac{8.8x10^{4}}{1x10^{6}}$ = 8.8 x 10^{-2} MCi Sr^{90}/Mt fission

$8.8x10^{-2}$ x 2000 = 176 MCi Sr^{90} produced/2000 Mt fission

The surface air concentration has been determined to be $1x10^{-8}$ µCi/m^3/MCi of nuclide injected into the stratosphere.

$1x10^{-8}\mu Ci/_{m^3}$ x 176 MCi Sr^{90} = 1.76 x 10^{-6}µCi $Sr^{90}/_{m^3}$

This is the surface air concentration of Sr^{90} per 2000 Mt fission. The product of this value and the unit air concentration of Sr^{90} in milk provides the average daily concentration of Sr^{90} in milk for a 12-month period following the injection of 2000 Mt fission into the stratosphere.

$1.76x10^{-6}\mu Ci\ Sr^{90}/m^3$ x 520 $\frac{\mu Ci/liter}{\mu Ci/m^3}$ = 9.2 x 10^{-4}µCi Sr^{90}/ liter milk/day per 2000 Mt fission

$\underline{Cs^{137}}$

(The f_M value for Cs^{137} is $7.5x10^{-3}$)

$C_M = (f_M)(UAF)(R)(F_{eq})$

$C_M = (7.5x10^{-3})(45)(.67)(19200)$

$C_M = 4.3x10^{3}\ \frac{\mu Ci/liter}{\mu Ci/m^3}$

This is the concentration of Cs^{137} in milk in terms of the unit air concentration ($1\mu Ci/_{m^3}$).

$1.5x10^{5}$Ci Cs^{137} produced /Mt fission

$\frac{1.5x10^{5}}{1x10^{6}}$ = 0.15 MCi Cs^{137} produced/Mt fission

0.15 x 2000 = 300 MCi Cs^{137} produced/2000 Mt fission

The product of the surface air concentration per MCi of nuclide and the total amount produced provides the surface air concentration of Cs per 2000 Mt fission.

$1x10^{-4}\mu Ci/m^3 \times 500$ MCi $Cs^{137} = 3x10^{-6}\mu Ci\ Cs^{137}/m^3$ per 2000 Mt fission

The product of this value and the unit air concentration of Cs in milk provides the average daily concentration of Cs^{137} in milk for a 12-month period following the injection of 2000 Mt fission into the stratosphere.

$$3x10^{-6}\mu Ci\ Cs^{137}/m^3 \times 4.3x10^3 \frac{\mu Ci/liter}{\mu Ci/m^3} = 1.3x10^{-2}\mu Ci\ Cs^{137}/liter\ milk/day\ per\ 2000\ Mt\ fission$$

The Rate of Ingestion of Sr^{90} and Cs^{137} Via Milk For One Year Post-Attack*

This value is simply the product of the average daily concentration of the nuclide in milk/liter and days/year.

$\underline{Sr^{90}}$

$9.2x10^{-4}\mu Ci\ Sr^{90}$/liter milk/day per 2000 Mt fission x 365 = $3.4x10^{-1}\mu Ci\ Sr^{90}$/year

$\underline{Cs^{137}}$

$1.3x10^{-2}\mu Ci\ Cs^{137}$/liter milk/day per 2000 Mt fission x 365 = 4.7 $\mu Ci\ Cs^{137}$/year

The One-Year Post-Attack Radiation Dose Rates Via Milk to Whole Body and Bone in Terms of B_1, the Unit Dose-Rate Ingestion Rate.

Estimations of the one-year post-attack radiation dosage rates via milk to whole body and bone were made in terms of the unit dose-rate ingestion rate, B_1, which is defined:

*milk consumption is assumed to be 1 liter/day.

B_1 = ingestion rate in μCi/year that results in a 1 rad/year dose-rate.*

$$B_1 = \frac{\mu Ci/year}{rad/year}$$

$\frac{1}{B_1}$ = the dose rate in rad/year that corresponds to a rate of ingestion of 1μCi/year

$$\frac{1}{B_1} = \left(\frac{rad/year}{\mu Ci/year}\right) \text{ x rate of ingestion } (\mu Ci/year) = \text{dose-rate (rad/year)}$$

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*Derivationof the Expression for B_1, the Unit Dose-Rate Ingestion Rate

The equilibrium dose-rate to a tissue in rad/year is related to the equilibrium concentration of a radionuclide in tissue $n_B(EQ)$ by the expression

$$D_R\ (EQ) = 1.85 \times 10^4\ Q n_B\ (EQ), \qquad (1)$$

where Q is expressed in Mev and n_B (EQ) is expressed in μCi/g.

If we assume first-order kinetics and a constant rate of ingestion of B μCi/day, $n_B(t)$ is determined by

$$\frac{dn_B(t)}{dt} = \frac{f_B B}{m} - \lambda_E\, n_B(t), \qquad (2)$$

where m is expressed in g and λ_E in day $^{-1}$. The tissue concentration at equilibrium would then be

$$n_B(EQ) = \frac{f_B B}{m\lambda_E} \qquad (3)$$

If, in Equation 2 this expression is substituted for $n_B(EQ)$ and $D_R(EQ)$ is set equal to 1 rad/year, then solving for B_1 results in the expression for the unit-dose-rate ingestion rate, *i.e.*,

$$B_1 = \frac{5.4 \times 10^{-5}\, m\lambda_E}{Qf_B}$$

Ng (1973) has prepared tables of B_1 values for the whole body and bone, for both the adult and the child. These tables, including B_1 values for 100 elements and their isotopes, will be included in the forthcoming publication of the revised LLL Handbook. Dr. Ng has provided the author with a copy of these tables in advance of publication.

The Annual Radiation Dosage Rates Via Milk to the Adult Whole Body and Bone From Sr^{90}

Bone

$$B_1 = \frac{\mu Ci/yr}{rad/yr}$$

$$4.07 \times 10^{-2} = \frac{3.4 \times 10^{-1}}{rad/yr}$$

rad/yr = 8.35 x 0.7 (correction factor)

rad/yr = 5.8

Whole Body

The dose rate for Sr^{90} in the adult whole body is 1/10 that in bone = 0.58 rad/yr.

The Annual Radiation Dosage Rates Via Milk to the Adult Whole Body and Bone From Cs^{137}

Bone

$$B_1 = \frac{\mu Ci/yr}{rad/yr}$$

$$1.09 \times 10^{1} = \frac{4.7}{rad/yr}$$

rad/yr = 0.431 x 0.729 (correction factor)

rad/yr = 0.31

Whole Body

The dose rate for Cs^{137} in the adult whole body is the same as that in bone = 0.31 rad/yr.

The Concentration of Nuclides in Meat

Sr^{90}

Due to the paucity of field data on the concentrations of nuclides in meat (particularly in the case of Sr^{90}), Ng and Tewes based their assessment of this problem on comparisons of the predicted and observed ratios of the concentrations in meat to that in milk.

The concentration of stable Sr/g^{Ca} in meat is 2x that in milk*

The concentration of Sr^{90}/gCa in meat has also been found to be 2x that in milk**

The stable Ca content in milk = 1.3g Ca/liter

The stable Ca content in meat - 0.1g Ca/kg (Ng, *et al.*, 1968)

Thus, on the basis of the stable Ca content in milk and meat, the ratio of the average concentration of Sr^{90} in meat to that in milk would be expected to be 0.15:

$$\frac{Sr^{90} \text{ in meat}}{Sr^{90} \text{ in milk}} = \frac{2x0.1g \text{ Ca/kg}}{1.3g \text{ Ca/liter}} = 0.15$$

This represents the predicted ratio of the concentration of Sr^{90} in meat to that in milk. The observed ratios, as determined from studies reported in the literature, ranged from 0.05 to 0.26 (Aarkrog, Lippert, and Petersen, 1963, and Aarkrog and Lippert, 1964, 1965. Also, Fallout Program Quarterly Summary Reports, U.S. Atomic Energy Commission Health and Safety Laboratory, New York Operations Office).

*Strontium - 90 in Human Diet in the United Kingdom 1958, Great Britain Agricultural Research Council, Report ARCRL-1, 1959.
**Radiobiological Laboratory Annual Report 1963-64, Great Britain Agricultural Research Council Report ARCRL-12, 1964. Radiobiological Laboratory Annual Report 1964-1965, Great Britain Agricultural Research Council Report ARCRL-14, 1965.

With due consideration for the predicted and observed ratios, the value assumed as the ratio for the concentration of Sr^{90} in meat to that in milk, was 0.2. Since the concentration of Sr^{90} in milk was determined to be 9.2×10^{-4} μCi/liter, the concentration of Sr^{90} in meat would be as follows:

$$\frac{Sr^{90} \text{ in meat}}{Sr^{90} \text{ in milk } (9.2 \times 10^{-4} \text{ Ci/liter})} = 0.2$$

$$Sr^{90} \text{ in meat} = (9.2 \times 10^{-4}) \times 0.2 = 1.8 \times 10^{-4} \mu Ci/kg$$

$\underline{Cs^{137}}$

A value for the concentration of Cs^{137} in meat was established in a manner similar to that employed for Sr^{90}, *i.e.*, by determining a ratio for the concentration of Cs^{137} in meat to that in milk. The lowest ratio of Cs^{137} in meat to milk as determined from studies in the literature was greater than 3; however, the range of these ratios varied considerably, apparently as a result of local environmental factors and the animal feeding practices employed in the areas where the studies were conducted. A value of 10 was assumed for the meat to milk ratio of Cs^{137}, as representative of these data. Since the concentration of Cs^{137} in milk was determined to be 1.3×10^{-2} μCi/liter, the concentration of Cs^{137} in meat would be

$$\frac{Cs^{137} \text{ in meat}}{Cs^{137} \text{ in milk } (1.3 \times 10^{-2} \mu Ci/\text{liter})} = 10$$

$$Cs^{137} \text{ in meat} = (1.3 \times 10^{-2}) \times 10 = 1.3 \times 10^{-1} \mu Ci/kg$$

The Rate of Ingestion of Sr^{90} and Cs^{137} Via Meat For One Year Post-Attack

This value is the product of the average daily concentration of the nuclide in the meat consumed per day and days/year.

$\underline{Sr^{90}}$

The concentration of Sr^{90} in meat was determined to be 1.8×10^{-4} μCi/kg; however, meat consumption was assumed to be 300 g/day.

$$\frac{1.8 \times 10^{-4}}{3.3} = 5.4 \times 10^{-5} \mu Ci \ Sr^{90}/day \times 365 = 1.9 \times 10^{-2} \mu Ci \ Sr^{90}/year$$

Cs^{137}

The concentration of Cs^{137} in meat was determined to be $1.5x10^{-3}$ µCi/kg (rate of recent consumption = 500g/day).

$$\frac{1.5x10^{-3}}{5.5} = 3.9x10^{-2}\mu Ci\ Cs^{137}/day \times 365 = 14.2\ \mu Ci\ Cs^{137}/year$$

The Annual Radiation Dosage Rates Via Meat to the Adult Whole Body and Bone From Sr^{90}

Bone

$$B_1 = \frac{\mu Ci/yr}{rad/yr}$$

$$4.07x10^{-2} = \frac{1.9x10^{-2}}{rad/yr}$$

$$rad/yr = .46 \times 0.7 \text{ (correction factor)}$$

$$rad/yr = .32$$

Whole Body

The dose rate for Sr^{90} in the adult whole body is 1/10 that in bone = 0.03 rad/yr.

The Annual Radiation Dosage Rates Via Meat to the Adult Whole Body and Bone From Cs^{137}

Bone

$$B_1 = \frac{\mu Ci/yr}{rad/yr}$$

$$1.09x10^{1} = \frac{14.2}{rad/yr}$$

$$rad/yr = 1.3 \times .729 \text{ (correction factor)}$$

$$rad/yr = 0.95$$

Whole Body

The dose rate for Cs^{137} in the adult whole body is the same as that in bone = 0.95 rad/yr.

The Validity of the Chronic-Contamination Model

The chronic-contamination model was structured primarily upon the development of proportionality factors between the average nuclide concentrations in milk or meat and the average nuclide concentrations in surface air. It is fortuitous that experimental data have become available which not only validate the assumptions made in the step-wise development of the model, but, in addition, indicate that a reasonable degree of precision may be anticipated with regard to the predicted radiation dosage estimates made via use of the model. The experimental data for testing the model were provided by Wilson, *et al.* (1969), with results described elsewhere.

APPENDIX H - RUSSELL'S ASSESSMENT OF THE RADIOLOGICAL HAZARD TO MAN FROM LONG-LIVED NUCLIDES AFTER A NUCLEAR WAR

The results of the study by Russell, *et al.*, indicate a lesser radiological hazard from long-lived nuclides (Sr^{90} and Cs^{137}) than that predicted in earlier studies. This re-assessment of the problem became possible when Russell and his colleagues had accumulated sufficient empirical data to clarify the role of several steps in the transport of Sr^{90} into food chains (areas of the problem which had been heretofore bridged by unsupported assumptions and/or conjecture).

The analysis deals primarily with the hazard of Sr^{90} to man via milk. The Sr^{90} contribution from both early (near-in) and delayed (worldwide) fallout sources are combined for this analysis.

In the case of early (near-in) fallout, the deposition of Sr^{90} in those areas where the external gamma dose is 100 R/hr at 1 hr was calculated to be 500 mCi Sr^{90}/km^2.

The delayed or worldwide deposition of Sr^{90} resulting from 5000 Mt fission was calculated to be 1100 mCi Sr^{90}/km^2 in the first year after detonation.

The factors disclosed by Russell and his colleagues which provided the basis for lowering the Sr^{90} hazard were these:

(a) the uptake of Sr^{90} from the soil decreases by about 14% annually (prior to this study UNSCEAR had assumed a constant rate for the annual reduction in uptake from the soil at 2%).

(b) the downward movement of Sr^{90} in the soil removes it from areas of root absorption for pasture plants.

The dose commitment (first decade) for Sr^{90} to bone marrow was calculated to be approximately 1 rad, and that from Cs^{137} to be 1 rad to bone marrow and 1 rad to the whole body (the distribution of cesium is fairly uniform throughout the body).

In the case of the predictive model developed by Ng and Tewes, their assessment of the radiological hazard to man following early fallout is considered more realistic than that presented by Russell, *et al.* This is particularly true in the case of the thyroid dose from I^{131} via

milk. However, it must be pointed out that Ng and Tewes consider only the consequences of unfractionated nuclides deposited on vegetation. In the case of the radiological hazard from long-lived nuclides from worldwide fallout, the assessment made by Russell, *et al.*, is considered superior to that made by Ng and Tewes, because Russell's study takes into consideration fractionation and the contribution of Sr^{90} in the soil year by year for the first decade.

In the area where the initial deposit of near-in fallout delivered 100 R/hr at 1 hr and there was subsequent worldwide fallout from 5000 Mt of fission, the dose commitment (ingested Sr^{90} and Cs^{137}) would be about 2 rads to the bone marrow of the population and 1 rad to the whole body (worldwide fallout would be responsible for the major part of these doses).

It is now widely recognized that long-lived fission products would make a negligible contribution to the radiation exposure of the population in heavily contaminated areas shortly after a nuclear attack. The external radiation dose would usually be dominant, and, if simple precautions were taken to avoid the superficial contamination of foodstuffs, the entry of I^{131} into milk would cause the only important problem of dietary contamination. Thus, for example, infants probably would not receive doses of more than 0.1 rad to bone marrow from Sr^{90} nor more than 0.01 rad from Cs^{137} in the weeks after a nuclear attack if they were fed continuously with milk produced in an area where the external dose rate at 1 hr after detonation had been 100 R/hr. Doses to the thyroid from I^{131} might, however, exceed 200 rads (Russell Interlaken paper). Considerably higher doses were expected until it became evident that the physical properties of near-in fallout much reduce the entry of radioactivity into food chains.

In more lightly contaminated areas, expecially where deposition does not occur for many hours or days, internal radiation would give rise to a larger fraction of the total radiation dose, partly because short-lived nuclides would have decayed before fallout descended and partly because fission products contained in the more finely divided and soluble distant fallout enter food chains more readily. The relative contributions of I^{131}, Sr^{90}, and Cs^{137} to the internal radiation dose would, however, be comparable to those in near-in localities.

Civil defense planning is naturally concerned primarily with the early period when external radiation is dominant, but this is not the whole story. Years after a nuclear war, long-lived nuclides will remain in the soil and will continue to descend in worldwide fallout. Therefore two questions are relevant:

(1) What radiation doses will be received from these sources by the survivors of a nuclear war?

(2) Is it prudent and realistic to prepare plans for long-term remedial action against the contamination of agricultural produce?

Radiation Doses from Long-Lived Fission Products in Diet After a Nuclear War.

Consider the situation in an area receiving an external radiation dose of 100 R/hr from early fallout 1 hr after the detonation of a weapon (the total amount of fission occurring in the entire war being 5000 Mt).

Dose from Sr^{90}

Near-in fallout would deposit approximately 1000 mCi of Sr^{90}/km^2 in a fallout field of 100 R/hr at 1 hour. The large particle size of the debris will undoubtedly lower its solubility by a considerable factor: 500 mCi of Sr^{90}/km^2 is assumed to be present in forms accessible to plant roots in postwar year 1 (one).

The results of surveys of worldwide fallout combined with estimates of nuclear fission released by nuclear tests, which are reviewed in this Appendix * suggest that 5000 Mt of fission would give rise to a deposit of about 1100 mCi of Sr^{90} per km^2 in the first year, with a half-residence time in the atmosphere of about 12 months; these estimates refer to temperate latitudes in the hemisphere where detonation occurred.

Dose from Cs^{137}

It is well known that the fixation of Cs^{137} in clay minerals causes it to enter food chains to only a very small extent a year or two after the detonation.

Data re Cs^{137} are severe in relation to that re Sr^{90}. That which is available has been reviewed by UNSCEAR.

The dose commitment to the bone marrow of the population from Cs^{137} in worldwide fallout appears to be about 90% of that from Sr^{90}, the same dose from Cs^{137}being received by all tissues, of course. Within the limits of accuracy practicable in the present discussion, we may therefore assume that the dose commitment from Cs^{137} to all tissues after the postulated war would be similar to that from Sr^{90} to the bone marrow, *i.e.*, about 1 rad.

*Supplementary information, following.

The Fatal Dose

For present purposes it is unnecessary to consider nuclides other than Sr^{90} and Cs^{137}. Other fission products will be trivial sources of dietary contamination.

Accordingly, we may conclude that, after a nuclear war involving 5000 Mt of fission, the dose commitment from Sr^{90} and Cs^{137} to the inhabitants of the hemisphere in which the war took place would be approximately 2 rads to the bone marrow and 1 rad to the whole body for long-lived nuclides.

Discussion

Civil defense planning is naturally concerned primarily with the early period when external radiation is dominant.

The other side of the problem is that for years after a nuclear war, long-lived nuclides will remain in the soil and will continue to dsecend in worldwide fallout.

(A) What radiation doses will be received from these sources by the survivors of a nuclear war?

Even when the maximum allowance is made for uncertainties, the following facts are evident:

(1) Doses from long-lived nuclides will be trivial relative to those received from short-lived activities in the earlier period in areas of appreciable near-in fallout.

(2) Assuming that a nuclear war is of considerable magnitude (5000 Mt*is in this category), worldwide fallout and not near-in debris would usually be the dominant source of dietary contamination with long-lived nuclides.

(3) The direct contamination of growing crops is likely to be responsible for about half the dietary contamination with Sr^{90}.

This last statement should be no surprise. It is now more than a decade since unequivocal evidence became available that in times of relatively high fallout the direct contamination of plants and not, as it was first suggested, absorption from the soil was the major route by which Sr^{90} entered diet. Implicit also in the analyses that could be made at that time was the fact that the average extent to which Sr^{90} would enter plants from the soil over a long period was likely to be overestimated.

*Fission

If the soil were low in calcium the Sr^{90} contribution could be greater than is suggested here.

B) Is it prudent and realistic to prepare plans for long-term remedial action?

The literature contains numerous suggestions for modifying the transfer of fission products through food chains, but unfortunately the majority of these do not relate to situations likely to arise in practice.

A quarter or more of the casualties from long-lived nuclides after a nuclear war would apparently be due to external radiation from Cs^{137}; this risk could not be mitigated over a wide area by any practicable method. Reduction of the average level of radioactivity in agricultural produce by a large factor also seems impossible. Russell's Figure 3 shows that, during the early years when dose would be highest, the major part of the internal dose from Sr^{90} and, of course, almost the entire internal dose from Cs^{137} comes from entrapment of the deposit on growing plants. Therefore it seems that the intake of radioactivity in diet could be reduced by a considerable factor only if stocks of stored foods were available for several years or if crops were grown in greenhouses to protect them from direct contamination by fallout.

The following conclusions are inescapable. A large part of the dose from long-lived nuclides could not be avoided, and procedures available for mitigating some fraction of the dose would involve considerable effort and would possibly restrict food supplies.

SUPPLEMENTARY INFORMATION

Dose to Bone Marrow of Infants

It is now widely recognized that, because of the risk of leukemia, the radiation dose to bone marrow is the appropriate basis for assessing risks from Sr^{90}.

To estimate the highest dose to this tissue which any individual could receive annually, we have assumed that the entire bone of infants, starting in the first year of life, is in equilibrium with diet each year, that the ratio of Sr^{90} to calcium in their bone is 0.25 of that in the diet, and that 1 pCi Sr^{90}/g Ca in bone will deliver 0.82 mrad/yr to bone marrow. On this basis, infants in their first year will receive the radiation doses shown in Russell's Figure 3. In postwar year 1 the doses to bone marrow would be about 0.25 rad/year. Over the next few years the dose would decrease relatively rapidly to about 0.1 rad/yr in the fourth year and about 0.03 rad/yr after 10 years.

Alternatively, the dose commitment to the population can be estimated by using the procedure of UNSCEAR. In this calculation it is necessary to assume the relation between the ratio of Sr^{90} to calcium in the total diet and that in milk. In the majority of countries where those ratios have been examined, this ratio in the total diet is 1 to 1.5 times that in milk.

In the present calculations the higher value of 1.5 was used. On this basis, the dose commitment from Sr^{90} is about 1 rad, nearly all of which is received in the first 10 years.

Some 90% of the total dose commitment would come from worldwide fallout, the early fallout in an area where the external gross dose was 100 R/hr at 1 hour contributing only a minor fraction of the total.

Infants probably would not receive doses of more than 0.1 rad to bone marrow from Sr^{90} nor more than 0.01 rad from Cs^{137} in the weeks after a nuclear attack if they were fed continuously with milk products in an area where the external dose rate at 1 hour after detonation had been 100 R/hr. Doses to the thyroid from I^{131} might, however, exceed 200 rad.

Entry of Sr^{90} Into Food Chains From the Soil

The best approach is to analyze the results of surveys of deposition of worldwide fallout and contamination of foodstuffs, thus partitioning the contamination of food between direct contamination (*i.e.*,

the retention of the recent deposits on vegetation) and that resulting from uptake from the soil.

Russell describes the development of a procedure for estimating (calculating) the Sr^{90} contamination of milk from observed/measured fallout levels (i.e., describes the relation between the deposition of fallout and the contamination of milk).

The original equation had two defects:

(1) First, the equation assumed that all Sr^{90} entering milk which was not attributable to the entrapment of the current deposit on vegetation came from the cumulative total in the soil, whereas it was evident from agricultural considerations that the direct entrapment of Sr^{90} on vegetation in the previous year must make an appreciable contribution (the "lag-rate" effect).

(2) Second, the assumption that a constant fraction of the cumulative deposit in the soil enters plants each year was clearly incorrect because of the mechanisms which either remove it from the rooting zone or otherwise reduce its accessibility to plants.

	P_r	P_d	P_l
1961 Data	0.76	0.19	
1964 Data	0.70	0.11	1.13

(UNSCEAR selected value of 2% for value by which Sr^{90} decreased from the soil annually.)

From the viewpoint of predicting dietary contamination over long periods, the particular advantage of Russell's Eq 3 is that it provides an objective basis for estimating the extent to which the uptake of Sr^{90} from the soil changes with time.

S = 0.86 = reduction factor by which the uptake of Sr^{90} from soil decreases annually through processes other than the decay of radioactivity.

The value of 0.86 for "S" indicates a decrease by some 14% annually after allowance has been made for the decay of radioactivity. This value is in surprising agreement with the findings of Van der Stricht, *et al.*, who deduced an annual reduction in uptake from the soil by about 13%.

United Kingdom experiments showed that pasture grasses can remove 2-5% of recently introduced Sr^{90} from soil in a single summer. Beyond this the downward movement of Sr^{90} in the soil by only a few centimeters will frequently cause an appreciable reduction in absorption since the roots of pasture plants draw nutrients largely from the upper soil layers, Strontium 90, like calcium, can be leached to greater depths in the soil, and in some soils physiochemical changes may bring about a small reduction in uptake by plants.

The present value of "S" does not appear in conflict with any known facts; *i.e.*, it closely describes the situations in 1968 and 1969 when the mean interval since the deposition of Sr^{90} was 6 to 7 years.

Note: value of "S" indicated that absorption of Sr^{90} is initially appreciably higher than was previously inferred. (First crop will get rid of considerable amount of Sr^{90}.)

A test of the validity of the situation in the United Kingdom with respect to the general situation in other temperate regions was provided in a report by UNSCEAR in which its tabulation of milk levels from 14 localities in the North Temperate Zone between 1955 and 1967 was very close; therefore, Russell, *et al.*, accepted U. K. data as representative of situations in temperate countries until a better assessment became available.

The results of surveys of worldwide fallout combined with estimates of the quantity of nuclear fission released by nuclear tests, which have been reviewed here*, suggest that 5000 Mt of fission would give rise to a deposit of about 1100 mCi of Sr^{90} per km^2 in the first year.

We have assumed that the entire bone of infants in the first year of life is in equilibrium with diet each year, that the ratio of Sr^{90} to calcium in their bone is 0.25 of that in the diet, and that 1 pCi Sr^{90}/g Ca in bone will deliver 0.82 mrad/yr to bone marrow. In postwar year 1 the doses to bone marrow would be about .25 rad/yr.

Effect of Fractionation of Fission Products

The volatility of Kr^{90}, the gaseous precursor of Sr^{90}, is likely to deplete Sr^{90} in the near-in deposit by a factor that may be conservatively estimated at 5.

*in the following.

Thus, a deposit of 1000 mCi/km^2 is expected when the external gamma dose rate is 100 R/hr at 1 hour.

Solubility of Sr^{90} in the Soil

There is much evidence that the deposit in such areas will be of low solubility (probably not more than 10%), but, to avoid understatement of the quantities of Sr^{90} which may enter food chains in subsequent years, we assumed 50% becomes soluble in the soil.

Deposition of Sr^{90} in Near-in Fallout when External Gamma Dose is 100 R/hr at 1 hour

Dunning and Hilcken estimated that a deposition of 800 MCi of mixed fission products per square mile 1 hour after fission would give an external gamma dose rate of 4000 R/hr at 3 feet above a theoretically flat plane.

Assuming:

that the roughness of the ground would attenuate the external radiation dose by a factor of 2,
that Sr^{90} contributes 0.0013% of the total fallout activity at 24 hours (Adjusted for a half-life of 28 years),
that mixed fission products are deposited in fission yield, and that they decay by a factor of 36 in 24 hours,

the expected deposit of Sr^{90} would be 5000 mCi/km^2 when the external gamma dose rate is 100 R/hr at 1 hour.

An alternative calculation, based on Glasstone,gives about one-third of this value.

Relation Between the Extent of Nuclear Fission and Worldwide Fallout in the Same Hemisphere

The pattern of fallout from the series of nuclear tests in 1962 provides a basis for estimating the deposition of Sr^{90} in worldwide fallout after a nuclear war.

Tests in the USSR are estimated to have yielded 60 Mt of fission with a mean time of origin at mid-September 1962.

The average deposition of Sr^{90} in the United Kingdom in 1963 was 19 mCi/km^2, and measurements of fission-product ratios indicated that, in the spring and summer of that year, 20% of the Sr^{90} was from tests held in 1962.

If we assume that 60 Mt of fission caused 0.7 x 19 = 13.3 mCi/km^2 to be deposited in the year after the detonations occured, then, assuming similar latitude and height of the injection, 5000 Mt of fission would give rise to 1100 mCi of Sr^{90}/km^2 in the first year after detonation.

Note: The near-in fallout was calculated to be $1x10^{-3}\mu Ci/m^2$ when the external gamma dose rate is 100 R/hr at 1 hour.

By use of his Equation 3, Russell, *et al.* derived the levels of Sr^{90} in milk caused by the initial deposit and by worldwide fallout. These values, along with the fractions of the total contamination attributable to absorption from the soil each year, are the basis for the discussions above.

Dose From I^{131} to the Thyroid Gland

UNSCEAR (1964) calculated the accumulated radiation dose (D) to the thyroid gland as follows:

$$D = \frac{K \times I \times F \times T}{m}$$

K = dose rate factor (0.01 mrad/day per pCi/g tissue)

I = total intake by ingestion of I^{131} (pCi)

F = fraction of ingested I^{131} which reaches the thyroid (0.3)

T = mean effective time of storage of I^{131} in thyroid (11 days)

m = mass of thyroid (2g)

(Use: F = 0.35 for infants and m = 1.8g)

Calculate D, where I = 1 μCi I^{131}

$$D = \frac{(.01)(10^6)\ (.35)(11)}{1.8}$$

D = 21,000 mrad or

1 μCi I^{131} → 21 rad infant's thyroid.
Russell says 20 rad, or

1 rad is delivered by 0.05 μCi I^{131}

The total intake of I^{131} per day will be approximately 10x the intake on the day when the concentration is highest. Hence, 1 rad will be received by an infant which ingests 0.005 μCi I^{131} on that day (day of peak concentration).

Taking the daily intake of milk as 0.7 liters, the corresponding level of I^{131} in milk is 0.007μCi I^{131}/liter. (= (0.7/1.1) x 0.005)

From earlier results, this peak concentration could result from 0.05 μCi I^{131}/m^2 if deposited in a finely divided soluble deposit.

The peak concentration of I^{131} is reached on day 2, at which time the concentration is 0.14 μCi/liter per μCi/m^2.

Dose From Cs^{137} to the Whole Body

FRC (1965) estimated that 1 μCi Cs^{137} ingested by an infant (10 kg = 22 lbs) will deliver 0.13 rads to the whole body, *i.e.*, 1 rad is delivered by ~ 7.7 μCi Cs^{137}.

It can be calculated that the integrated intake of Cs^{137}after a single release will be about 33 times the intake in milk on the day of highest contamination. Hence, 1 rad will be received by an infant which consumes ~ 0.23 μCi Cs^{137} on that day.

(The highest concentration of Cs^{137} is reached on the eighth day, *i.e.*, 0.30 μCi/liter per μCi/m^2.)

Assuming an intake of 0.7 liter this corresponds to ~ 0.33 μCi Cs^{137}/liter.

Earlier results show that this level of contamination will result when the deposit is ~ 1.1 μCi Cs^{137}/m^2.

Dose From Sr^{89} to Bone Marrow

FRC (1965) concluded that a mean dose of 1 rad would be delivered to bone marrow if the maximum conc. of Sr^{89} in milk were 0.37μCi/liter, continuous intake being assumed. From earlier results, it is evident that this level of contamination would result from a deposition of ~ 20 μCi Sr^{89}/m^2.

.37μCi Sr^{89}/liter milk → 1 rad to bone marrow

Peak (day 4) conc. = 0.019μCi/liter per μCi/m^2

Dose From Sr^{90} to Bone Marrow

The ratio of Sr^{90} to calcium in bone is 0.25 of that in the diet (UNSCEAR, 1964).

1 pCi Sr^{90}/g Ca in bone → 0.82 mrad/yr to the bone marrow

$5x10^{-3}$ μCi Sr^{90}/g Ca in the diet delivers 1 rad/yr to the bone marrow

It has been shown that under average conditions in the U.K. the presence of

1 mCi Sr^{90}/km^2 → 0.11 pCi Sr^{90}/g Ca in milk

What level of soil contamination → $5x10^{-3}$μCi Sr^{90}/g Ca in milk?

1 mCi/km^2 → $1.1x10^{-7}$μCi/g Ca in milk

Therefore, 45000. = the number of mCi Sr^{90}/km^2 that will lead to .005 μCi Sr^{90}/g Ca in milk

45000 mCi Sr^{90}/km^2 = 45 Ci Sr^{90}/km^2 or
45 μCi Sr^{90}/m^2

A deposit of 45 Ci Sr^{90}/km^2 (45μCi Sr^{90}/m^2) would cause bone marrow to receive 1 rad/yr.


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