UCRL--89037

DE83 012106

UCRL- 89037
PREPRINT

Radiological-Dose Assessments Of Atolls In The Northern Marshall Islands

W. L. Robison

This paper was prepared for submittal to The Eighteenth Annual Meeting of the National Council On Radiation Protection
Washington, D.C. April 5-8, 1983

April 1983

Lawrence Livermore Laboratory

RADIOLOGICAL-DOSE ASSESSMENTS OF ATOLLS IN THE NORTHERN MARSHALL ISLANDS*

William L. Robison
Environmental Sciences Division
Lawrence Livermore National Laboratory
University of California
Livermore, California 94550

ABSTRACT

The Marshall Islands in the Equatorial Pacific, specifically Enewetak and Bikini Atolls, were the site of U.S. nuclear testing from 1946 through 1958. In 1978, the Northern Marshall Islands Radiological Survey was conducted to evaluate the radiological conditions of two islands and ten atolls downwind of the proving grounds. The survey included aerial external gamma measurements and collection of soil, terrestrial, and marine samples for radionuclide analysis to determine the radiological dose from all exposure pathways. The methods and models used to estimate doses to a population in an environment where natural processes have acted on the source-term radionuclides for nearly 30 y, data bases developed for the models, and results of the radiological dose analyses are described.

The radionuclide ^{137}Cs accounts for over 90% of the total estimated whole-body and bone-marrow doses. The next most significant radionuclide, contributing principally to the bone-marrow dose, is ^{90}Sr. The radionuclides $^{239+240}$Pu and ^{241}Am contribute a small portion of the lung and bone-marrow doses. The terrestrial food chain accounts for between 50 and 80% of the estimated doses; the external gamma between 15 and 45%; and the marine food chain, inhalation, and cistern water and groundwater pathways the remainder.

The dose assessments are determined for two dietary conditions to indicate the range of doses based on current diet surveys. Doses have been estimated for the major islands at each atoll assuming continuous residence on each

* Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-Eng-48.

island and all local food derived from that island. Some of the islands are used part-time for residence or agriculture, but we estimate the dose assuming continuous occupation to indicate the dose relative to current residence islands.

The maximum, annual dose-equivalent rates for atolls downwind of the proving grounds for all exposure pathways excluding cosmic radiation are less than 30 mrem/y, regardless of the assumed diet. The only significant source of natural external background exposure in the Marshall Islands is the 22 mrem/y from cosmic radiation. The total external background dose in the U.S., for reference, is 54 mrem/y based on the population-weighted average. Thus, depending on the diet, most atolls have estimated doses from all exposure pathways excluding cosmic radiation that range from about 4 to 57% of the U.S. external background dose. These doses can also be compared to the U.S. Federal guideline of 500 mrem/y above background for an individual. The doses at most atolls are from 1 to 5% of the guideline, depending on which diet is assumed to apply. The highest estimated dose equivalent for an inhabited atoll is for the southern islands at Rongelap, where the doses range from about 10 to 50% of the guideline.

The 30- and 50-y integral dose equivalents provide a similar picture. The 30-y integral dose equivalents for atolls downwind of the proving grounds range from 0.14 to less than 0.7 rem, depending on the diet. This is less by a factor of 20 to 33 than U.S. Federal guidelines of 5 rem/30 y for a population and less than the integrated 30-y external background dose in the U.S., which ranges from 1.6 to 5.5 rem.

The estimated doses for the southern islands at Enewetak Atoll are low. The estimated dose equivalent for the northern island of Enjebi, calculated using the average value for all the parameters in the dose models, is less than 300 mrem/y for the annual dose-equivalent rate and about 6 rem for the 30-y integral dose equivalent. The U.S. Government has elected to multiply by a factor of 3 these estimated annual doses and compare the resulting number with the Federal guideline of 500 mrem/y. Thus, the maximum, annual dose-equivalent rate presented to the Enewetak people and used for risk analysis for Enjebi Island is 900 mrem/y when imported foods are available.

The maximum, annual dose-equivalent rate for Bikini Island at Bikini Atoll is about 1 rem/y when imports are available. The corresponding 30-y integral dose equivalent is 22 rem. However, at neighboring Eneu Island, the estimated annual dose-equivalent rate is about 140 mrem/y when imported foods are available and the corresponding 30-y integral dose equivalent is about 3 rem. Again, the annual dose equivalent results for both islands were multiplied by 3 and presented to the Bikini people along with the associated risk analysis.

INTRODUCTION

In March 1946, the United States relocated the Bikini people to Rongerik Atoll to conduct a nuclear testing program at Bikini Atoll. They were again moved to Kwajalein Atoll in March 1948 and eventually to Kili Island in fall 1948. A second testing site was made available in 1947 when the Enewetak people were moved from Enewetak to Ujelang Atoll. From 1946 through 1958, 43 tests were conducted at Enewetak and 23 at Bikini Atoll. The atolls of the Northern Marshall Islands are shown in Fig. 1.

Some of the Bikini people elected to return to Bikini Atoll in 1970 after a limited radiological survey had been conducted and a radiological dose analysis completed. Housing was built and coconut, breadfruit, and Pandanus trees were planted on Bikini Island. Coconut trees were also planted on Eneu Island (see Fig. 2).

In 1972, the Enewetak people requested to return to their home atoll. It was decided that prior to any resettlement, a thorough radiological survey should be conducted and potential doses estimated for the preferred and historical living patterns at the atoll, which included Enewetak Island in the south and Enjebi Island in the north (Fig. 3). Thus, the survey was conducted in 1972 and 1973 and the radiological analysis completed [1]. The analysis indicated that the terrestrial food chain was potentially the most significant exposure pathway. However, the analysis also identified areas where additional data were needed to make more precise dose estimates. Therefore, a field program was began at Enewetak Atoll in 1975 to develop the required data base. Crops historically used by the Marshallese for subsistence were planted on Enjebi Island to determine the concentration of radionuclides in locally grown

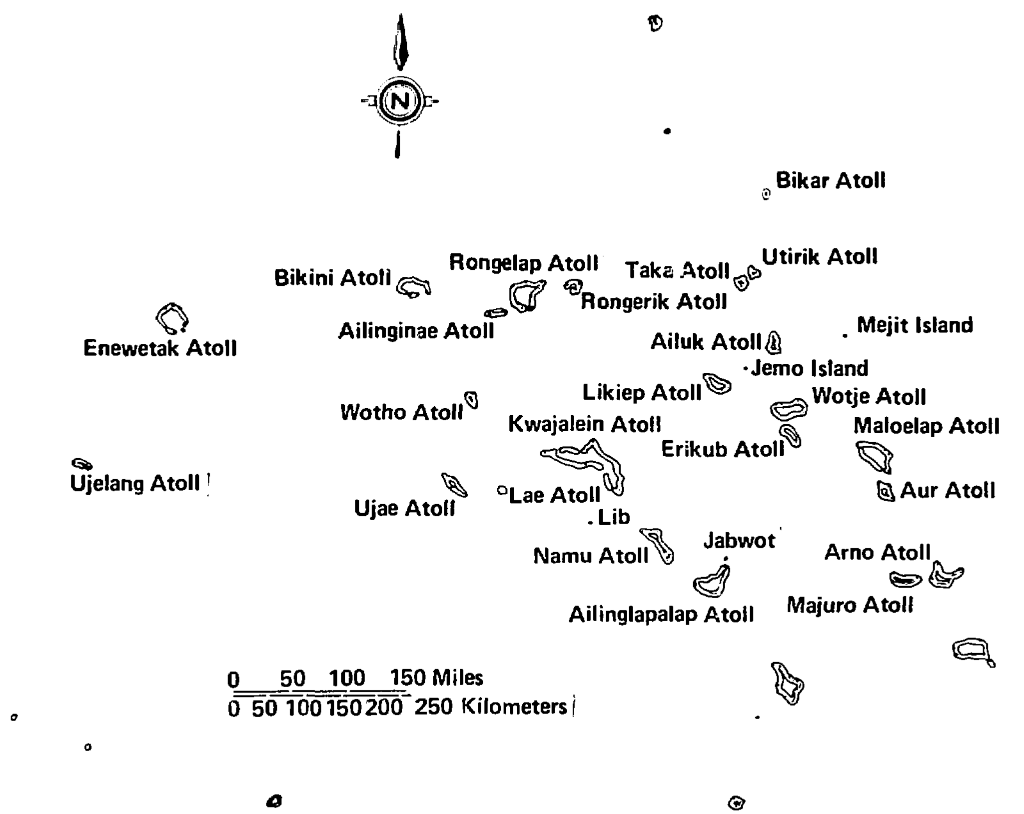

Figure 1. Atolls and islands of the Northern Marshall Islands radiological survey.

foods and the concentration ratio between the radionuclide concentration in edible foods and soil. In addition, experiments were initiated to evaluate the cycling of radionuclides and to determine the residence time in the atoll ecosystem.

There were also plans in 1975 to start a second phase of housing on Bikini Island at Bikini Atoll. However, external gamma measurements available from earlier surveys indicated that selection of housing locations was important to minimize the dose to residents. Thus, a resurvey of Bikini and

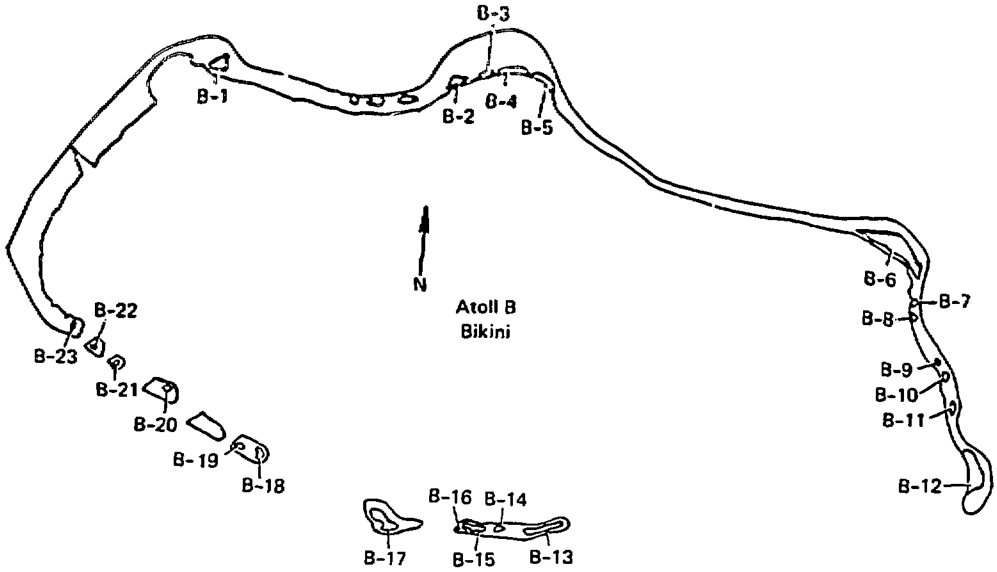

Figure 2. Map of Bikini Atoll.

Eneu Islands was conducted in 1975 including collection of available samples to evaluate exposure via food chains as well as by external gamma. Although very few food crops were available to directly measure the radionuclide concentrations on either island, the results did indicate that estimated doses for Bikini Island exceeded Federal guidelines and were about 8 to 10 times greater than doses estimated for Eneu Island [2-5]. As a result, a field program was initiated in 1977 at Bikini Atoll. Subsistence crops were planted on Eneu Island to supplement the coconut trees, which had been planted on both islands in 1970 and were due to begin bearing fruit within the year, to measure the radionuclide concentration in subsistence foods.

In 1977, a clean-up program was also began at Enewetak Atoll directed toward removing scrap and debris remaining from World War II and the subsequent test series. Also a radiological clean-up, which consisted of soil removal, was conducted on those islands that had the highest transuranic radionuclide concentrations. The clean-up was completed in 1979. External gamma measurements were made and soil samples were analyzed for the critical radionuclides.

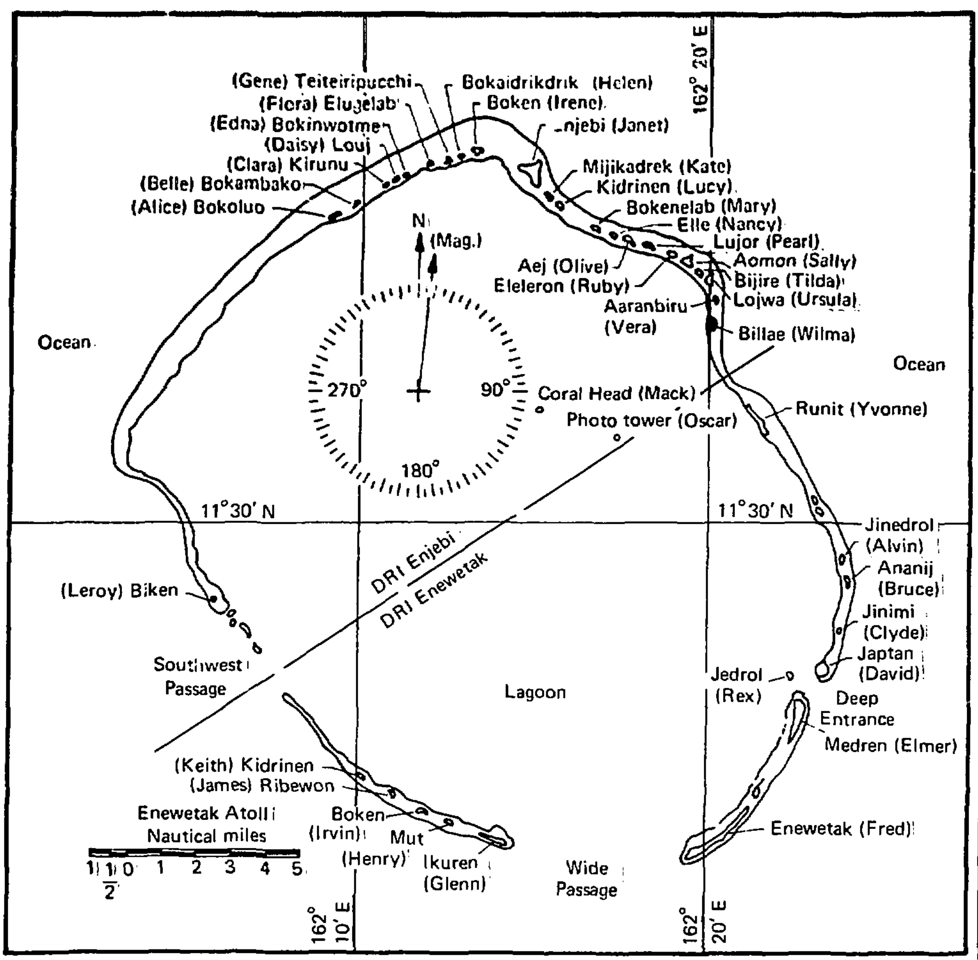

Figure 3. Map of Enewetak Atoll.

Concurrently with the ongoing programs at Bikini and Enewetak Atolls, the U.S. Government decided to evaluate the radiological conditions of two islands and ten atolls downwind of the Enewetak and Bikini proving ground prior to the termination of the United National Trust Territory agreement under which the United States administers Micronesia. Thus in 1978, we conducted the Northern Marshall Islands Radiological Survey (NMIRS) of Rongelap, Utirik, Rongerik, Wotho, Likiep, Ailuk, Mejit, Ailinginae, Ujelang, Bikar, Taka, and Bikini (see Fig. 1). The survey included aerial external gamma measurements and the collection of soil, terrestrial, and marine samples for radionuclide analysis to determine the radiological dose from all exposure pathways [6-9].

The methods and models used to estimate the doses to a returning population in an environment where natural processes have acted on the source-term radionuclides for nearly 30 y, the data bases developed for the models, and the results of the radiological dose analyses at the various atolls are described here.

MAJOR RADIONUCLIDES

The most significant radionuclides at the atolls in order of the contribution to the total estimated doses are: ^{137}Cs, ^{90}Sr, $^{239+240}Pu$, ^{241}Am, and ^{60}Co. The ^{137}Cs, both from external gamma exposure and uptake into food crops, accounts for over 90% of the total estimated whole-body and bone-marrow doses. The ^{90}Sr is the next most significant radionuclide contributing principally to the bone-marrow dose. The transuranic radionuclides contributed the least to the lung and bone-marrow doses. The contribution to the estimated dose for ^{60}Co only occurs through the external gamma pathway and at most atolls is insignificant; even at those atolls where it does make a minor contribution, it is rapidly becoming insignificant because of its short radiological half-life (5.7 y).

EXPOSURE PATHWAYS

External and internal pathways are the sources of exposure for persons living at or resettling an atoll.

(1) External exposure
- (a) Natural background
- (b) Man-made gamma and beta rays

(2) Internal exposure
- (a) Radionuclides inhaled
- (b) Radionuclides in drinking water
- (c) Radionuclides in terrestrial foods
- (d) Radionuclides in marine foods

The exposure pathways in order of their contribution to the total estimated doses are: terrestrial food chain, external gamma, marine food chain, inhalation, and cistern water and groundwater. The terrestrial food chain accounts for between 50 and 80% of the estimated doses, the external gamma between 45 and 15%, and the other pathways the remainder.

MODELS USED FOR DOSE CALCULATIONS

THE ^{90}SR METHODOLOGY

Bone-marrow doses and dose rates are calculated in two steps. First, the model of Bennett [10-12] is used to correlate the ^{90}Sr concentrations in diet with that in mineral bone. Second, the dosimetric model developed by Spiers [13] is used to calculate the bone-marrow dose rate from the concentration in mineral bone.

Bennett's empirical model is developed from ^{90}Sr concentrations found in foods and autopsy bone samples from New York and San Francisco from 1951 through 1981. A similar model developed by Papworth and Vennart based on the ^{90}Sr content of the diet and bone samples in the U.K. from gives similar results [14]. The concentrations in the diet are the concentrations expected to result from worldwide fallout. The models use as input the actual dietary ^{90}Sr concentration and the output is the actual ^{90}Sr concentration in mineral bone determined from analysis of autopsy samples. They also include age-dependent variations to make dose estimates for children as well as adults. Figure 4 shows the comparative results of the models. The major differences occur between the ages of 5 and 15 where the ratio of Papworth and Vennart to Bennett ranges from 1.2 to about 1.6. The two models are essentially the same from age 18 through adulthood.

The estimated calcium content of the normal Marshallese diet is more than 0.8 g/d, which is very similar to the 0.9 g/d estimated for U.S. diets [15]. Therefore, the similar intake of calcium of the overall Marshallese and U.S. diets would indicate no major problems in applying the ^{90}Sr model to the Marshallese population.

Using Spiers' model, we calculate the dose rate D_0 to a small, tissue-filled cavity in bone from the ^{90}Sr concentration in mineral bone. Then from geometrical considerations, the dose rates to the bone marrow D_m and endosteal

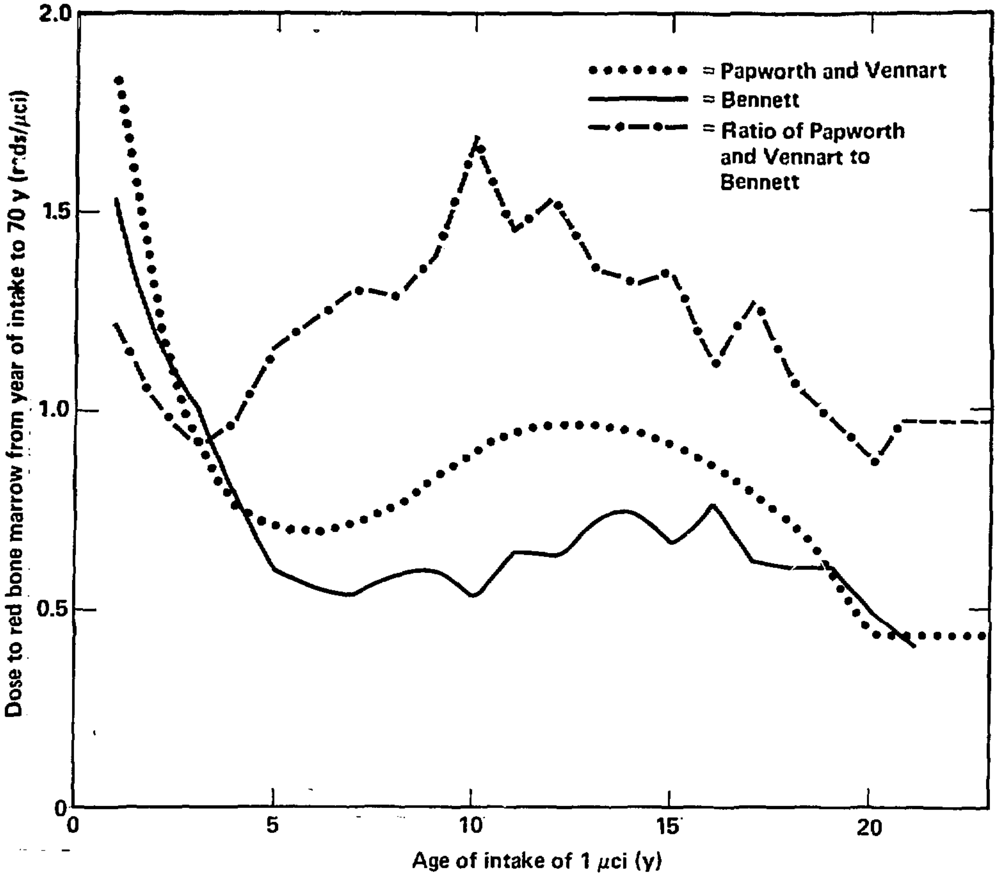

Figure 4. Comparison of the Bennett and Papworth and Vennart ^{90}Sr bone-dose models.

cells D_s are calculated using conversion factors $D_m/D_o = 0.32$ and $D_s/D_o = 0.43$, respectively. These factors are quoted by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [16,17] and are equivalent to a bone-marrow dose rate of 1.4 mrad/y per pCi ^{90}Sr/g calcium and an endosteal cell dose rate of 1.9 mrad/y per pCi ^{90}Sr/g calcium.

THE ^{137}CS AND ^{60}CO METHODOLOGY

Ingestion

For ^{137}Cs and ^{60}Co, the methods of the International Commission on Radiological Protection (ICRP)[18-20] and the National Council on Radiation Protection and Measurements (NCRP) [21] as developed by Killough and Rohwer in their INDOS code [22] are used for the dose calculations. This code is used as published; however, the output is modified to show the body burdens for each year. For ^{137}Cs, which is of major importance in the Marshall Islands, the model for adults consists of two compartments with removal half-times of 2 and 110 d, with 10% of the intake going to the 2-d compartment and 90% to the 110-d compartment. These data are consistent with preliminary data obtained by Brookhaven National Laboratory (BNL) on the half-time of the long-term compartment in the Marshallese [23]. The gut transfer coefficient for ^{137}Cs is 1.

The half-time of ^{137}Cs in children is determined in two stages. The equation used to determine the half-time of ^{137}Cs, developed by Snyder at Oak Ridge National Laboratory, is $T_{1/2}$ = 1.63 M, where M is the body mass in kilograms [24]. The constant of 1.63 is adjusted from the original 1.43 to account for the now-accepted, 110-d long-term compartment. The M as a function of age is determined using equations given by Spiers [13]. When the Snyder and Spiers equations are combined, the half-time as a function of age can be determined. The average half-time using the above approach for ages 5 through 10 is about 42 d. Data from BNL whole-body counting for 14 Marshallese children in this age bracket is 43 d. For ages 11 to 15, the Snyder-Spiers method gives an average half-time of about 70 d, while the BNL data for nine adolescents in this age bracket is 69 d [25].

External Gamma

The primary external gamma exposure is from ^{137}Cs, with a very small contribution from ^{60}Co. To convert external gamma measurements in μr/h to an absorbed dose in tissue, we chose to use the conversion factor from exposure dose in air to abosrbed dose in tissue given in the UNSCEAR report [17] that is (0.87)(0.82) = 0.71 where 0.87 is the conversion from exposure to absorbed dose in air and 0.82 is the conversion from absorbed dose in air to absorbed dose in the body. In ICRP Publication 21, the conversion factor for ^{137}Cs gamma rays (0.66 MeV) is 0.65 and it is 0.7 for ^{60}Co (1.17 MeV) [26].

The value for total body given by O'Brien and Sanna for 0.5-MeV gamma rays is 0.52; for 1 MeV the value is 0.56 [27]. For the skeleton, the conversion factors are 0.49 and 0.54 for 0.5 and 1.0 MeV, respectively.

TRANSURANIC RADIONUCLIDES METHODOLOGY

Inhalation

The inhalation model used for the various isotopes of plutonium and for ^{241}Am is that of the ICRP Task Group [28,29]. Parameters for the lung model are also those of the ICRP--the gut-to-blood transfer for plutonium isotopes is 10^{-4} and for ^{241}Am it is 5×10^{-4} [30]. Both ^{241}Am and plutonium are assumed to be class-W compounds.

Ingestion

For the ingestion pathway, the gut transfer coefficients are, as stated above, 10^{-4} for plutonium and 5×10^{-4} for ^{241}Am. The critical organs are bone and liver with a biological half-life of 100 y in bone and 40 y in liver. Of the plutonium and ^{241}Am transferred to blood, 45% is assumed to reach the bone and 45% is assumed to reach the liver. The remaining 10% is distributed among other organs.

The $^{239+240}Pu$ dose to bone marrow and endosteal cells is calculated by Spiers' method in a manner analagous to ^{90}Sr [7,31,32]. First, a dose to bone mass D_B is determined based on the concentration in pCi/g. Second, the ratios D_m/D_B and D_S/D_B are applied to find the specific doses to the tissues of interest. The D_B is related to D_o by

$$D_B = \frac{D_o}{(S_T/S_B)} ,$$

where S_T and S_B are the stopping powers for tissue and bone respectively.

S_T/S_B = 1.225
D_B = 0.2636 (mrad/d • pCi • g)
D_m/D_B = 0.26
D_S/D_B = 3.11.

DATA BASES FOR INPUT PARAMETERS IN THE DOSE MODELS

EXTERNAL EXPOSURE--*IN SITU* MEASUREMENTS

External exposure rates for ^{137}Cs, ^{60}Co, and ^{241}Am were obtained from *in situ* measurements performed by EG&G as part of the NMIRS [33]. These measurements were made with 40 12.7-cm-diameter by 5.1-cm-thick sodium iodide scintillation detectors mounted on 2 pods on a Sikorski SH-3 helicopter. Flight lines were on a 46-m grid at an altitude of 38 m over the islands. For a detailed description of this methodology, see Ref. 11. The average external exposure for Bikini Island is 31 μR/h for ^{137}Cs and 1.9 μR/h for ^{60}Co and for Eneu Island it is 2.3 and 0.2 μR/h, respectively. In addition, external gamma measurements were made at Eneu and Bikini Island, using portable scintillation detectors [2]. Measurements were made 1 m above the ground on a 30-m grid on Bikini Island and a 120-m grid on Eneu Island. The response of the scintillation detector was compared with that of a pressurized ion chamber and two types of thermoluminescent dosimeters. The measurements from the scintillation detector were normalized to the pressurized chambers. The aerial and ground surveys agree quite well [33]. The external gamma doses presented here are based on the island average external exposure. However, the Marshallese spend considerable time (30 to 50%) in or around the housing area. As a result, the housing provides shielding that reduces the average outside exposure by as much as a factor of 2. Also, coral gravel spread 20 to 40 ft around houses, a common practice in the Marshall Islands, can reduce the external exposure by another factor of 2 (see Ref. 2).

The natural background at the atolls is 3.5 μR/h or 22 mrem/y and results primarily from cosmic radiation. The natural background is not included in the doses presented here.

INHALATION

Airborne concentrations of respirable $^{239+240}$Pu and ^{241}Am are estimated from data developed in resuspension experiments conducted at Bikini Atoll in May 1978. We briefly describe the resuspension methodology here; further details can be found in a paper summarizing the studies at Enewetak and Bikini Atolls [34]. Four simultaneous experiments were conducted: (1) a characterization of the normal (background) suspended aerosols and the contributions from sea spray off the windward beach leeward across the island, (2) a study of resuspension of radionuclides from a field purposely laid bare by bulldozers as a worst-case condition, (3) a study of resuspension of radioactive particles by vehicular and foot traffic, and (4) a study of personal inhalation exposure using small dosimeters carried by volunteers during daily routines.

The normal or background mass loading measured by gravimetric methods for both atolls is approximately 55 μg/m^3. The Bikini Island experiments show that 34 μg/m^3 of this total is from sea salt, which is present across the entire island as a result of ocean, reef, and wind action. The mass loading from terrestrial origins is therefore about 21 μg/m^3. The highest terrestrial mass loading observed was 136 μg/m^3 immediately after bulldozing.

Concentrations of $^{239+240}$Pu have been determined for (1) collected aerosols for normal ground cover and conditions in coconut groves, (2) in areas being cleared by bulldozers and being tilled, and (3) stabilized bare soil in cleared areas after a few days of weathering. We have defined an enhancement factor (EF) as the $^{239+240}$Pu concentration in the collected aerosol mass divided by the $^{239+240}$Pu surface soil concentration (0 to 5 cm).

The EF of less than 1 for hi-vol data for normal, open-air conditions is apparently the result of selective particle resuspension in which the resuspended particles have a different plutonium concentration than is observed in the total 0- to 5-cm soil sample. In addition, approximately 10% of the mass observed on the filter is organic matter, which has a much lower plutonium concentration than the soil. Similarly, the EF of 3.1 for high-activity conditions results from the increased resuspension of particle sizes with higher plutonium concentration than observed in the total 0- to 5-cm soil sample.

We have developed additional personal dosimeter enhancement factors (PDEFs) from personal dosimeter data. These data are normalized to the hi-vol data for a particular condition and represent enhancement that occurs around an individual because of his daily activities (different from the open-air measurement made with the hi vols). The total enhancement used to estimate the amount of respired plutonium is the combination of the hi-vol and personal dosimeter values.

In the scenario adopted for the calculations, we assume that a person spends 8 h/d under high-activity conditions and 16 h/d under normal conditions. Finally, a breathing rate of 23 m^3/d (9.6 m^3 under high-activity conditions and 13.4 m^3 under normal conditions) and the surface soil concentration (0 to 5 cm) for each island are used to complete the calculation for plutonium and americium intake via inhalation.

The dose contribution from the inhalation pathway is a major source of exposure to the transuranic radionuclides, but both the inhalation pathway and the transuranics contribute a minor portion of the total doses predicted over the next several decades.

DRINKING WATER

The drinking water pathway contributes a very small portion of the total dose received via all pathways. However, we have included an evaluation to demonstrate its relative contribution and to complete the assessment of all major pathways. Several reports outline the radionuclide concentrations in cistern water and groundwater [4,7,35-37].

The range of radionuclide concentrations observed in the drinking water for various atolls is listed in Table 1. Cistern water is preferred and most often used; however, well water is used when drought conditions exist. When well water is used, the suspended material is allowed to settle out prior to consumption. In addition to drinking water, the Marshallese consume quantities of coffee and Kool-Aid (Malolo) for which they again primarily use cistern water. The total fluid intake using cistern water and well water was determined to be approximately 1 L/d according to the Micronesian Legal Services Corporation (MLSC) survey at Ujelang Atoll [15].

TERRESTRIAL FOODS

Locally grown foods, when available, are collected and measured for the concentration of gamma-emitting radionuclides and for ^{90}Sr, $^{239+240}$Pu, and ^{241}Am. Ocassionally, samples are also analyzed for ^{239}Pu and ^{241}Pu. On major residence islands at Enewetak and Bikini Atoll where no local foods were available, we established test plots of the common foods historically used by the Marshallese. These include coconut, breadfruit, _Pandanus_ fruit, papaya, Table [illegible]. Radionuclide concentrations in cistern water and groundwater in pCi/L.

Atoll and island	^{137}Cs Cistern water	^{137}Cs Ground water	^{90}Sr Cistern water	^{90}Sr Ground water	$^{239+240}Pu$ Cistern water	$^{239+240}Pu$ Ground water
Bikini						
Eneu	0.31	31	0.24	31	0.0044	0.009
Bikini	1.9	430	0.61	120	0.0063	0.045
Likiep						
Likiep	0.058	0.18	0.070	0.28	0.0001	<0.0001
Rikuraru	0.066	0.3	0.055	0.21	0.0002	<0.00004
Wotho	0.086	0.12	0.090	0.033	0.0003	<0.0001
Ujelang						
Ujelang	0.110	0.41	0.090	0.028	0.0004	0.00012
Ailuk						
Enijabro	0.10	0.25	0.074	0.45	<0.0001	0.00011
Ailuk	0.078	0.6	0.049	0.14	0.0003	0.00030
Mejit	0.14	0.76	0.046	0.11	0.0002	0.0015
Utirik						
Utirik	0.14	6.5	0.097	0.882	0.0005	0.0002
Rongelap						
Rongelap	0.46	1.0	0.15	0.082	0.003	0.0002
Enietok	1.1	0.28	0.0012	--	--	--
Kwajalein						
Kwajalein	0.080	0.052	0.0002	--	--	--

banana, squash, sweet potato, and a few other items. In addition, we collected and analyzed samples of domestic meats, such as pigs and chickens, and of land crabs that are occasionally consumed.

Nearly 100 coconut trees have been sampled on a continuing basis and thousands of coconuts have been analyzed from Bikini and Eneu Islands to estimate the average concentration of the radionuclides in coconut meat and fluid [15]. At Enewetak Atoll, about 100 trees that we planted on Enjebi Island in 1975 have recently started bearing fruit and are now available for analysis. Coconut trees were sampled at each atoll during the NMIRS [6]. Fewer breadfruit, Pandanus fruit, papaya, etc. are available at the atolls, so the numbers of trees sampled at Bikini and Enewetak range from 8 to 50; the number of trees sampled was more limited at atolls visited as part of the NMIRS. Samples from a half-dozen pigs and many chickens have been analyzed to determine the average concentration in domestic meats. About 5000 samples from Bikini, 5500 from Enewetak, and 5600 from the NMIRS of plant, soil, animal, marine and water samples have been collected since 1975.

The data presented in Table 2 are the concentrations observed in food products at Bikini Atoll. The radionuclide concentrations in the same food products for atolls visited for the NMIRS are much less than those shown in Table 2 for Bikini Atoll [9]. The concentration of ^{137}Cs in coconut is lognormally distributed as shown in Figs. 5 through 7. This is typical of all radionuclide concentration data in islands where we have sufficient data to evaluate the distribution. The mean value of the data falls at about the 70th percentile of the distribution; three times the mean value falls at about the 96th percentile.

It is preferable to have local foods available so that we can directly measure the radionuclide concentration in the edible portion of the plant. However, frequently it is necessary to evaluate a living pattern where the proposed residence island is void of any food crops. It is then necessary to use a predictive methodology to determine the radionuclide concentration that might be expected if people were to resettle the island and plant subsistence foods. We accomplish this by developing concentration ratios between the radionuclide concentration in the plant to those in the soil on those islands where local foods are available.

Soil Radionuclide Concentrations

All soil profile samples are collected for the following increments: 0 to 5 cm, 5 to 10 cm, 10 to 15 cm, 15 to 25 cm, 25 to 40 cm, and 40 to 60 cm. A total of approximately 500 to 1000 g of soil is collected for each profile increment. Samples are then analyzed by high-resolution gamma spectroscopy to determine the ^{137}Cs and ^{241}Am concentrations and by radiochemical procedures to determine the concentrations of ^{90}Sr; $^{239+240}$Pu; and in some cases, ^{241}Am and ^{241}Pu.

Radionuclide concentrations for the profiles 0 to 5 cm, 0 to 10 cm, 0 to 15 cm, 0 to 25 cm, 0 to 40 cm, and 0 to 60 cm are calculated using equal weights for each 5-cm increment. The island average for each depth profile (i.e., 0 to 5 cm, 0 to 10 cm, 0 to 15 cm, etc.) is calculated by averaging the results for each profile taken on the island. The results are summarized in

Table 2. Radionuclide concentrations in local food products at Bikini and Eneu Islands.

Dietary item	Concentration (pCi/g wet weight) ^{137}Cs	^{90}Sr	$^{239+240}Pu$	^{241}Am
Bikini Island				
Chicken muscle	6.9	0.057	--	--
Chicken liver	6.9	0.057	--	--
Chicken gizzard	6.9	0.057	--	--
Pork muscle	232	1.73	--	--
Pork kidney	216	1.79	--	--
Pork liver	94	0.67	--	--
Pork heart	123	1.04	--	--
Bird muscle	0.055	0.04	3.8 (-4)[a]	1.9 (-4)
Bird viscera	0.4	0.04	--	--
Bird eggs	0.033	0.018	3.8 (-4)	1.9 (-4)
Chicken eggs[b]	6.9	0.057	--	--
Pandanus fruit	199	9.5	1.5 (-4)	2.1 (-4)
Pandanus nuts	199	9.5	1.5 (-4)	2.1 (-4)
Breadfruit	21.6	4.34	8.1 (-5)	5.7 (-5)
Coconut fluid	85	0.0195	5.02 (-5)	7.1 (-6)
Coconut milk copra	238	0.22	9.6 (-5)	2.4 (-5)
Tuba/Jekaro	169	0.22	9.6 (-5)	2.4 (-5)
Drinking coconut meat	193	0.22	9.6 (-5)	2.4 (-5)
Copra meat	238	0.22	9.6 (-5)	2.4 (-5)
Sprouting coconut	260	0.22	9.6 (-5)	2.4 (-5)
Marshallese cake	238	0.22	9.6 (-5)	2.4 (-5)
Papaya	98	1.9	7.7 (-5)	9.8 (-5)
Rainwater	1.9 (-3)	6.1 (-4)	6.3 (-6)	3.2 (-6)
Wellwater	0.43	0.12	4.5 (-5)	2.2 (-5)
Malolo	1.9 (-3)	6.1 (-4)	6.3 (-6)	3.2 (-6)
Coffee/tea	1.9 (-3)	6.1 (-4)	6.3 (-6)	3.2 (-6)
Eneu Island				
Chicken muscle[c]	1.7	0.014	--	--
Chicken liver[c]	1.7	0.014	--	--
Chicken gizzard[c]	1.7	0.014	--	--
Pork muscle[c]	52	0.43	--	--
Pork kidney[c]	36	0.3	--	--
Pork liver[c]	25	0.21	--	--
Pork heart[c]	31	0.25	--	--
Bird muscle	0.055	0.04	3.8 (-4)	1.9 (-4)
Bird viscera	0.4	0.04	--	--
Bird eggs[b]	0.033	0.018	3.8 (-4)	1.9 (-4)
Chicken eggs	1.7	0.014	--	--
Coconut fluid	9.8	5.1 (-3)	2.21 (-5)	1.90 (-5)
Coconut milk copra	37	0.063	9.1 (-5)	5.68 (-5)
Tuba/Jekaro copra	21	0.063	9.1 (-5)	5.68 (-5)
Drinking coconut meat	19	0.063	9.1 (-5)	5.68 (-5)

Table 2. (Continued)

Dietary item	Concentration (pCi/g wet weight)			
	^{137}Cs	^{90}Sr	$^{239+240}Pu$	^{241}Am
	Eneu Island (continued)			
Copra meat	37	0.063	1.4 (-4)	1.1 (-4)
Sprouting coconut	40	0.063	1.4 (-4)	1.1 (-4)
Marshallese cake	37	0.063	1.4 (-4)	1.1 (-4)
Papaya	14	0.2	8.6 (-6)	5.7 (-5)
Squash	8.5	0.064	8 (-6)	4 (-6)
Pumpkin	8.5	0.064	8 (-6)	4 (-6)
Banana	0.86	--	--	--
Watermelon	2.6	0.031	1.3 (-5)	4.2 (-6)
Arrowroot	0.93	--	--	--
Rainwater	3.1 (-4)	2.4 (-4)	4.5 (-6)	2.3 (-6)
Wellwater	0.031	0.031	9.2 (-6)	4.6 (-6)
Malolo	3.1 (-4)	2.4 (-4)	4.5 (-6)	2.3 (-6)
Coffee/tea	3.1 (-4)	2.4 (-4)	4.5 (-6)	2.3 (-6)

[a] Values in parentheses indicate powers of ten.

[b] Assumed to be the same as chicken.

[c] Pig and chicken data from Bikini Island.

Table 3 for 94 profiles from Bikini Island and 84 profiles for Eneu Island. Hundreds of soil profiles have been analyzed from Enewetak Atoll and from the atolls visited during the NMIRS.

The ^{137}Cs concentrations in the soil on Eneu Island are lognormally distributed as indicated in Fig. 8. Similar results were observed for soil radionuclide concentrations at Bikini Island and other islands at various atolls.

Concentration Ratios

Because of the scarcity or absence of locally grown foods at some atolls and islands, we have developed concentration ratios between food products and soil (pCi/g wet weight in food per pCi/g dry weight in soil) for each radionuclide. The mean, median, and the high and low values for the

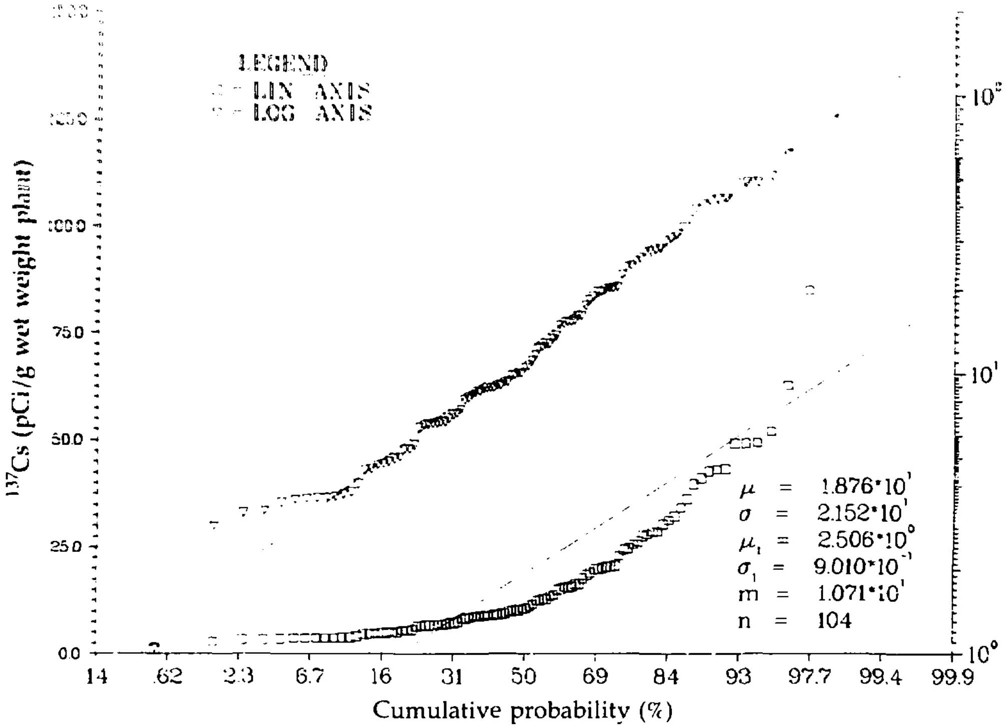

Figure 5. Log probability plot of ^{137}Cs concentration in drinking coconut meat on Eneu Island.

concentration ratios developed from samples collected through March 1980 at Bikini Atoll are listed in Tables 4-6 for ^{137}Cs, ^{90}Sr, and $^{239+240}$Pu, respectively. The ^{241}Am is similar to $^{239+240}$Pu. The concentration ratios are developed from soil profiles taken to a depth of 40 cm through the root zone of the plants being sampled. This depth is used because we observe that it encompasses most of the active root zone of the subsistence plants we have studied on Enewetak and Bikini Atolls. A report on the root activity of large, mature coconut and banana trees in other tropical regions showed most of the activity in the 0- to 60-cm depth, although root activity did vary with age and species [38]. The report is consistent with our observations of the physical location of the root zone at Enewetak and Bikini Atolls.

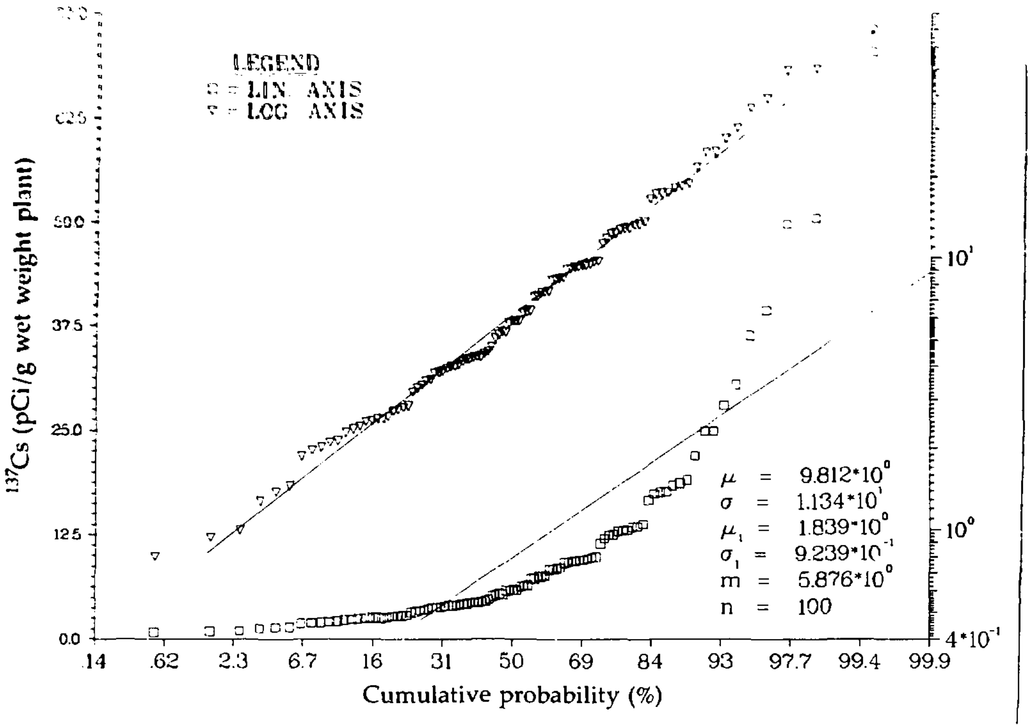

Figure 6. Log probability plot of ^{137}Cs concentration in drinking coconut fluid on Eneu Island.

Thus, once the concentration ratios are developed from islands where local foods are available, they can be multiplied by the soil radionuclide concentration measured on islands where no local foods are available to estimate the radionuclide concentration in edible foods if resettlement should occur and subsistence food were planted. This predictive method has been used at many islands where resettlement is being considered but local foods are unavailable for analysis. The concentration ratios are lognormally distributed.

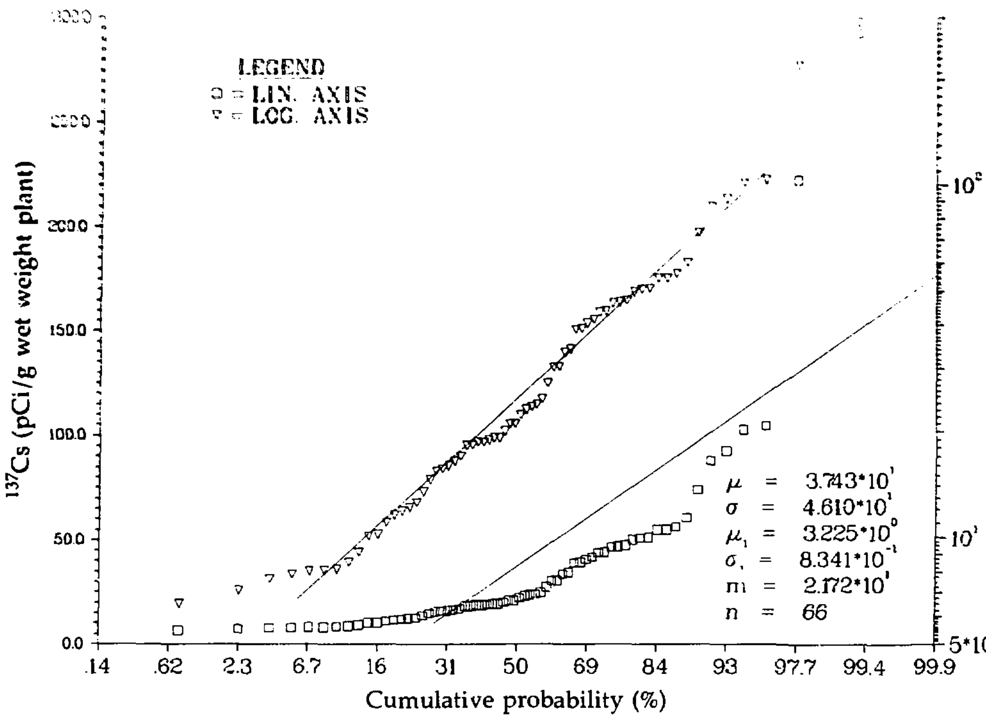

Figure 7. Log probability plot of ^{137}Cs concentration in copra meat on Eneu Island.

Table 3. Average soil concentrations for over 100 soil profiles for both Bikini and Eneu Islands.

Profile (cm)	Soil concentration (pCi/g dry weight)							
	Bikini Island				Eneu Island			
	^{137}Cs	^{90}Sr	$^{239+240}$Pu	^{241}Am	^{137}Cs	^{90}Sr	$^{239+240}$Pu	^{241}Am
0 to 5	101	103	11	8.7	7.4	4.8	0.82	0.41
0 to 10	90	108	10	8	6.1	4.2	0.73	0.39
0 to 15	79	108	9.7	7.3	5.3	4	0.73	0.42
0 to 25	62	93	8.2	6.4	4.3	4.1	0.75	0.46
0 to 40	49	73	7.1	5.4	3.4	4.5	0.76	0.5

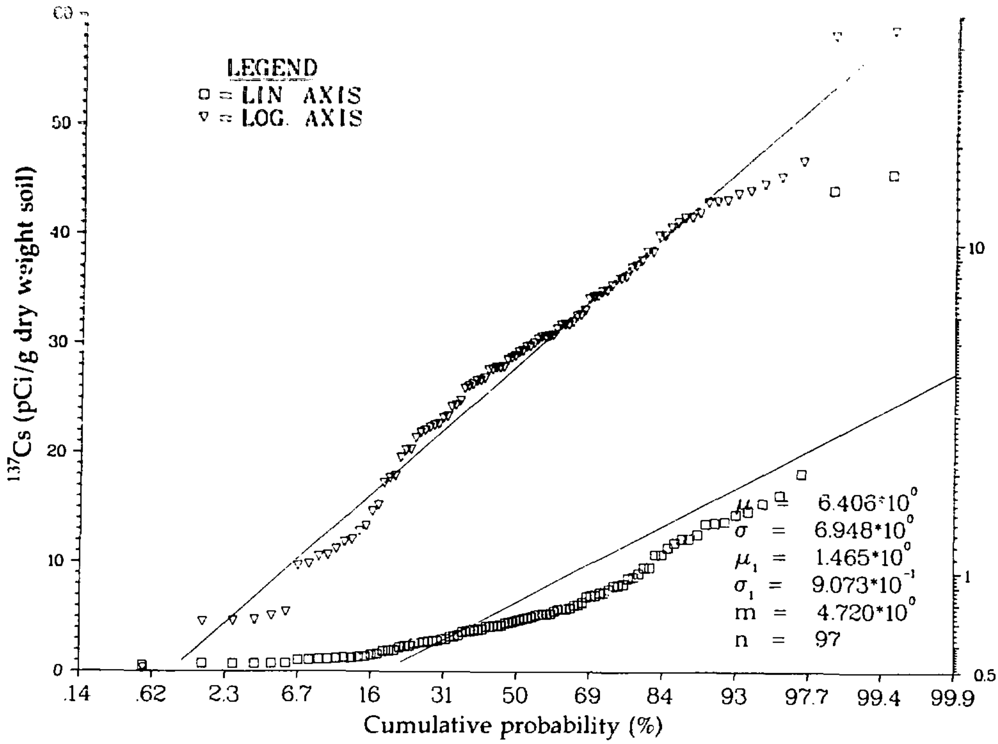

Figure 8. Log probability plot of ^{137}Cs concentration in the top 0 to 5 cm of soil at Eneu Island.

Marine Foods

The radionuclide concentrations in marine foods are listed in Table 7 for Bikini Atoll. The details for the radionuclide concentrations in fish at various atolls are listed and discussed elsewhere [8,39-41]. The data represent the analyses of hundreds of the five or six most common species consumed by the Marshallese. The radionuclide concentration for most species is very low, and the marine pathway contributes a very small portion of the total estimated doses at an atoll.

Table 4. Concentration ratios of ^{137}Cs estimated over a 0- to 40-cm soil profile for subsistence crops at Bikini and Eneu Islands.

Dietary item	Number of trees or plants	Number of samples	Number of fruits[a]	Mean Concentration ratio[a]	High value	Median	Low value
Drinking coconut meat	82	150	750	6	40	3.7	0.34
Drinking coconut fluid	82	147	735	3	18	1.9	0.1
Copra meat	82	98	490	10	41	6.3	0.82
Sprouting coconut	44	74	370	10	79	5.9	0.92
Breadfruit	10	15	75	0.54	16	0.38	0.12
Pandanus fruit	8	11	22	7.8	34	3.6	0.18
Papaya	48	59	885	2.6	18	0.73	0.036
Squash[b]	13	12	19	2.8	6.1	2.2	0.98
Banana	6	5	50	0.16	0.28	0.14	0.075
Watermelon[b]	17	17	49	1.1	3.3	1.1	0.11

[a] The pCi/g fruit wet weight per pCi/g soil dry weight.

[b] Concentration ratio for a 0- to 5-cm soil profile because of shallow root system.

Table 5. Concentration ratios of ^{90}Sr estimated over a 0- to 40-cm soil profile for subsistence crops at Bikini and Eneu Islands.

Dietary item	Number of trees or plants	Mean Concentration ratio[a]	High value	Median	Low value
Coconut meat	26	9.8 (-3)[b]	7.3 (-2)	5.1 (-3)	8.6 (-4)
Coconut fluid	17	1.8 (-3)	5.9 (-5)	9 (-4)	7.6 (-3)
Breadfruit	9	0.07	0.15	5.5 (-3)	5.8 (-3)
Pandanus fruit	3	0.46	0.69	0.42	0.26
Papaya	15	4.1 (-2)	1.1 (-1)	2.8 (-2)	9.8 (-3)
Squash	6	2.4 (-2)	4 (-2)	2.4 (-2)	8.8 (-3)
Banana	3	9.6 (-3)	1.5 (-2)	7.7 (-3)	5.8 (-3)
Watermelon	8	1.8 (-2)	2.9 (-2)	1.5 (-2)	7.2 (-3)

[a] The pCi/g fruit wet weight per pCi/g soil dry weight.

[b] Values in parentheses indicate powers of ten.

Table 6. Concentration ratios of $^{239+240}Pu$ estimated over a 0- to 40-cm soil profile for subsistence crops at Bikini and Eneu Islands.

Dietary item	Number of trees or plants	Mean Concentration ratio[a]	High value	Median	Low value
Coconut meat	22	9.7 (-5)[b]	4.8 (-4)	3.1 (-5)	1.7 (-6)
Coconut fluid	11	1.2 (-5)	--	--	--
Breadfruit	8	1.5 (-5)	4.7 (-5)	1.2 (-5)	1.6 (-6)
Pandanus fruit	3	4.3 (-5)	8.9 (-5)	3.3 (-5)	6.4 (-6)
Papaya	16	3.6 (-5)	1.8 (-4)	2 (-5)	3.3 (-7)
Squash	5	1.9 (-5)	4 (-5)	1.2 (-5)	3.3 (-6)
Banana	3	2.4 (-5)	6.4 (-5)	7.2 (-6)	8.4 (-7)
Watermelon	8	4 (-5)	8.9 (-5)	3.2 (-5)	7.1 (-6)

[a] The pCi/g fruit wet weight per pCi/g soil dry weight. The mean concentration ratio for ^{241}Am is similar to Pu.

[b] Values in parentheses indicate powers of ten.

Table 7. Measured and estimated radionuclide concentrations in marine species and birds and coconut crabs at Bikini Atoll.

Dietary item	Concentration (pCi/g wet weight)			
	^{137}Cs	^{90}Sr	$^{239+240}Pu$	^{241}Am
Fish (reef)	0.16	0.002	3.8×10^{-4}	1.9×10^{-4}
Fish (pelagic)	0.14	0.002	3.8×10^{-4}	1.9×10^{-4}
Shellfish	0.005	0.005	1.7×10^{-3}	0.85×10^{-3} [b]
Clams[a]	0.011	0.006	1.4×10^{-3}	0.7×10^{-3}
Birds	0.055	0.04	1.3×10^{-4} [c]	0.65×10^{-4} [c]
Bird eggs	0.033	0.018	1.3×10^{-4} [c]	0.65×10^{-4} [c]
Crabs	48	8.81	6.8×10^{-3}	3.4×10^{-3}

[a] Includes both muscle tissue and hepatopancreas.

[b] Calculated using the fish $^{239+240}Pu$ to ^{241}Am ratio of 2.

[c] Assumed to be the same as fish muscle.

DIET

The estimated average diet used in the dose assessment is a very critical parameter--doses will correspond directly with the ingested activity, which is directly related to the quantity of locally grown food that is consumed. Therefore, an accurate estimate of the average daily consumption rate of each food item is important.

Because we have been unable to obtain information on the dietary habits of the people at all of the atolls, the diets used in this dose assessment are those recently developed from the MLSC survey conducted of the Enewetak people on Ujelang Atoll and from the BNL surveys at Rongelap, Utirik, and Ailuk Atolls. More detailed information on the MLSC survey can be found in Refs. 15 and 42 and a discussion of the BNL survey appears in Ref. 43.

Briefly, in the MLSC survey there were 144 persons, approximately 25% of the Ujelang population, who were interviewed. Two females failed to complete the dietary questionnaire. The breakdown by age group was 36 adult males, 36 adult females, 19 children 12 through 17 y of age, 37 children 4 through 11 y of age, and 16 children 0 through 3 y of age.

Some people were away from the atoll during the interview, so selection was limited to those households where several people were available. The households were selected at random from the available pool. According to Michael Pritchard of the MLSC, "the household survey met three major needs: it provided in descriptive fashion an account of the eating habits for the entire population of Ujelang; it provided data on certain special diets for certain types of individuals such as pregnant women; and served as a census document for locating individuals for the IMD survey."

The recent BNL report on dietary information on Rongelap, Utirik, and Ailuk was developed by the authors from personal observations while living with the Marshallese and from answers to questionnaires [43].

The observations and questionnaires were directed more toward estimating the food prepared for a family rather than the amount of food actually consumed. Because food is shared and some food prepared is fed to pigs or chickens, these two are not necessarily the same. In the report the authors state, "the averages which we obtained from the interview study are for one reason or another consistently overestimated and should be considered maximum estimates or overestimates."

The diet patterns are divided into three categories representing three types of communities. Community A has a maximum availability of local foods, a highly depressed local economy (living within income provided by selling copra), a low population, and little or no ability to buy imported food. Community B has a low availability of local foods except fish because of excellent fishing in the area, is overpopulated--resulting in low availability of local foods, and has good supply of imported foods and readily available jobs. Community C has a low availability of local foods and poor fishing, a large government food program, is overpopulated, and has a good supply of imported foods and availability of cash to buy them.

The data from the MLSC Survey and from BNL are compared in Table 8. The largest discrepancy between the two surveys is for coconut fluid. The range in the MLSC survey is 142 to 217 g/d for the average intake when imported foods are available and unavailable, respectively. The range in the BNL survey for the average prepared for a household is 305 g/d for community C to 1025 g/d for community A. The prepared coconut meat in the BNL survey is 40 to 50% higher than that consumed according to the MLSC survey. The Pandanus fruit prepared is nearly double the MLSC consumption value.

Fish consumption in the MLSC survey is within the range observed by BNL. The intake of squash and papaya is also very similar in the two reports. However, intake of shellfish, clams, coconut crabs, domestic meat, wild birds, breadfruit, and arrowroot is greater in the MLSC survey than in the BNL survey.

In the summary of a survey conducted during July and August of 1967 at Majuro Atoll, the average coconut use was reported to be approximately 0.5 coconut per day per person [44]. This included young drinking coconuts, old nuts used for grated meat and pressed for small volumes of milk, and sprouting nuts used for the sweet, soft core. Recent data from Eneu Island shows that an average drinking coconut contains 325 mL of fluid (standard deviation = 125 mL), so that even if the entire average coconut use of 0.5/d were all drinking nuts, the average intake would be about 160 g/d. This is in agreement with the results from the MLSC survey at Ujelang.

In evaluating all available data on dietary habits in the Marshall Islands, there are a few general conclusions to be drawn.

(1) The dietary intakes used here are based on the most current diet surveys.

Table 8. Diet comparison of the maximum diet from the MLSC survey at Ujelang and the BNL study at Rongelap and Utir...

Dietary item	Intake for adult female, MLSC Ujelang survey: Imports available (g/d)	Imports unavailable (g/d)	Intake from BNL Marshall Islands survey[a] (g/d)
Fish	42	90	84 to 194
Shellfish[b]	5.1	25	0.14 to 0.4
Clams	8.9	44	5 to 15
Coconut crabs[c]	3.1	13	1 to 2
Domestic meat[d]	21	35	0.7 to 4.4
Wild birds	4	18	0.6 to 9
Eggs[e]	11	56	2.4
Pandanus	9	33	64 to 96
Breadfruit	27	93	36 to 53
Coconut fluid	142	217	430 to 521
Coconut meat	63	187	268 to 280
Squash (pumpkin)	1.2	2.7	0 to 5
Arrowroot	3.9	47	0
Papaya	7	14	0 to 12
Banana	0.02	0.3	17 to 19

[a] Reference 43.

[b] Marine crab and lobster.

[c] Includes land crabs.

[d] Pork and chicken.

[e] Bird, chicken, and turtle.

(2) The dietary habits of a people are atoll specific and one should not arbitrarily generalize from one atoll to another.

(3) There is still some uncertainty as to what an average diet really is at any atoll.

(4) Many factors can affect the average diet over any specific year.

(5) Further atoll-specific dietary studies are needed to improve the precision of the dose assessments.

Throughout our discussion of diet and estimated dose, three expressions are used extensively: imports available, imports unavailable, and local foods. Imports-available conditions exist when field ships arrive on schedule and imported and local foods are both available. Imports unavailable indicates a condition where there is an absence or greatly reduced availability of imported foods. Local foods is our expression for the locally grown foods of the MLSC and BNL surveys. Under normal conditions, imported foods provide a greater percentage of the diet than do local food items. When imports are unavailable, it is assumed that local food consumption increases and that the intake of imported foods would be much more limited. This condition is then projected over a lifetime.

The daily food intake in grams per day is multiplied by the radionuclide concentrations in the food products to give the average daily intake of radionuclides for the various atolls and islands as input to the dose codes. The distribution of dietary intake as determined from the MLSC survey is lognormally distributed, (Fig. 9). The distribution for the dietary intake by the male population is similar to that for the female.

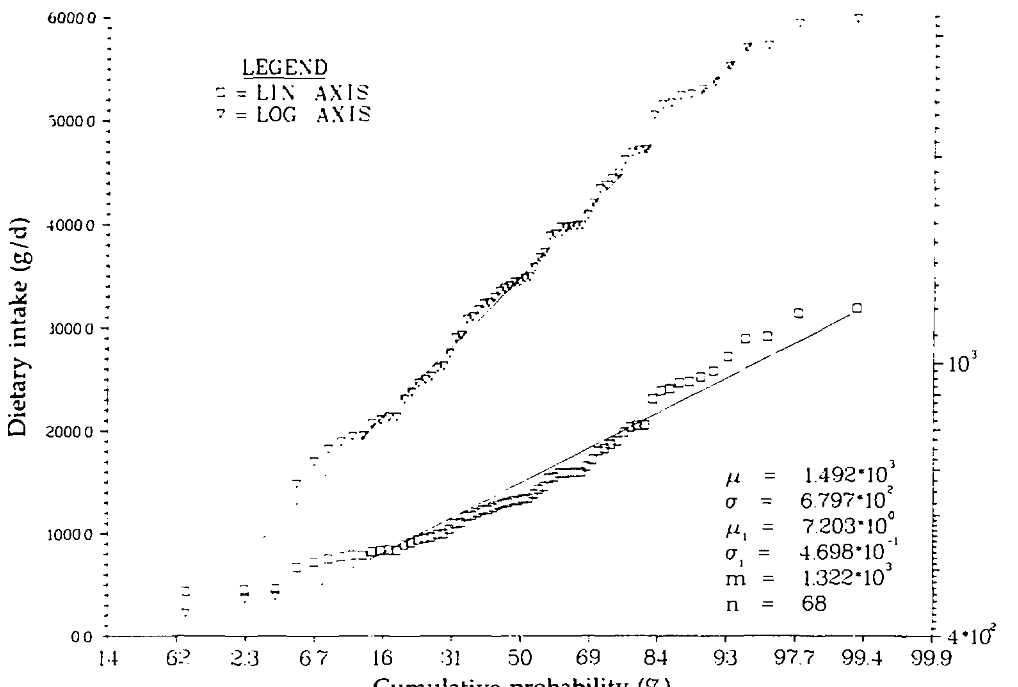

Figure 9. Log probability plot of the dietary intake of 34 Marshallese females.

LIVING PATTERNS

Doses have been estimated for the major islands at each atoll assuming a continuous residence on each island and all local food derived from that island. Some of the islands listed are only used part time for residence or for agricultural purposes, but we have estimated the dose assuming continuous occupation to indicate the dose relative to current residence islands.

BODY AND ORGAN WEIGHTS

Data from BNL have been summarized to determine the body weights of the Marshallese people [25,45]. The average, adult male body weight is 72 kg for Bikini, 71 kg for Enewetak, 61 kg for Rongelap, and 69 kg for Utirik; the weighed means is 69.9 kg, very near the 70-kg value of reference man [46]. As a result, we have used 70 kg as the average body weight in our dose calculations. The average body weight for 113 adult females in the Enewetak population is 61 kg; it is 67 kg for 30 Utirik females and 63 kg for 36 Rongelap females. The distribution of body weights for Marshallese males and females appear to be more nearly lognormally distributed than normally distributed as shown in Fig. 10 for the female. The distribution for male body weights is similar to the female distribution.

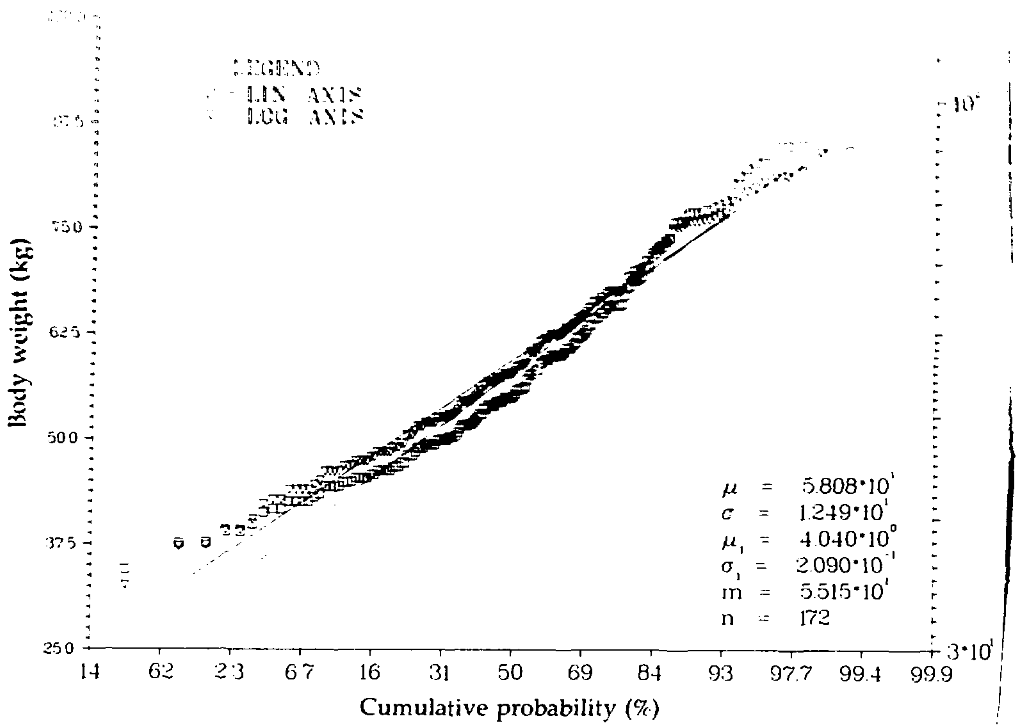

Figure 10. Log probability plot for the body weight of 172 adult Marshallese females.

RESIDENCE TIME OF ^{137}Cs IN THE BODY

Cesium-137 accounts for a significant fraction of the total dose at the atolls and essentially contributes all of the whole-body exposure. Therefore, specific information on the residence time of ^{137}Cs in the human body is important. Measurements of ten Marshallese males by BNL show that the mean residence time is 114 d (range: 76 to 178 d) for the long-term compartment, which is very consistent with published information on other populations [23]. For 21 females, the mean value is 83 d (range: 63 to 126 d). Our summary of the BNL data shows the residence time of 151 adult males to be lognormally distributed (Fig. 11).

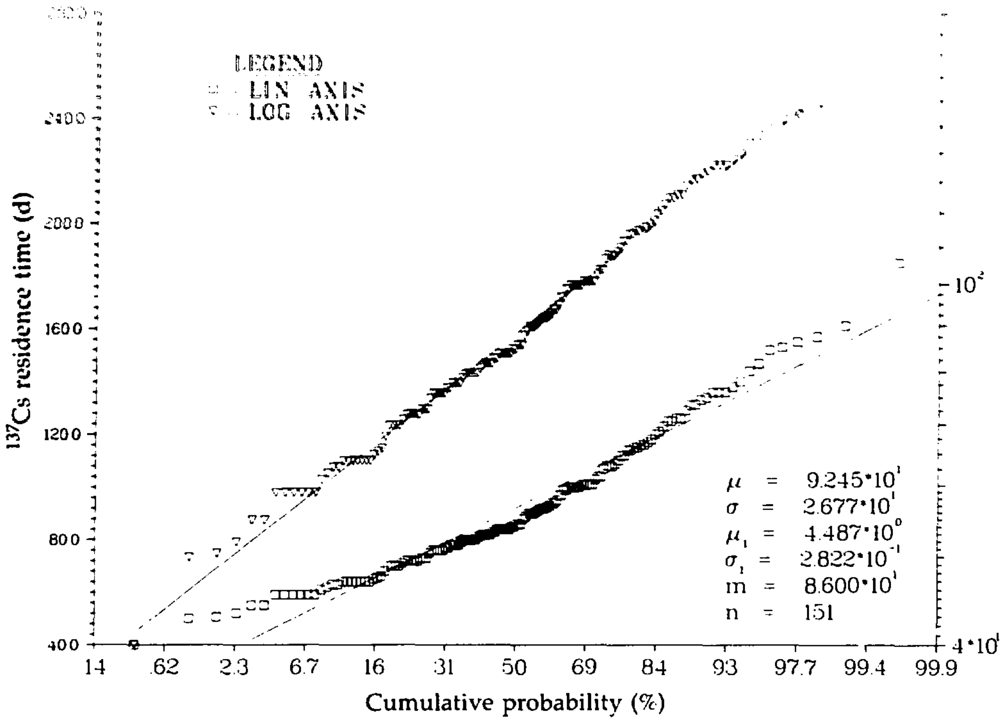

Figure 11. Log probability plot of the residence time of ^{137}Cs in the body of 152 adult Marshallese males.

RESULTS

Here we present the predicted, maximum annual dose-equivalent rates and the 30- and 50-y integral dose equivalents for the different living patterns and resettlement options. The doses are calculated using the average dietary intake, radionuclide concentration, radionuclide fraction absorbed into the body from that ingested, biological residence time, and external dose rate. The maximum annual dose rate for the whole body is defined as the dose rate in that year after the Marshallese return when the sum of the whole-body ingestion dose from ^{137}Cs and the external gamma dose is a maximum. For bone marrow, the maximum occurs when the bone-marrow ingestion dose from ^{137}Cs and ^{90}Sr and the external gamma dose is a maximum.

The estimated, maximum annual dose-equivalent rates for three living patterns at Enewetak Atoll based on the Ujelang Diet are listed in Table 9. The whole-body and bone-marrow dose equivalent rates range from 235 to 500 mrem/y for Enjebi Island depending on whether imported foods are available or unavailable and from 3.7 to 7.8 mrem/y for Enewetak or other southern islands. The third living pattern, with doses intermediate to the other two living patterns, is a case where residence would be on Enjebi Island but most of the food products would come from the southern islands. The 30- and 50-y integral dose equivalents for the Enjebi Island living pattern are listed in Table 10. The 30-y integral, whole-body dose equivalent is 5.7 rem when imported foods are available and 10 rem when unavailable. The corresponding 50-y integral doses are 8.4 and 15 rem, respectively. Evaluation of other living patterns is given in Ref. 42.

The maximum, annual dose-equivalent rates for the two major residence islands at Bikini Atoll are listed in Table 11. The doses, based on the MLSC diet when imports are available and unavailable, range from 1 to about 2 rem/y for Bikini Island and from 130 to 260 mrem/y for Eneu Island. The 30-y integral dose equivalents given in Table 12 range from 22 to 45 rem for Bikini Island and from 2.9 to 5.5 rem for Eneu Island; the integral doses are listed to show the contribution of each radionuclide. The ^{137}Cs through ingestion of local food and external gamma exposure accounts for over 90% of the total dose. The ^{90}Sr is the next most significant contributor to the bone-marrow dose. If the BNL diet was used, the doses would be about 2.7 times those listed in the tables.

The 30-y integral dose equivalents for Bikini and Eneu are listed by exposure pathway in Table 13 to show the relative contribution of each pathway. The terrestrial food chain is most significant potential exposure pathway; the external gamma exposure pathway is next in significance. The other pathways are relatively minor contributors. More detail on the Bikini Atoll dose assessment can be found in Ref. 15.

The maximum, annual whole-body dose-equivalent rates for the atolls downwind of the proving grounds are listed in Table 14 for the inhabited atolls. The doses are given as the range observed between the various diet options discussed previously. For example, the range observed for Likiep Atoll is from 3.2 mrem/y for the MLSC diet to 23 mrem/y for the applicable BNL diet. The highest estimated doses for the inhabited atolls are for the

Table 9. Maximum, annual dose-equivalent rates in mrem/y for adult females for diet conditions when imports are available and unavailable.[a]

Location	Type of diet	Organ	Pathway: Ingestion	Pathway: External gamma	Total	Year of maximum dose
Enjebi	Imports available	Bone marrow	237	54	291	10
		Whole body	222	55	277	9
	Imports unavailable	Bone marrow	500	54	554	10
		Whole body	455	54	509	10
Southern islands	Imports available	Bone marrow	3.9	1.2	5.1	3
		Whole body	3.3	1.2	4.5	2
	Imports unavailable	Bone marrow	9.8	1.1	11	5
		Whole body	7.4	1.2	8.6	3
Enjebi Island and southern islands	Imports available	Bone marrow	39	47	86	9
		Whole body	21	62	83	2
	Imports unavailable	Bone marrow	107	43	150	12
		Whole body	63	47	110	9

[a] The listed doses can be converted to SI units by the equation 100 mrem = 1 mSv.

southern islands of Rongelap where the doses range from 35 to 110 mrem/y. Most of the estimated annual dose equivalents for the uninhabited atolls are low with the exception of the northern islands at Rongelap where they range from 91 to 330 mrem/y (Table 14).

The 30-y integral dose equivalents are listed in Table 15 for all of the atolls. At most atolls the doses are less than 0.3 rem. The estimated doses for the southern islands of Rongelap range from 0.76 to 2.5 rem. If the northern islands of Rongelap were inhabited on a continuing basis, the estimated doses would range from 2.1 to 11 rem. A more detailed analysis of the estimated doses for atolls downwind of the proving grounds can be found in Refs. 7-9.

Table 10. The 30- and 50-y integral dose equivalents for adult females when imported foods are both available and unavailable for the Enjebi Island living pattern.

Pathway and nuclide	30-year integral dose (rem)				50-year integral dose (rem)			
	Whole body		Bone marrow		Whole body		Bone marrow	
	Imports available	Imports unavailable	Imports available	Imports unavailable	Imports available	Imports unavailable	Imports available	Imports unavailable
Ingestion								
^{137}Cs	4.3	8.7	4.3	8.7	6.5	13	6.5	13
^{90}Sr	--	--	0.38	1.2	--	--	0.59	1.9
$^{239+240}Pu$	--	--	0.0033	0.014	--	--	0.0088	0.037
^{241}Am	--	--	0.0046	0.018	--	--	0.013	0.050
^{241}Pu (^{241}Am)	--	--	0.0021	0.0077	--	--	0.0078	0.029
External gamma								
^{137}Cs + ^{60}Co	1.4	1.4	1.4	1.4	1.9	1.9	1.9	1.9
Inhalation								
$^{239+240}Pu$	--	--	0.23	0.23	--	--	0.61	0.61
^{241}Am	--	--	0.099	0.098	--	--	0.26	0.26
^{241}Pu (^{241}Am)	--	0.026	0.026	--	--	--	0.094	0.094
TOTAL	5.7	10	6.1	11	8.4	15	9	17

A comparison of the estimated body burdens from our dose models and data using the two diet models with that from the BNL whole-body counting observations are shown in Table 16. The predicted average body burden for Bikini Island for the MLSC diet is 5.5 μCi when imported foods are available and 11 μCi when imported foods are unavailable; the predicted body burden for the BNL diet is about 20 μCi. The BNL-measured average body burdens in 1978 in the Bikini people is 2.4 μCi in males and 1.7 μCi in females [47,48]. At Rongelap Atoll, the average measured body burden in 1978 for adults was 0.17 μCi [49]. The models predict an average body burden of 0.19 μCi for tne MLSC diet when imported foods are available and 0.42 μCi when unavailable and 0.58 μCi for the BNL diet. At Utirik Atoll, the predicted average body burden using the MLSC diet is 0.043 μCi when imported foods are available and 0.098 μCi when unavailable; the predicted body burdens are 0.18 μCi using the BNL diet. The BNL-measured average body burden was 0.053 μCi for adults in 1978 [49].

Table 11. Maximum, annual dose-equivalent rates in mrem/y for adults for living patterns consisting of (1) 100% time on Bikini Island and all locally grown foods from Bikini and (2) 100% time on Eneu Island and all locally grown foods from Eneu.

Organ	Radionuclide ingestion[a]	External gamma[b]	Total	Year of maximum dose
		Bikini Island		
		Imports available		
Whole body	815	189	1000	3
Bone marrow	845	189	1030	3
		Imports unavailable		
Whole body	1685	189	1870	3
Bone marrow	1775	189	1960	3
		Eneu Island		
		Imports available		
Whole body	116	14	130	3
Bone marrow	122	14	140	3
		Imports unavailable		
Whole body	231	14	250	3
Bone marrow	249	14	260	3

[a] Whole-body ingestion dose from ^{137}Cs. Bone-marrow ingestion dose from ^{137}Cs and ^{90}Sr.

[b] Background substracted.

Table 12. The 30-y integral dose equivalents in rem for adults for a living pattern consisting of (1) 100% time on Bikini Island and all locally grown foods from Bikini and (2) 100% time of Eneu Island and all locally grown foods from Eneu.

Pathway and radionuclide	Imports available		Imports unavailable	
	Whole body	Bone marrow	Whole body	Bone marrow
Bikini Island				
Ingestion				
^{137}Cs	18	18	38	38
^{90}Sr	--	1	--	3
$^{239+240}Pu$	--	0.00012	--	0.00045
^{241}Am	--	0.00033	--	0.0010
External gamma				
$^{137}Cs + ^{60}Co$	4.2	4.2	4.2	4.2
Inhalation				
$^{239+240}Pu$	--	0.033	--	0.033
^{241}Am	--	0.035	--	0.035
^{241}Pu (^{241}Am)	--	0.005	--	0.005
TOTAL	22	23	42	45
Eneu Island				
Ingestion				
^{137}Cs	2.6	2.6	5.2	5.2
^{90}Sr	--	0.2	--	0.61
$^{239+240}Pu$	--	0.00011	--	0.00038
^{241}Am	--	0.00035	--	0.0011
External gamma				
$^{137}Cs + ^{60}Co$	0.32	0.32	0.32	0.32
Inhalation				
$^{239+240}Pu$	--	0.024	--	0.024
^{241}Am	--	0.016	--	0.016
^{241}Pu (^{241}Am)	--	0.00038	--	0.00038
TOTAL	2.9	3.1	5.5	6.1

Table 13. Comparison of the 30-y integral dose-equivalent contributions in rem for adults for five exposure pathways at Bikini and Eneu Islands when imported foods are available.

Pathway	Bikini Island			Eneu Island		
	Whole body	Bone marrow	Lung	Whole body	Bone marrow	Lung
Terrestrial foods	18	20	19	2.6	2.8	2.6
External gamma	4.2	4.2	4.2	0.32	0.32	0.32
Marine foods	0.0037	0.0072	0.0037	0.0037	0.0072	0.0037
Inhalation	--	0.075	--	--	0.0045	--
Cistern water	0.0017	0.0056	0.0017	0.00028	0.0019	0.00028
Groundwater	0.19	0.55	0.19	0.014	0.11	0.014

Table 14. Maximum, annual whole-body dose-equivalent rates from the NMIRS.

Atolls	Range of maximum, annnual whole-body dose-equivalent rates using MLSC and BNL diets (*mrem/y*)[a]
Inhabited	
Likiep (all islands)	3.3 to 23
Ailuk (all islands)	3.9 to 34
Wotho (all islands)	2.4 to 10
Ujelang (all islands)	3.3 to 5.7
Mejit (Mejit)	5.9 to 31
Utirik (all islands)	11 to 29
Rongelap (southern islands)	35 to 110
Uninhabited	
Taka	3.6 to 6.1
Bikar	6.0 to 23
Jemo	4.2 to 14
Ailinginae	13 to 76
Rongerik	42 to 81
Rongelap (northern islands)	91 to 330

Note: The Federal guideline for an individual is 500 mrem/y. The average annual U.S. external background doses range from about 54 to 182 mrem.

[a] Includes all exposure pathways except 22 mrem/y from background cosmic radiation.

Table 15. The 30-y integral dose equivalents from the NMIRS.

Atolls and islands	Range of 30-y integral whole-body dose-equivalent rates using MLSC and BNL diets (rem)[a]
Likiep (all islands)	0.072 to 0.13
Ailuk (all islands)	0.088 to 0.14
Wotho (all islands)	0.055 to 0.24
Ujelang (all islands)	0.075 to 0.13
Taka (all islands)	0.082 to 0.14
Bikar (all islands)	0.14 to 0.52
Mejit (Mejit)	0.13 to 0.71
Jemo (Jemo)	0.096 to 0.33
Utirik (all islands)	0.25 to 0.65
Ailinginae (all islands)	0.28 to 1.7
Rongerik (all islands)	0.94 to 1.8
Rongelap (southern islands)	0.76 to 2.5
Rongelap (northern islands)	2.1 to 11

Note: The Federal guideline for 30-y integral dose is 5 rem. The integrated 30-y U.S. external background dose ranges from about 1.6 to 5.5 rem.

[a] Includes all exposure pathways except 0.66 rem over 30 y from background cosmic radiation.

Table 16. Comparison of the predicted and measured body burdens of ^{137}Cs for three atolls in the Marshall Islands.

Atoll	Predicted adult body burdens using dose models and various diet diet options (μCi)			Measured average body burden in 1978 by BNL (μCi)	
	MLSC diet		BNL diet		
	Imports available	Imports unavailable	Community B	Average	Maximum
Bikini	5.5	11	∿20	2.4 (M)[a] 1.7 (F)[b]	5.7 (M) 2.7 (F)
Rongelap	0.19	0.42	0.58	0.17 (A)[c]	
Utirik	0.043	0.098	0.18	0.053 (A)	

[a] Male.

[b] Female.

[c] Adult.

DISTRIBUTION OF DOSES AROUND THE ESTIMATED AVERAGE DOSE

The doses presented herein are calculated using the mean value of the data available for each parameter in the dose models. For example, model parameters include body weight, residence time of radionuclides in the body, radionuclide concentrations in either foods or soil, dietary intake (measured in grams per day), and fractional deposition of radionuclides in body organs or compartments. Data for all of these parameters have a lognormal distribution as shown in Figs. 5-11. The mean values fall between the 60 to 70th percentile; that is, for a given parameter, approximately 60 to 70% of the data points fall below the mean value. Thus, if the mean values for the parameters are used in the dose models and the data sets are lognormally distributed, the final calculated dose are also lognormally distributed.

The method for calculating the distribution in the final dose is based on the distribution of each of the model parameters and is briefly reviewed here. The 30-y integral dose equivalent for the ingestion of ^{137}Cs has been simulated using Monte Carlo techniques. The equations used are:

$$q(t) = q(\phi) \sum_{i=1}^{N} A_i e^{-\alpha_i t} + f_1 f_2' I \sum_{i=1}^{N} A_i\left(1 - e^{-\alpha_i t}\right)/\alpha_i ,$$

$$Q(t) = \int_0^t q(t) = q(\phi) \sum_{i=1}^{N} A_i\left(1 - e^{-\alpha_i t}\right)/\alpha_i + f_1 f_2' I \sum_{i=1}^{N} \frac{A_i}{\alpha_i}\left[t - \left(1 - e^{-\alpha_i t}\right)/\alpha_i \right] ,$$

$$R = \frac{51.2E \times q(t)}{M} ,$$

$$D = \frac{51.2E \times Q(t)}{M} ,$$

where

I = intake rate (μCi/d)--concentration (μCi/g) x dietary intake (g/d),

$q(0)$ = initial organ burden (μCi) at time $t = t_0$,

$q(t)$ = organ burden (μCi) at time t,

$Q(t)$ = cumulative activity at time t (μCi) since t_0,

f_1 = fraction of ingested activity from gut to blood,

f_2 = fraction of activity in blood to organ of interest,

A_i = fraction of $q(t)$ in compartment i of organ,

B_i = biological elimination rate for compartment i of organ (d^{-1}),

λ = radioactive decay rate of nuclide (d^{-1}),

N = number of organ compartments,

α_i = $\lambda + B_i$ = effective decay rate of compartment i (d^{-1}),

M = organ mass (g),

E = effective energy of nuclide for organ (MeV),

51.2 = units conversion factor,

R = dose rate at time t (rem/d), and

D = integrated dose at time t (rem).

The distributions of variables of interest I, B_i, and M are lognormal, while A_i is uniformly distributed. The values for the variables are generated using International Mathematics and Statistical Laboratory routines for lognormal and random (uniform) deviates. Each run generates the appropriate random numbers for each variable for calculating the dose. After storing the dose in the proper histogram bin, the procedure is repeated until 10,000 (or 100,000) trials have been made. The distribution from 100,000 trials is shown in Fig. 12. The log probability (cumulative distribution) plot for the final doses is shown in Fig. 13.

In addition, the same input data were used with a totally different method for determining the distribution of the final dose based on the distribution of each of the model parameters [50]. In this approach, the distribution of each input parameter is expressed by a finite probability distribution (FPD), which is a discrete approximation of the continuous probability density function of the parameter. The dose, expressed as an FPD, is estimated by systematically combining the input FPDs in the dose model according to the rules of probabilistic arithmetic and storing the results in the proper, predetermined discrete output bins. The two methods give very similar results.

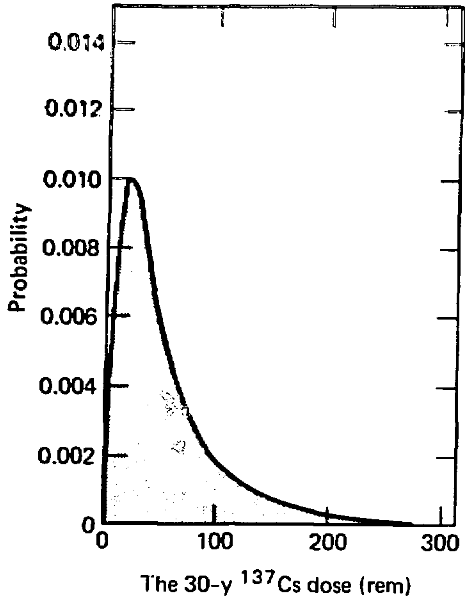

Figure 12. Linear plot of the 30-y integral dose-equivalents from 100,000 trials.

The average doses presented here and calculated using mean values for all of the parameters in the model, fall at about the 68th percentile on the distribution for both methods; that is, 68% of the population would be expected to have doses below this value. A dose equal to twice the average falls near the 88th percentile for both methods; a dose three times the average falls at or above the 95th percentile. Thus, about 68% of the population on Eneu and Enjebi would have a 30-y integral dose equivalent less than 3 and 6 rem, respectively, when imported foods are available. Based on this analysis, there is less than a 5% chance for a person to receive a dose that is greater than three times the average dose.

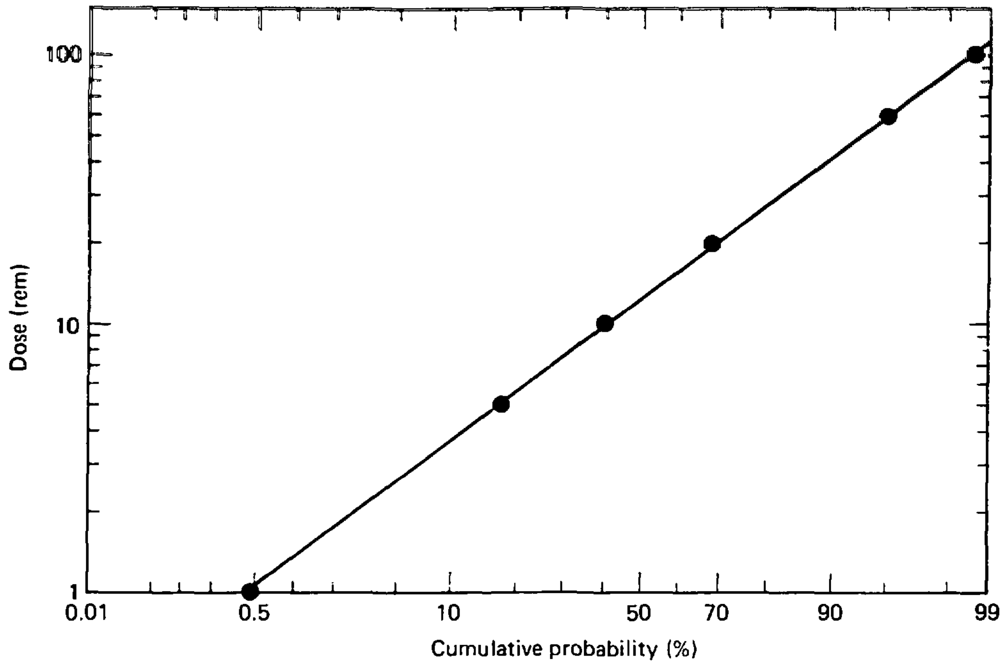

Figure 13. Log probability plot of 30-y integral dose-equivalents with the Monte Carlo method.

SUMMARY AND CONCLUSIONS

The maximum, annual dose-equivalent rates for atolls downwind of the proving grounds, that is, Likiep, Wotho, Ujelang, Mejit, Ailuk, Taka, Jemo, and Bikar for all exposure pathways excluding cosmic radiation are less than 6 mrem/y if the MLSC diet is used and less than 30 mrem/y even when the BNL diet is used. The only significant source of natural external background exposure in the Marshall Islands is the 3.5 μR/h or 22 mrem/y from cosmic radiation [2]. For reference, these doses can be compared with the external background doses observed in the U.S. The total external background dose in the U.S. is 54 mrem/y based on the U.S. population-weighted average; 107 mrem/y for Denver, Colorado, which has a population of about 500,000 (urban population of about 1,500,000); and about 182 mrem/y for Leadville, Colorado, which has a population of about 10,000 [51]. Thus, depending on the diet, most of the atolls have estimated doses from all exposure pathways excluding cosmic radiation that range from about 4 to 57% of the U.S. population-weighted background dose; from about 2 to 29% of the Denver, Colorado dose; and from about 1 to 17% of the Leadville, Colorado dose. When the 22 mrem/y of cosmic radiation background dose in the Marshall Islands is added, the total doses at the atolls for all exposure pathways range from 45 to 100% of the U.S. population weighted external background dose; from about 23 to 50% of the Denver, Colorado external background dose; and from 13 to 29% of the Leadville, Colorado external background dose, depending on which diet is employed. The natural internal dose will be similar in the U.S. and the Marshall Islands.

For additional reference, these estimated doses for the various atolls can be compared to the U.S. Federal guideline of 500 mrem/y above background for an individual [52]. The doses at most atolls are from 1 to 5% of the guideline, depending on which diet is assumed to apply. The highest estimated dose equivalent for an inhabited atoll is for the southern islands at Rongelap where the doses range from about 10 to 50% of the guideline, depending on the diet.

The 30- and 50-y integral dose equivalents provide a similar picture. The 30-y integral dose equivalents for Likeip, Wotho, Ujelang, Mejit, Ailuk, Taka, Jemo, and Bikar for the MLSC diet are less than 0.14 rem and for the BNL diet they are less than 0.7 rem. This is less by a factor of 20 to 33 than U.S. Federal guidelines of 5 rem/30 y for a population [52] and less than the integrated 30-y external background dose in the U.S., which ranges from 1.6 to 5.5 rem [51]. The 30-y integral dose equivalents for the MLSC diet are less than 0.25 rem for Utirik, less than 0.49 rem for Ailinginae, less than 1.3 rem for the southern islands of Rongelap and for Rongerik, less than 7.4 rem for Naen Island on northern Rongelap, and less than 3.3 rem for the other northern islands of Rongelap if they were to be continuously inhabited. Similarly, for the BNL diet, the doses are less than 0.72 rem for Utirik, less than 2.1 rem for Ailinginae, less than 2.5 rem for the southern islands of Rongelap, less than 14 rem for Naen Island at Rongelap, and less than 7.6 rem for the other northern islands at Rongelap for continuous occupation.

The global deposition of ^{137}Cs in the 10 to 15° N. latitude of the Pacific region through 1974 was about 30 mCi/km^2 [53]. Adjusting this to 1978 and comparing it with the concentrations of ^{137}Cs determined here, we see that 30% of the ^{137}Cs soil concentration (and therefore the dose) listed for Likiep, Wotho, Ailuk, Mejit, Ujelang, Bikar, Jemo, and Taka is from worldwide fallout and is not specific to the Marshall Islands. The worldwide fallout of ^{137}Cs accounts for about 7% of the ^{137}Cs at Utirik and about 2% at Rongerik and Rongelap Islands. The other 70, 93, and 98% of the ^{137}Cs concentrations, respectively, are due to intermediate range fallout.

The global deposition of ^{137}Cs between 30 and 50° N., which includes the U.S., is greater by more than a factor of 3 than that in the 10 to 15° N. latitude. Thus, the deposition of ^{137}Cs from global fallout between 30 to 50° N. is nearly equal to the total ^{137}Cs observed at Likiep, Wotho, Ailuk, Mejit, Ujelang, Bikar, Jemo, and Taka. The deposition of other radionuclides follows a similar pattern.

Another comparison for this latitude and this area of the Pacific is the background concentrations of ^{137}Cs in the soils at Ponape, Truk, Palau, and Guam. The ^{137}Cs soil concentration averaged over 10 cm range from 0.1 to 0.5 pCi/g [54]. The range of ^{137}Cs concentration in the 0- to 10-cm soil averaged for Likiep, Wotho, Ailuk, Ujelang, Mejit, and Jemo is 0.2 to 0.7 pCi/g, very similar to the background levels at the other areas of Micronesia, although slightly higher.

The estimated doses for the southern islands at Enewetak Atoll are very low and resettlement has occurred on these islands. However, half of the Enewetak population, who lived on Enjebi prior to their relocation and who own the land in the northern half of the atoll, wish to return and establish permanent residence. The estimated dose equivalent for Enjebi Island, calculated using the average value for all the parameter in the dose models, is less than 300 mrem/y for the annual dose-equivalent rate and about 6 rem for the 30-y integral dose equivalent (Tables 9 and 10). The U.S. Government has elected to multiply by a factor of 3 these estimated annual doses and compare the resulting number with the Federal guideline of 500 mrem/y. Thus, the maximum, annual dose-equivalent rate presented to the Enewetak people and used for risk analysis for Enjebi Island is 900 mrem/y when imported foods are available. After evaluating the maximum doses and the associated risk, the Enjebi people requested to proceed with resettlement plans and that the U.S.

provide housing, public buildings, and an agricultural plan. The U.S. Government has not agreed to the resettlement of Enjebi and the Enjebi people through legal counsel are continuing their efforts to resettle the island.

At Bikini Atoll, the people were again removed from Bikini Island in 1978 and the atoll is currently uninhabited. The people were relocated when doses based on the 1975 Survey [5] were estimated to exceed the Federal guidelines by factors of 4 or 5 and when increasing body burdens were confirmed by the BNL whole-body counting program as local foods become available. The current assessment of Bikini Atoll (Tables 11 and 12) again indicate the magnitude of the doses currently estimated for Bikini Island. However, at neighboring Eneu Island, the estimated annual dose-equivalent rate is about 140 mrem/y when imported foods are available and the corresponding 30-y integral dose equivalent is about 3 rem. Again, the annual dose equivalents results for both islands were multiplied by 3 and presented to the Bikini people along with the associated risk analysis. After evaluating this information, a segment of the Bikini population is pursuing, with the U.S. Government, resettlement of Eneu Island. The U.S. has not agreed to resettlement and currently no agreement or plans have been adopted.

Uncertainty in the final dose values can result from uncertainty in three sources of input data: (1) radionuclide concentration in food (or soil); (2) dietary intake; and (3) the biological parameters such as radionuclide turnover times in the body, fractional deposition in various organs, and body or organ weight. However, evaluation of these data indicates that a value three times the mean is a reasonable, maximum value.

First, the distributions of radionuclide concentration data in relatively large vegetation and soil sample populations from Bikini and Eneu Islands at Bikini Atoll are lognormal [15]. The number of food plants with a concentration three times the mean value is less than 5% of the total. Therefore, the probability of a person finding his entire diet for 1, 5, 10, or 30 y from food crops with a concentration three times the mean value is very small. The observed lognormal distribution of radionuclide concentrations in soils and plants at the atolls is consistent with most elemental distributions in nature. Also, the observation that three times the mean value includes more than 95% of the population distribution is consistent with other observations, several of which have recently been summarized by Cuddihy et al. [55].

The ^{90}Sr concentration distributions in bone have been specifically addressed by Kulp and Schulert [56]. They found that ^{90}Sr from fallout was distributed lognormally and that the 98th percentile value was 2.3 times the mean value. Maximum values observed for ^{90}Sr in bone by Bennett were three times the mean; that is, most of the data fell below three times the mean [10-12]. These data also reflect the combined variability of the ^{90}Sr concentration in food products and in dietary intake.

The ^{137}Cs gamma-exposure data, which are listed in Refs. 2 and 33, show that the maximum exposure rate at an isolated point on the island is, for most islands, less than three times the mean value. In many cases, the maximum observed value is only two times the mean value. Because of the movement of people around their residence island, tne variation of individual doses around the average dose is probably minimized and would not add much variability to the distribution of doses calculated for the ingestion pathway. In addition, we have not included in the external doses the reduction in external exposure that would occur from spreading crushed coral around the houses and shielding by the houses.

Second, the dietary intake of local foods is a major source of input data that is somewhat uncertain and could lead to higher average doses than presented here if the average intake were significantly greater than we have assumed. For example, if the atoll current lifestyle should change drastically with a total reliance on local foods, the average doses would be higher than those listed here. This is a very unlikely occurrence because the people have a source of income and imported foods are now considered a staple and a necessity, not a luxury. The people will have access to outside goods and will trade with either the United States or other world governments. Conversely, if the diets were to include more imported foods, the doses would be lower than listed here.

Third, the range of values observed for the retention of ^{137}Cs in humans has been summarized by the ICRP [19,20] and the NCRP [21]. For example, the range of observed values for the retention time for the short-term compartment is 0.5 to 2.1 d with a mean of 1 d; the upper limit that has been observed is greater than the mean by only a factor of 2. For the long-term compartment, the data range from 60 to 165 d with a mean value of 110 d; the maximum value in this case is less than twice the mean value. The fraction of the intake that has been observed to go to the short-term compartment (i.e., 2 d) ranges from 0.02 to 0.22 with a mean of 0.1; for the long-term compartment (i.e., 110 d), the range is 0.78 to 0.97 with a mean value of 0.9. For both cases, the maximum value is less than twice the mean.

There are several reasons why the average doses we present might be lower. First, the doses are calculated assuming residence since 1978. For uninhabited atolls, doses would be expected to be about 2.3% lower per year until resettlement occurs based on the radiological decay of cesium and strontium. Second, we still do not know the environmental residence time of cesium in the atoll ecosystem. If it were 30 y (i.e., equal to the radiological half life), the estimated doses would be half (50%) of those presented in the tables. If the environmental residence time were as long as 50 y, the doses would be 34% lower, and if it should be as short as 20 y, the estimated doses would be 64% lower. We have experiments underway to determine the environmental residence time. Third, we have not included shielding from external gamma exposure that occurs from the housing structure and from coral gravel that is commonly spread in a 10- to 15-m area around the houses. The people spend considerable time in and around their houses [2]. Therefore, a significant reduction in the external exposure around the housing area can occur. This reduction from shielding by the house can be a factor of 2 based on a 30 to 40% occupancy and depending on the type of housing. If coral gravel is spread around the house, another factor of 2 reduction can be obtained. Depending on the location and type of the housing, the extent of use or non-use of coral gravel, and the percentage of time spent in or near the house, the external dose reduction could range from 15 to 80% [2]. Fourth, we have used the average values for all of the parameters in the dose models and the resulting doses fall at about the 68% point on the distribution. If we used the median values to estimate the doses for the midpoint of the distribution, the doses would be lower. Fifth, if there should be a greater future reliance on imported foods with a concurrent decrease in consumption of local foods, the estimated doses would be lower. Also, the BNL diets applied to most atolls downwind of the proving grounds are considered to be upper limits for current lifestyles with a good probability that a typical, average diet would be less than that listed in the BNL report [43].

The doses to children have been calculated previously and are always less than the estimated adult doses [15,42]. That is, the 30- and 50-y integral doses starting at birth through 30 or 50 y are less than similar doses calculated for an adult. If the dietary intake of ^{137}Cs for children is equal to or less than that for adults, the dose to children will never exceed that to the adult [21,24]. The data from both the MLSC and BNL diet surveys indicate that the consumption of key local food items for ages 1 to 18 are less than those for adults, and therefore the radionuclide intake would also be less.

REFERENCES

1. United States Atomic Energy Commission, Enewetak Radiological Survey, United States Atomic Energy Commission, Washington, DC, NVO-140 (1973), vols. I-III.
2. P. H. Gudiksen, T. R. Crites, and W. L. Robison, External Dose Estimated for Future Bikini Atoll Inhabitants, Lawrence Livermore Laboratory, Livermore, CA, UCRL-51879 Rev. 1 (1976).
3. M. E. Mount, W. L. Robison, S. E. Thompson, K. O. Hamby, A. L. Prindle, and H. B. Levy, Analytical Program--1975 Bikini Radiological Survey, Lawrence Livermore Laboratory, Livermore, CA, UCRL-51879 Pt. 2 (1976).
4. V. E. Noshkin, W. L. Robison, K. M. Wong, and R. J. Eagle, Evaluation of the Radiological Quality of the Water on Bikini and Eneu Islands in 1975: Dose Assessment Based on Initial Sampling, Lawrence Livermore Laboratory, Livermore, CA, UCRL-51879 Pt. 4 (1977).
5. W. L. Robison, W. A. Phillips, and C. S. Colsher, Dose Assessment at Bikini Atoll, Lawrence Livermore Laboratory, Livermore, CA, UCRL-51879 Pt. 5 (1977).
6. W. L. Robison, C. L. Conrado, R. J. Eagle, and M. L. Stuart, The Northern Marshall Islands Radiological Survey: Sampling and Analysis Summary, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-52853 Pt. 1 (1981).
7. V. E. Noshkin, R. J. Eagle, K. M. Wong, T. A. Jokela, and W. L. Robison, Radionuclide Concentrations and Dose Assessment of Cistern Water and Groundwater at the Marshall Islands, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-52853 Pt. 2 (1981).
8. W. L. Robison, V. E. Noshkin, W. A. Phillips, and R. J. Eagle, The Northern Marshall Islands Radiological Survey: Radionuclide Concentrations in Fish and Clams and Estimated Doses via the Marine Pathway, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-52853 Pt. 3 (1981).
9. W. L. Robison, M. E. Mount, W. A. Phillips, C. L. Conrado, M. L. Stuart, and A. C. Stoker, The Northern Marshall Islands Radiological Survey: Terrestrial Food Chain and Total Doses, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-52853 Pt. 4 (1982).
10. B. C. Bennett, Strontium-90 in Human Bone, 1972 Results from New York City and San Francisco, United States Atomic Energy Commission Health and Safety Laboratory, New York, NY, HASL-274 (1973).

11. B. C. Bennett, Strontium-90 in Human Bone, 1976 Results from New York City and San Francisco, United States Atomic Energy Commission Health and Safety Laboratory, New York, NY, HASL-328 (1977).
12. B. C. Bennett and C. S. Klusek, Strontium-90 in Human Bone, 1977 Results from New York City and San Francisco, United States Department of Energy Environmental Measurements Laboratory, New York, NY, EML-344 (1978).
13. F. W. Spiers, Radioisotopes in the Human Body: Physical and Biological Aspects (Academic Press, New York, 1968).
14. D. G. Papworth and J. Vennart, "Retention of ^{90}Sr in Human Bone at Different Ages and the Resulting Radiation Doses," Phys. Med. Biol. 18, 169 (1973).
15. W. L. Robison, M. E. Mount, W. A. Phillips, M. L. Stuart, S. E. Thompson, C. L. Conrado, and A. C. Stoker, An Updated Radiological Dose Assessment of Bikini and Eneu Islands at Bikini Atoll, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53225 (1982).
16. United Nations Scientific Committee on the Effects of Atomic Radiation, Ionizing Radiation: Sources and Biological Effects (United Nations, New York, 1982).
17. United Nations Scientific Committee on the Effects of Atomic Radiation, Sources and Effects of Ionizing Radionuclides, (United Nations, New York, 1977).
18. International Commission on Radiological Protection, A Review of Radiosensitivity of the Tissues in Bone (Pergamon Press, New York, 1968), pub. 11.
19. International Commission on Radiological Protection, Evaluation of Radiation Doses to Body Tissues from Internal Contamination due to Occupational Exposure (Pergamon Press, Oxford, 1968), pub. 10.
20. International Commission on Radiological Protection, The Assessment of Internal Contamination Resulting from Recurrent or Prolonged Uptakes (Pergamon Press, Oxford, 1971), pub. 10A.
21. National Council on Radiation Protection and Measurements, Cesium-137 from the Environment to Man: Metabolism and Dose, National Council on Radiation Protection and Measurements, Washington, DC, NCRP-52 (1977).
22. G. G. Killough and P. S. Rohwer, INDOS-Conversational Computer Codes to Implement ICRP-10-10A Models for Estimation of Internal Radiation Dose to Man, Oak Ridge National Laboratory, Oak Ridge, TN, ORNL-4916 (1974).

23. R. Miltenberger, E. T. Lessard, and N. A. Greenhouse, ^{60}Co and ^{137}Cs Long Term Biological Removal Rate Constants for the Marshallese Population, Brookhaven National Laboratory, Upton, NY (1979).

24. H. L. Fisher, Jr. and W. L. Snyder, Health Physics Division Annual Report, Oak Ridge National Laboratory, Oak Ridge, TN, ORNL-4168 (1967), pp. 261-267.

25. E. T. Lessard, N. Greenhouse and R. Miltenberger, Brookhaven National Laboratory, Upton, NY, private communication (1979).

26. International Commission on Radiological Protection, Recommendations of the International Commission on Radiological Protection. Data for Protection Against Ionizing Radiation from External Sources: Supplement to ICRP Publication 15 (Pergamon Press, NY, 1973), Pub. 21.

27. K. O'Brien and R. Sanna, "The Distribution of Absorbed Dose-Rates in Humans from Exposure to Environmental Gamma Rays," Health Phys. 30, 71-78 (1976).

28. D. V. Bates, B. R. Fish, T. F. Hatch, T. T. Mercer, and P. E. Morrow, "Deposition and Retention Models for Internal Dosimetry of the Human Respiratory Tract," Health Phys. 12, 173 (1966).

29. International Commission on Radiological Protection Task Group of Committee 2, The Metabolism of Compounds of Plutonium and Other Actinides (Pergamon Press, New York, 1972), pub. 19.

30. International Commission on Radiological Protection, Limits for Intakes of Radionuclides by Workers (Pergamon Press, New York, 1979), pub. 30, pt. 1.

31. F. W. Spiers, J. R. Whitwell, and A. H. Beddoe, "Calculated Dose Factors for the Radiosensitive Tissues in Bone Irradiated by Surface-Deposited Radionuclides," Phys. Med. Biol. 23, 481 (1978).

32. F. W. Spiers and R. Whitwell, "Dosimetry of ^{239}Pu and ^{226}Ra in Man and Animals," in The Health Effects of Plutonium and Radium, S. S. Webster and P. Lee, Eds. (J. W. Press, Salt Lake City, UT, 1976).

33. W. J. Tipton and R. A. Meibaum, An Aerial Radiological and Photographic Survey of Eleven Atolls and Two Islands within the Northern Marshall Islands, EG&G, Las Vegas, NV, EGG-1183-1758 (1981).

34. J. H. Shinn, D. N. Homan, and W. L. Robison, Resuspension Studies at Bikini Atoll, Lawrence Livermore Laboratory, Livermore, CA, UCID-18538 (1980).

35. V. E. Noshkin, K. M. Wong, R. J. Eagle, and G. Brown, Preliminary Evaluation of the Radiological Quality of the Water on Bikini and Eneu Islands, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-51971 (1975).
36. V. E. Noshkin, K. M. Wong, K. Marsh, R. Eagle, G. Hollaway, and R. W. Buddemeier, "Plutonium Radionuclides in the Groundwaters at Enewetak Atoll," in Proc. IAEA Symp. Transuranium Nuclides in the Environment (International Atomic Energy Agency, Vienna, Austria, IAEA SM-199/33, 1976), pp. 517-543.
37. K. V. Marsh, T. A. Jokela, R. J. Eagle, and V. E. Noshkin, Radiological and Chemical Studies of Ground Water at Enewetak Atoll, 2. Residence Time of Water in Cactus Crater, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-51913 Pt. 2 (1978).
38. International Atomic Energy Agency, Root Activity Patterns of Some Tree Crops, International Atomic Energy Agency, Vienna, Austria, No. 170 (1975).
39. V. E. Noshkin, R. J. Eagle, K. M. Wong, T. A. Jokela, J. L. Brunk, and K. V. Marsh, Concentrations of Radionuclides in Reef and Lagoon Pelagic Fish from the Marshall Islands, Lawrence Livermore National Laboratory, Livermore, CA, UCID-19028 (1981).
40. V. E. Noshkin, K. M. Wong, and R. J. Eagle, "Plutonium Concentrations in Fish and Seawater from Kwajalein Atoll," Health Phys. 37, 549-556 (1979).
41. V. E. Noshkin, R. J. Eagle, K. M. Wong, and T. A. Jokela, "Transuranic Concentrations in Reef and Pelagic Fish from the Marshall Islands," in Impacts of Radionuclide Releases into the Marine Environment (International Atomic Energy Agency, Vienna, Austria, 1981), pp. 293-317.
42. W. L. Robison, W. A. Phillips, M. E. Mount, B. R. Clegg, and C. L. Conrado, Reassessment of the Potential Radiological Doses for Residents Resettling Enewetak Atoll, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53066 (1981).
43. J. Naidu, N. A. Greenhouse, G. Knight, and E. C. Craighead, Marshall Islands: A Study of Diet and Living Patterns, Brookhaven National Laboratory, Upton, NY, BNL-51313 (1981).
44. C. Domnick and M. Seelye, "Subsistence Patterns Among Selected Marshallese Villagers," in Laura Report, L. Mason, Ed., University of Hawaii, Honolulu, HI (1967), pp. 1-41.

45. R. A. Conrad, Ed., A Twenty Year Review of Medical Findings in a Marshallese Population Accidentally Exposed to Radioactive Fallout, Brookhaven National Laboratory, Upton, NY, BNL-50424 (1975).

46. International Commission on Radiological Protection, Report of the Task Group on Reference Man (Pergamon Press, New York, 1975), pub. 23.

47. R. P. Miltenberger, N. A. Greenhouse and E. T. Lessard, "Whole Body Counting Results from 1974 to 1979 for Bikini Island Residents," Health Phys. 39, 395-407 (1980).

48. E. T. Lessard, R. P. Miltenberger, and N. A. Greenhouse, "Dietary Radioactivity Intake From Bioassay Data: A Model Applied to ^{137}Cs Inake by Bikini Residents," Health Phys. 39, 177-183 (1980).

49. E. T. Lessard, N. A. Greenhouse, and R. P. Miltenberger, A Reconstruction of Chronic Dose Equivalents for Rongelap and Utirik Residents--1954 to 1980, Brookhaven National Laboratory, Upton, NY, BNL-51257 (1980).

50. L. L. Edwards, MACRO 1: Code to Test a Methodology for Analyzing Nuclear-Waste Management Systems, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-52736 (1979).

51. National Council on Radiation Protection and Measurement, Natural Background Radiation in the United States, National Council on Radiation Protection and Measurement, Washington, DC, report 45 (1975).

52. Federal Radiation Council, Background Material for the Development of Radiation Protection Standards, U.S. Department of Health, Education, and Welfare, Public Health Service, Washington, DC, report 1 (1960).

53. V. T. Bowen, V. E. Noshkin, H. D. Livingston, and H. L. Volchok, "Fallout Radionuclides in the Pacific Ocean: Vertical and Horizontal Distribution, Largely from GEOSECS Stations," Earth Planet. Sci. Lett. 49, 411-434 (1980).

54. V. A. Nelson, Radiological Survey of Plants, Animals, and Soil in Micronesia--November 1975, College of Fisheries, Laboratory of Radiation Ecology, University of Washington, Seattle, WA, NVO-269-35 (1979).

55. R. G. Cuddihy, R. O. McClellan, and W. C. Griffith, "Variability of Organ Doses in Individuals Exposed to Toxic Substances," Toxicol. Appl. Pharmacol. 49, 179-187 (1979).

56. J. L. Kulp and A. R. Schulert, "Strontium-90 in Man V," Science 136, 619-632 (1962).