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RADIONUCLIDE CONCENTRATIONS AND DOSE ASSESSMENT OF CISTERN WATER AND GROUNDWATER AT THE MARSHALL ISLANDS

ABSTRACT

A radiological survey was conducted from September through November of 1978 to determine the concentrations of radionuclides in the terrestrial and marine environments of 11 atolls and 2 islands in the Northern Marshall Islands.

More than 70 cistern and groundwater samples were collected at the atolls; the volume of each sample was between 55 and 100 l. The concentration of ^{90}Sr in cistern water at most atolls is that expected from world-wide fallout in wet deposition. Except for Bikini and Rongelap, ^{137}Cs concentrations in cistern water are in agreement with the average predicted concentration from wet deposition. The $^{239+240}Pu$ concentrations are everywhere less than the predicted fallout concentrations except at Rongelap, Ailinginae, and Bikini where the measured and predicted concentrations are in general agreement.

During the period sampled, most groundwater concentrations of ^{137}Cs were everywhere higher than the concentrations in cistern water. Groundwater concentrations of ^{90}Sr exceeded the levels in cisterns at Rongelap, Likiep, and Ailuk but were lower than the cistern levels at Utirik, Wotho, and Ujelang. Concentrations of the transuranics in filtered groundwater solution were everywhere comparable to or less than the concentrations in cistern water.

However, it is difficult to assess the significance of the radionuclides detected in groundwater at the different atolls. On many islands, the well was a simple hole in the ground lined with wood, metal, or concrete. Most well liners did not extend above the ground surface. Concentrations of radionuclides in the water will be affected by wind, human traffic, surface runoff, and other activity transporting contaminated debris into the pit. Therefore, the concentrations of radionuclides detected during any single period may not necessarily reflect the long-term average concentrations or the concentrations that might be observed if a lined well were extended above the surface.

In any case, at all atolls the ^{90}Sr and ^{137}Cs concentrations in groundwater are below the concentration guidelines for drinking water recommended by the Environmental Protection Agency.

The maximum annual dose rates and the 30- and 50-y integral doses are calculated for the intake of both cistern water and groundwater for each of the atolls. Doses from the ingestion of cistern water at Bikini, Rongelap, and Enieatok Islands are less than 0.1% (0.001) of the individual annual guidelines and the 30-y guideline; doses at the other atolls are about 0.01% of the guidelines.

Even if the total annual consumption were groundwater (an unrealistic situation) the estimated doses at Rongelap and Utirik are about 0.3% of the guidelines and less than 0.1% for the other atolls.

We conclude that the water sources at the atolls, especially the preferred cistern water, contribute a very small fraction of the estimated total doses from all exposure pathways.

INTRODUCTION

A radiological survey was conducted from September through November of 1978 to assess the concentrations of persistent man-made radionuclides in the terrestrial and marine environments of 11 atolls and 2 islands of the Northern Marshall Islands. The atolls and islands are shown in Fig. 1 and include Rongelap, Utirik, Taka, Bikar, Rongerik, Ailinginae, Likiep, Jemo, Ailuk, Mejit, Wotho, Ujelang, and Bikini. Concentrations of radionuclides on specific islands of Bikini Atoll have been well documented.[1-4] However, little radiological information is available for the remainder of the atoll or for other atolls that were considered most likely to have received fallout from nuclear tests conducted at the Pacific Proving Grounds between 1946 and 1958.

The survey consisted, in part, of an aerial radiological reconnaissance to map the external gamma-ray exposure rates over the islands of each atoll. Shore parties collected appropriate terrestrial and marine samples to assess the radiological dose from pertinent food chains to individuals residing on the atolls, or who may in the future reside on some of the presently uninhabited atolls, or who may now collect food from these atolls.

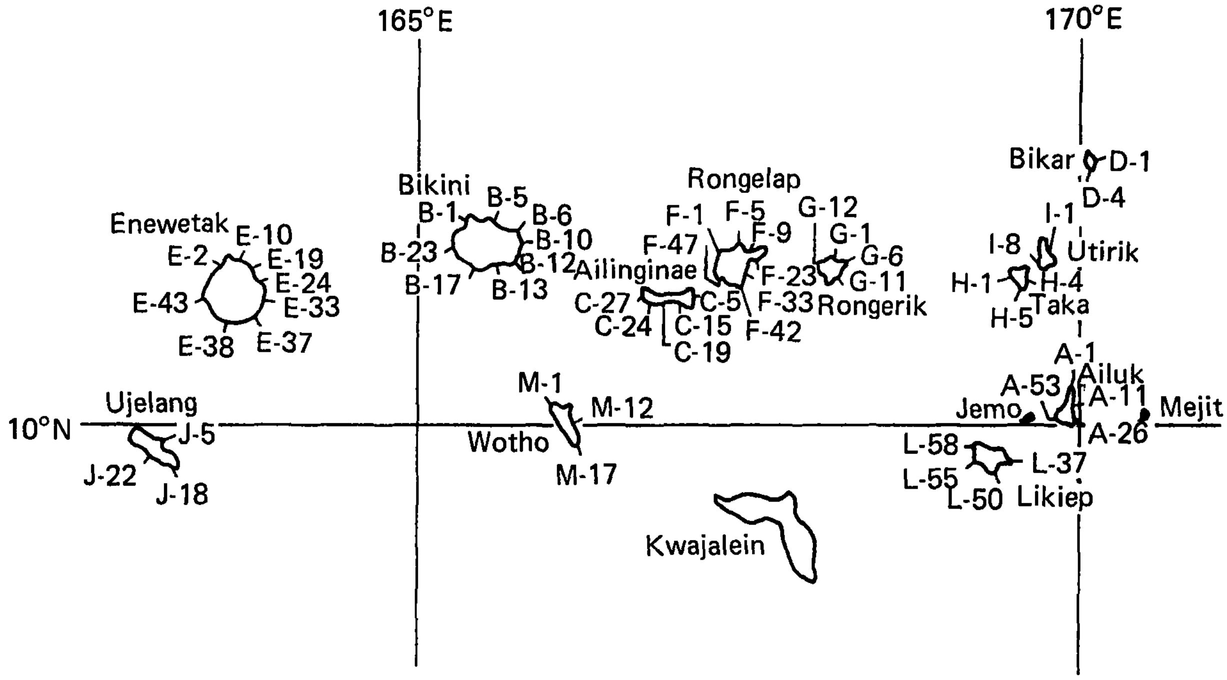

FIG. 1. Atolls and locations sampled in the Northern Marshall Islands.

Over 4000 terrestrial and marine samples were collected for radionuclide analysis from 76 different islands. Soils, vegetation, indigenous animals, and cistern water and groundwater were collected from the islands. Reef fish, pelagic species, clams, lagoon water, and sediments were obtained from the lagoons.

A considerable amount of radionuclide concentration data has been generated from the analysis of these samples. Results from different phases of the program will appear in separate reports. In the first report of this series we describe the general operation of the survey: the type and quantity of samples collected, locations sampled, and the methods used to process and analyze the samples. Other reports include a description of our analytical quality-control program, coordinated by D. Jennings of the Oregon College of Education, and radionuclide concentration in the marine and terrestrial environments. Some reports will contain the analytical results from individual atolls while in others the results will be of a general nature from all atolls. The final paper will provide an assessment of the total dose from the major exposure pathways including external gamma, terrestrial food chains including food products and drinking water, marine food chains, and inhalation.

Here we summarize the concentration data for ^{137}Cs, ^{90}Sr, $^{239+240}$Pu, ^{238}Pu, and ^{241}Am in cistern water and groundwater sampled at the atoll sites visited during the survey. Some concentrations measured in cistern water from Bikini and in other water supplies sampled since 1975 during our ongoing program at the Marshall Islands are also reported. Doses are calculated for consumption of both cistern water and groundwater. Radionuclide concentrations are also compared to the recommended maximum permissible levels of the Federal Radiation Council (FRC) part 20, standards for the protection against radiation; other U.S. Agency standards; and present fallout levels in rainwater from other Pacific locations and in other domestic water supplies. These comparisons are provided only as a reference to other standards and expected background concentrations.

WATER RESOURCES AND SAMPLING AT THE ATOLLS

Rainwater is the only source of fresh water for drinking, household, and agricultural purposes on the majority of the atolls in the Marshall Islands. Available rainfall records for the entire Pacific were summarized by

Taylor[5]; amounts recorded at locations in the Marshall Islands are shown in Table 1. Average annual rainfall in these islands ranges from 411 cm at 6°N latitude to 147 cm at 11.5°N latitude, indicating a strong correlation with latitude. The data in Table 1 are used to develop a predictive model to estimate mean amounts of rainfall on atolls where no records are kept. In Eq. (1), L is the degrees north latitude of an atoll with the minutes and seconds expressed as a fraction of a degree. For example, 11°21'N, the latitude of Enewetak Atoll, is expressed as 11.35.

$$\text{Annual mean rainfall (cm)} = 690 - 48.92L \; . \qquad (1)$$

Using Eq. (1), the predicted mean rainfall for Enewetak is 135 cm compared to the measured annual mean of 147 cm. This equation should only be used, however, to estimate mean amounts of rain. The annual amount of rain can be extremely variable and, for the most part, unpredictable from year to year. At Enewetak the annual rainfall in 1974 was 215 cm, one of the wettest years recorded. The next year there was only 102 cm of rain, which was one of the driest years of the last two decades.[7]

Because rainwater is preferred to groundwater for drinking, it must be stored and used sparingly in anticipation of unpredictable droughts, especially in the Northern Marshall Islands. At the inhabited atolls we visited, there were a variety of cisterns that were used for the storage of water drained through a series of troughs from residence or municipal roof catchments. Ailinginae was the only uninhabited atoll with a cistern and it collected only water that fell directly into it.

Cistern water sampled at Rongelap in 1956, 2 y after the Bravo event at Bikini, was found to contain over 500 pCi/l of ^{90}Sr.[8] This concentration exceeds present recommended U.S. guidelines for ^{90}Sr in drinking water but was, until now, the only reported measurement for ^{90}Sr in drinking water at the atoll. Usage and dilution with lower activity rainwater should have reduced the concentration so that today the radionuclide levels in cistern water would be expected to correlate with global fallout concentrations associated with recent wet deposition. However, as late as 1975, concentrations of $^{239+240}Pu$, ^{137}Cs, and ^{90}Sr in cistern water at Bikini Island were in excess of expected fallout concentrations,[3] indicating that at some atolls there may be an additional source of radionuclide contamination.

Part of the island rainfall evaporates or is taken up and partially transpired by plants. Essentially no water is lost by surface runoff. A fraction of the rain infiltrates the soil column and eventually reaches the groundwater table. The surface of the water table in the Marshall Islands is between 2.5 and 4 m below ground. On many of the larger islands the upper layer of the groundwater is fresh enough for human consumption, and at some atolls this water is used for household purposes and garden crops. There has been a determined effort to ensure a year-round supply of rain water in containment systems above ground, but when unanticipated droughts occur, the storage capacity may be exhausted and groundwater must be relied on for drinking water. Any radionuclides that have migrated through the soil column to the groundwater will contribute some internal radiological dose to individuals consuming it. Therefore, an evaluation of the significance of radionuclides detected in both the cistern water and groundwater was necessary to meet the survey objectives.

There were 55- to 100-l samples collected for analysis from cisterns and well pits. Unfiltered water was collected from the cisterns; groundwater was filtered through 1- and 0.45-μ filters to remove particulates. All samples were returned to the Lawrence Livermore National Laboratory (LLNL) for processing. One separation technique was used to isolate ^{90}Sr, ^{137}Cs, $^{239+240}Pu$, and ^{241}Am from all samples of water regardless of water salinity. Standardized carrier solutions were added to the acidified samples. The radionuclides were radiochemically purified using published procedures.[9,10] A fraction of the samples was analyzed at LLNL and the remainder, with prepared standards, duplicates, and blanks were sent to a contractor laboratory.

Radionuclide concentrations in cistern water sampled at Bikini Atoll since 1975 are shown in Table 2. Table 3 lists concentrations in cisterns and other fresh water supplies at other Northern Marshall Islands Atolls.

The concentration of radionuclides in groundwater at Rongelap, Utirik, Likiep, Ailuk, Mejit, Wotho, and Ujelang are shown in Table 4. Groundwater concentrations at Bikini and Enewetak have been previously discussed[3,11] and more recent results from these atolls will appear in future reports.

RADIONUCLIDE CONCENTRATIONS IN CISTERN WATER

COMPARISON WITH GLOBAL FALLOUT LEVELS IN WET DEPOSITION, NATIONAL STANDARDS, AND OTHER SUPPLIES OF FRESH DRINKING WATER

The Environmental Measurements Laboratory (EML) of the United States Department of Energy presently monitors, on a quarterly basis, the amount of rainfall and the concentrations of ^{90}Sr in wet deposition at a number of global sites. The average amounts of ^{90}Sr in rain between 1976 and the fourth quarter of 1978 are summarized from a recent EML report [12] and shown in Fig. 2 as a function of the collection-site latitude. During this period, minimum fallout concentrations were deposited in the Southern Hemisphere and equatorial regions, and maximum concentrations occurred in wet deposition near 40°N latitude.

The concentration of radionuclides in Bikini cistern water will be discussed in the next section. Comparing the measured concentrations of ^{90}Sr in cisterns at other atolls (Table 3) to the measured fallout levels in wet deposition shown in Fig. 2, we find that at most Marshall Islands Atolls the concentrations are comparable to levels in wet deposition at other global sites of comparable latitude. At no atoll (except Bikini) was the concentration of ^{90}Sr in cistern water higher than the concentration in rain in the states of New York, Illinois, or Washington or in the countries of Canada and Austria. The ^{90}Sr concentration in New York City tap water between 1975 and 1978 averaged 342 fCi/l,[13] while the cistern water at all atolls (except Bikini) sampled in 1978 contained from 40 to 302 fCi/l. Tap water at Enewetak Atoll is distilled from seawater; the source for the small levels of ^{137}Cs and $^{239+240}Pu$ measured is not known.

Several Pacific Islands are included among the global stations routinely sampled by EML. Concentrations of ^{90}Sr and rainfall amounts at these sites are summarized in Table 5; Fig. 3 shows the relationship between the concentrations and mean amounts of rain. Figure 2 and Eq. (1) are used to estimate the average ^{90}Sr concentrations expected in rain (and therefore in cistern water) at the latitude of each Marshall Islands Atoll. This estimated concentration is compared in Table 5 to the measured concentration in cistern water. Except for Bikini, Rongelap, and Ujelang, where the average measured concentration of ^{90}Sr in cristern water differs from the predicted concentration by a factor of two, the agreement is very satisfactory.

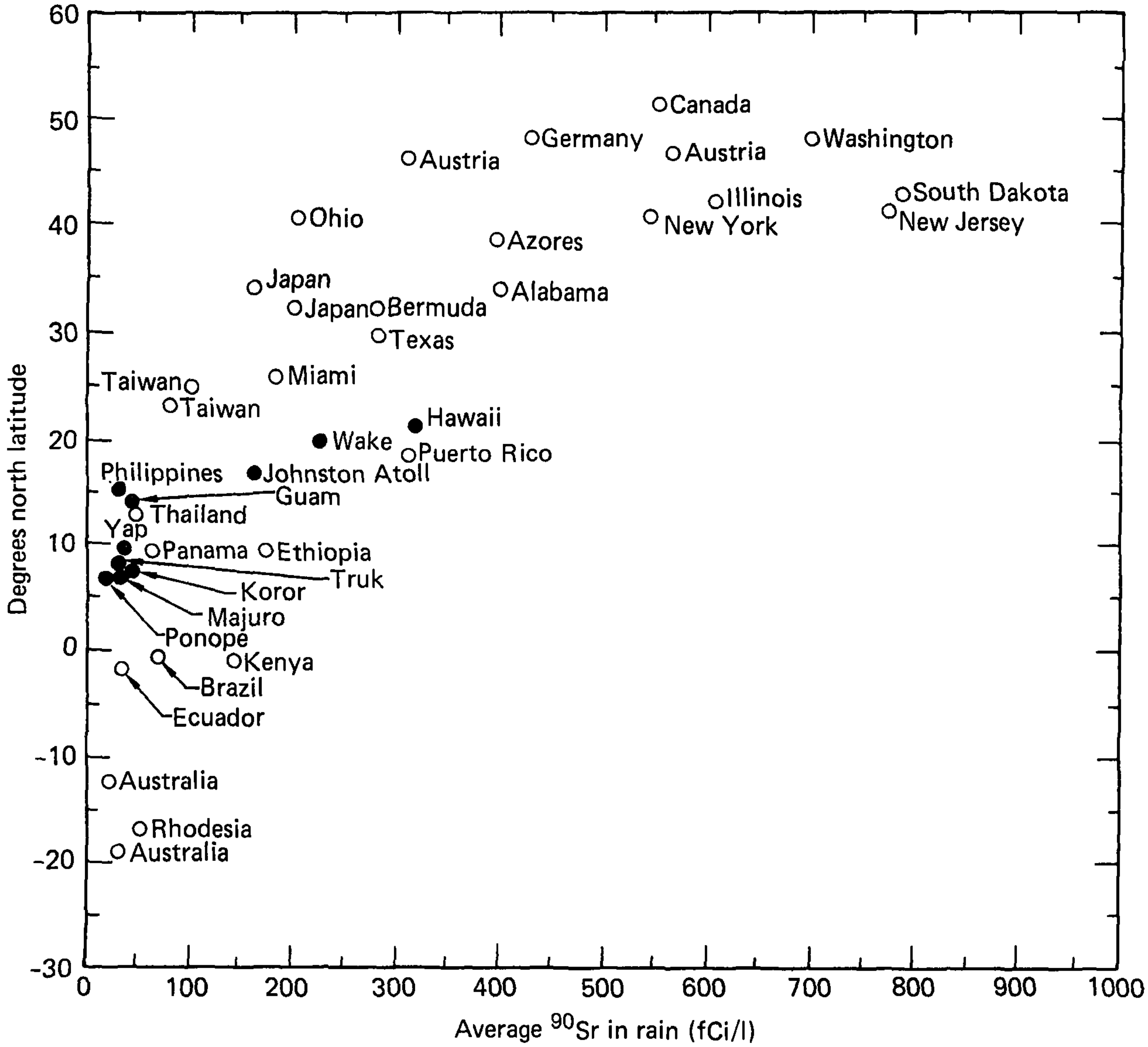

FIG. 2. The average ^{90}Sr in rain from 1976 to the fourth quarter of 1978 as a function of latitude.

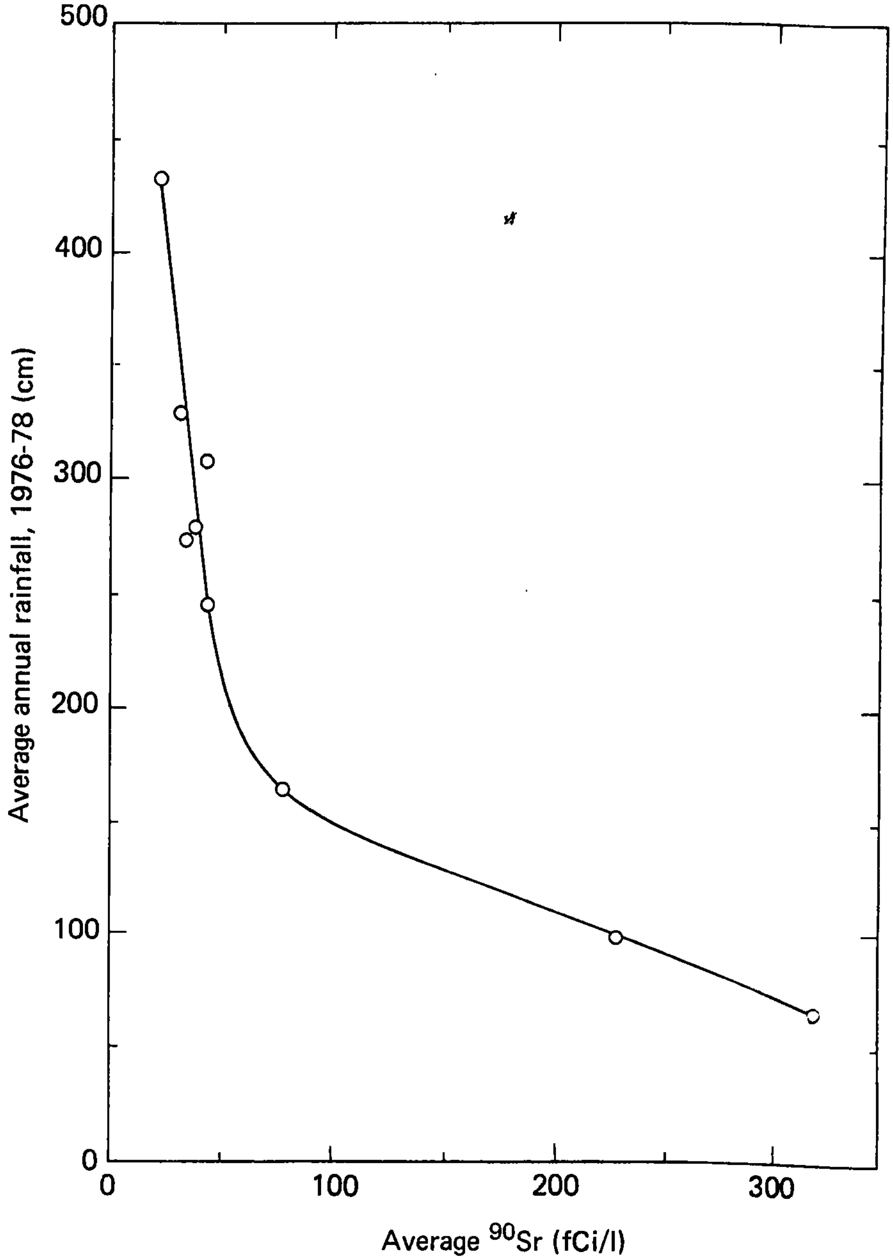

FIG. 3. Relationship between ^{90}Sr concentration and average rainfall at several Pacific Islands routinely sampled by the Environmental Measurements Laboratory.

Considerable data has been compiled to show that the global fallout ratio of ^{137}Cs to ^{90}Sr averages 1.45. A lesser, but still significant, amount of data shows the fallout $^{239+240}Pu$ to ^{90}Sr ratio averages 0.022. These ratios were confirmed in open-ocean air samples from the Equatorial Pacific collected in late 1977; a fallout $^{239+240}Pu$ to ^{137}Cs ratio of 0.013±0.003 was measured on the filters. This agrees with the ratio of 0.015, which can be computed from the reported ratios relating the average ^{137}Cs to ^{90}Sr and $^{239+240}Pu$ to ^{90}Sr in fallout. Expected fallout concentrations of ^{137}Cs and $^{239+240}Pu$ in rain are computed from the predicted concentrations of ^{90}Sr in Table 5 and the respective fallout ratios. Estimated concentrations are compared in Table 6 to measured concentrations from cistern water. Except for Rongelap and Bikini, the average concentration of ^{137}Cs measured in cistern water is found to be in agreement with the average, predicted concentration from wet deposition. The measured $^{239+240}Pu$ is less than the predicted concentration except at Rongelap, Ailinginae, and Bikini where the two values are in general agreement. A concentration less than expected fallout levels can only be explained by assuming that a fraction of the Pu is precipitated onto the interior walls of the cisterns or settles to the bottom with the particulates. Thus, concentrations of ^{90}Sr and ^{137}Cs in cistern water from the Northern Marshall Islands can be reasonably well predicted from rainfall and fallout measurements at other Pacific Islands.

The National Interim Primary Drinking Water Regulations, published by the Environmental Protection Agency (EPA), states "that the average annual concentration of beta particle and photon radioactivity from man-made radionuclides in drinking water shall not produce an annual dose equivalent to the total body or any internal organ greater than 4 millirem/year" based on a 2 l/d intake of drinking water.[14] If two or more radionuclides are present, the sum of their annual dose to the total body or to any organ shall not exceed 4 mrem/y. The average concentrations computed to produce a total-body or organ dose of 4 mrem/y are 8 pCi/l for ^{90}Sr and 200 pCi/l for ^{137}Cs.[14] The percent of the EPA limits represented by the ^{90}Sr and ^{137}Cs concentrations measured in the cistern water samples are shown in Tables 5 and 6. The present levels of ^{90}Sr and ^{137}Cs are everywhere less than 10% and 2%, respectively, of the EPA guidelines and less than 0.2% and 0.01%, respectively, of the FRC guidelines.[15] The average $^{239+240}Pu$ concentration at Bikini of 6.3 fCi/l is 0.001% of the FRC guideline of 500 X 10^3 fCi/l in drinking water.[15]

BIKINI ATOLL

Radionuclide concentrations measured in cistern water at Bikini, shown in Table 2, are less than recommended Federal guidelines for drinking water but are presently higher than the concentrations in water supplies at other atolls. Several processes may contribute to this phenomenon.

Water collects in the cisterns through troughs connected to sloping roof surfaces. These surfaces face the prevailing wind direction, the downwind direction, or are oriented at right angles to the wind. Cisterns connected to buildings 5, 10, 12, and 14 on Bikini Island receive water drained from windward-facing surfaces. There are downwind-facing surfaces on building 39 and the southern part of the Eneu Island mess hall. The school roof is oriented at a right angle to the wind. After the cistern water collected in 1975 was analyzed, it was suggested that some forms of contaminated particulates were being suspended by the wind and deposited on roof surfaces.[3] The particulates would subsequently wash into the cisterns with the next rain, thereby increasing radionuclide concentration. It was suspected that roofs facing the wind might accumulate more particulates than differently oriented surfaces. Therefore in January and November of 1977, water from Bikini Island cisterns connected to various buildings with differently oriented roof surfaces was collected for analysis. During both these periods, the water from building 39 had the lowest concentrations of radionuclides, but there was little difference between the concentrations in water from buildings 10 or 12 and the school cistern. These results provided some support for the resuspension argument.

We tested the theory further by completely washing down the windward-facing roof surface (51 m^2) of building 10 with 55 l of redistilled water. There was 38 l of wash water intercepted before it reached the cistern. A 2-wk period had elapsed since the previous rain. The wash contained 1,890 fCi of $^{239+240}Pu$ and 17,110 fCi of ^{90}Sr. The ^{137}Cs sample was lost during processing. The ratio of sodium to chloride in the water was similar to that in seawater, indicating that sea-salt aerosols are among the resuspended components on the roof surfaces.

Previous measurements at Bikini demonstrated that there was considerable variation in the radionuclide concentrations in soil over the island, but consistent ratios were found between different radionuclides.[2] The ^{90}Sr was everywhere between 10 to 20 times the $^{239+240}Pu$ concentration in surface soils and approximately 1.7 times the ^{137}Cs concentration. A ratio of 9 was found between the ^{90}Sr and $^{239+240}Pu$ concentrations in the roof wash, indicating that resuspended soil particulates could also be among the components collected on the roof surface. A full cistern at building 10 contains 15 m^3 of water. If the $^{239+240}Pu$ and ^{90}Sr deposited on the roof was eventually washed into the cistern, the concentrations in the water would increase only by 0.12 and 1.1 fCi/l, respectively. If resuspension of contaminates is a continuous process over the year and the amounts of radionuclides deposited on the roof of building 10 over the 2-wk interval are representative of the amounts accumulated during any 2-wk interval, then the annual amount of ^{90}Sr accumulated and drained would increase the concentration in a full cistern by only 28 fCi/l. This concentration is insignificant compared to present global fallout levels in annual wet deposition. Unlike the ratio of ^{90}Sr to ^{137}Cs in soils, the concentrations of ^{137}Cs in cistern water exceeds the levels of ^{90}Sr. Some contamination results from resuspension, but the amounts are not sufficiently large to account for the changes in concentration detected in the water since 1975.

Radionuclide concentrations in the cistern water during each sampling period at Bikini are averaged and summarized in Table 7. By November of 1977 the average concentrations of ^{90}Sr, ^{137}Cs, and $^{239+240}Pu$ had decreased to approximately 19% of the concentrations measured in 1975. A similar change occurred in the chloride concentration. Also, the concentrations of ^{90}Sr and ^{137}Cs were nearly equivalent to fallout levels expected in wet deposition. After 1977, the mean concentrations of ^{137}Cs and ^{90}Sr increased while the concentrations of Pu slightly declined.

The change in concentrations of ^{137}Cs closely paralleled the social changes that occurred at Bikini Atoll. By 1975, fewer than 60 people had moved back to Bikini Island. There was no large demand for fresh water and the amount stored in the cistern attached to individual residences probably satisfied normal requirements. A large increase in population occurred between 1975 and 1978. The need for fresh water increased and inventories in many of the previously unused cisterns were used. During this period, the average concentration of radionuclides in the water decreased significantly. In September 1978 all the Bikini residents were removed from the island by the Trust Territory Government. The average concentrations of ^{137}Cs and ^{90}Sr

in cistern water subsequently increased, with larger increases in certain cisterns. Contamination of the water supplies with resuspended particulates cannot account for the increases in concentrations detected, but there are two other possibilities.

The first requires an assumption that material used to construct the cisterns was contaminated. This is possible because local aggregate and water were used with cement to manufacture the cisterns. The ^{137}Cs or other radionuclides incorporated in the mixture could exchange with any water saturating the cistern walls. When water levels decrease with use, less of the interior surface area of the cistern is in direct contact with the water. As a result, less ^{137}Cs is mobilized from the matrix. New rain increases the volume of water in the cistern and dilutes the concentration of radionuclides in the residual water. A continuous use of water shortens the contact time between this lower activity water and the cistern walls. As a result, the radionuclide concentrations decrease as observed. When the cistern is full and there is no further use for the water, radionuclides continuously exchange between the cistern walls and the water.

A second possible cause is that concentrations of radionuclides in the water will decrease as a result of dilution with lower activity rainwater and increase if the standing water is allowed to evaporate. Heavy demands on the cistern water between 1975 and 1977 reduced the inventory of available water. Rainfall continuously replenished part of the cistern supply and diluted the residual radionuclide concentrations. During this period, concentrations in cistern water approached those expected in wet deposition. By September 1978, the average concentrations of ^{137}Cs and ^{90}Sr in the water were reduced to their lowest level since 1975. When water usage ceased, evaporation resulted in an increased radionuclide concentration. Some lower concentration rainwater diluted the radionuclide concentration of the cistern water, but the rate of the dilutant input was not equivalent to the evaporation rate. Evaporation rates for standing bodies of water have been measured at Bikini and average 0.5 cm/d.[16] With this assumption, concentration changes in Table 2 can be explained by a process of dilution, use, and evaporation. We are currently investigating the importance of these processes and how they may alter future radionuclide concentrations in atoll cistern water.

RADIONUCLIDE CONCENTRATIONS IN SURFACE GROUNDWATER AT RONGELAP, UTIRIK, LIKIEP, AILUK, MEJIT, WOTHO, AND UJELANG

Groundwater salinities shown in Table 4 range from 0.3 to 1 ppt at the well sites sampled during the survey. These salinities are sufficiently low so that this groundwater can be used for drinking if the need arises; however, we do not know how these salinities may change with time.

It is difficult to assess the significance of the radionuclides detected in groundwater at the different atolls. On many islands, the well was a simple hole in the ground lined with wood, metal, or concrete. Most well liners did not extend above the ground surface. Concentrations of radionuclides in the water will be affected by wind, human traffic, surface runoff, and other activity transporting contaminated debris into the pit. As a result, the concentrations of radionuclides detected during any single period may not necessarily reflect the long-term average concentrations or the concentrations that might be observed if a lined well were extended above the surface.

During the period sampled, most groundwater concentrations of ^{137}Cs were everywhere higher than the concentrations in cistern water. Groundwater concentrations of ^{90}Sr exceeded the levels in cisterns at Rongelap, Likiep, and Ailuk but were lower than the levels in cistern water at Utirik, Wotho, and Ujelang. Concentrations of the transuranics in filtered groundwater solution were everywhere comparable to or less than the concentrations in cistern water.

At all atolls, the ^{90}Sr and ^{137}Cs concentrations in groundwater are below the EPA recommended concentration guidelines for drinking water.[14]

RADIOLOGICAL DOSE ASSESSMENT OF INGESTION OF ATOLL WATER SUPPLIES

Radiological doses are calculated for the intake of both cistern water and groundwater. Although the preferred source of water is the former, the latter is used in cases of severe drought. By calculating the doses for both sources, the dose from any annual intake combination can be readily determined.

Radionuclide concentrations used for input data are listed in Tables 2 through 7; a 2 l/d intake is assumed for each source of water. The doses are calculated for ^{137}Cs, ^{90}Sr, $^{239+240}Pu$, and ^{241}Am, the four most significant radionuclides in the environment of each atoll.

The ^{137}Cs doses are calculated using the methods outlined by the International Commission on Radiological Protection (ICRP)[17-19] and the National Council on Radiation Protection and Measurements (NCRP).[20] The model consists of two exponential components with half-lives of 2 and 110 d, with 10% of the intake going to the 2-d compartment and 90% to the 110-d compartment. The gut-transfer coefficient for ^{137}Cs is assumed to be 1.

The ^{90}Sr doses are calculated in two steps. First, the model of Bennett is used to correlate the ^{90}Sr concentrations in the diet with that in mineral bone.[21-23] Second, the dosimetric model developed by Spiers is used to calculate the bone-marrow dose rate from the concentration in mineral bone.[24]

For the transuranics Pu and Am, the most recent ICRP values are used for the gut transfer: 1×10^{-4} for Pu and 5×10^{-4} for Am.[17] The critical organs are bone and liver with 100-y biological half-lives for Pu and Am in bone and 40 y in liver. Of the Pu and Am transferred to blood, 45% is assumed to reach bone and liver.

More detailed discussions of the dose calculation methodology for each radionuclide can be found in Ref. 25.

Both the maximum annual-dose rates and the 30- and 50-y integral doses are calculated. The maximum annual-dose rate for the whole body is defined as the dose rate in that year after consumption begins when the sum of the whole-body ^{137}Cs ingestion dose and the external gamma dose is a maximum. For bone marrow it is when the bone-marrow ^{137}Cs and ^{90}Sr ingestion dose and the external gamma dose is a maximum. Because of the accumulation of ^{90}Sr in bone via ingestion and the resultant buildup to a maximum dose at steady-state conditions and the continuously decreasing dose after the first year for ^{137}Cs for both ingestion and external gamma, the maximum annual-dose rate in bone marrow can occur in a different year than the maximum annual-dose rate for the whole body.

The maximum annual-dose rates for each of the atolls for intake of both cistern water and groundwater are listed in Table 8. The 30- and 50-y integral doses are listed in Tables 9 and 10, respectively. Table 11 lists the individual radionuclide contribution to the 30-y integral dose.

TABLE 2. Radionuclide concentrations in samples of unfiltered cistern water from Bikini and Eneu Islands, Bikini Atoll.

Island[b] and building sampled	Date collected	fCi/l (% σ)[a]					Chlorinity, ppm
		^{90}Sr	^{137}Cs	$^{239+240}Pu$	^{238}Pu	^{241}Am	
B-6, bldg. 5	6/21/75	1100(11)	2500(1)	7.9(5)	<0.1	--	35.6
B-6, bldg. 5	11/8/78	200(6)	820(2)	2.6(10)	<0.1	--	--
B-6, bldg. 5	4/23/79	500(4)	2700(1)	2.8(10)	<0.1	--	24
B-6, bldg. 10	1/24/77	430(5)	1450(1)	6.8(8)	0.6(70)	--	19.2
B-6, bldg. 12	11/18/77	150(8)	450(4)	5.3(7)	0.4(26)	--	5
B-6, bldg. 24	6/21/75	1900(2)	2800(2)	13.7(4)	<0.1	--	23.1
B-6, bldg. 24	11/9/78	360(3)	2510(1)	2.5(9)	<0.1	1.1(50)	--
B-6, bldg. 24	4/23/79	1500(2)	8500(1)	2(11)	<0.1	--	23
B-6, bldg. 39	1/24/77	230(11)	410(4)	4.9(9)	0.2(50)	--	15.5
B-6, bldg. 39	11/18/77	220(4)	300(2)	2.6(8)	0.1(60)	--	7.6
B-6, school	6/21/75	1420(7)	1700(2)	29(2)	<0.4	--	21.5
B-6, school	1/24/77	370(6)	1180(1)	6.3(4)	0.2(27)	--	14.4
B-6, school	11/21/77	240(2)	580(1)	3.8(6)	0.1(40)	--	6
B-6, school	11/8/78	200(2)	1030(1)	2(16)	<0	0.9(80)	--
B-6, school	4/23/79	390(3)	2000(1)	1.9(8)	0.1(40)	--	21
B-12, north mess hall	1/25/77	230(12)	lost	2.5(7)	0.2(40)	--	21
B-12, south mess hall	1/25/77	490(12)	lost	0.93(8)	0.1(50)	--	17
B-12, south mess hall	11/18/77	150(10)	210(3)	16.5(3)	2.5(9)	--	9.1
B-12, south mess hall	11/8/78	160(3)	270(2)	1.7(12)	0.2(35)	--	--
B-12, south mess hall	4/23/79	160(3)	450(3)	1.1(25)	<0.1	--	43

[a]Values in parentheses are the percent standard deviation of the counting error.

[b]From Fig. 1.

TABLE 3. Radionuclide concentrations in samples of unfiltered cistern and other fresh water from atolls in the Marshall Islands.

				fCi/l (% σ)[a]				
Atoll	Sample type	Island sampled[b]	Date collected	^{90}Sr	^{137}Cs	$^{239+240}Pu$	^{238}Pu	^{241}Am
Rongelap	Cistern	F-42	9/19/78	155(6)	195(4)	1.9(34)	<0.3	<0.2
Rongelap	Cistern	F-42	9/19/78	302(5)	720(3)	4.1(30)	1.2(80)	lost
Rongelap	Cistern	F-33	9/20/78	284(4)	1090(2)	1.2(19)	<0.1	0.6(30)
Utirik	Cistern	I-6	9/26/78	97(8)	141(4)	0.5(40)	0.2(75)	0.2(60)
Ailinginae	Cistern	C-23	10/6/78	70(5)	167(6)	2.5(16)	0.3(65)	1.7(28)
Likiep	Cistern	L-37	10/14/78	67(8)	42(5)	<0.1	<0.02	lost
Likiep	Cistern	L-37	10/14/78	72(6)	73(3)	0.1(80)	0.1(90)	<0.06
Likiep	Cistern	L-2	10/15/78	55(8)	66(3)	0.2(50)	0.1(70)	<0.1
Ailuk	Cistern	A-51	10/21/78	40(9)	49(5)	0.5(40)	0.2(80)	0.4(50)
Ailuk	Cistern	A-51	10/21/78	58(8)	107(4)	0.3(70)	<0.2	<0.1
Ailuk	Cistern	A-2	10/22/78	74(10)	104(3)	<0.1	<0.1	<0.1
Mejit	Cistern	A-2	10/24/78	46(6)	135(2)	0.2(50)	<0.1	<0.1
Wotho	Cistern	M-4	10/27/78	90(22)	86(6)	0.3(50)	<0.1	<0.1
Ujelang	Cistern	J-18	11/2/78	90(5)	108(3)	0.4(40)	<0.1	<0.1
Enewetak	Distilled seawater	E-37	3/18/78	--	18(8)	0.6(40)	<0.1	--
Enewetak	Distilled seawater	E-37	3/18/78	--	20(8)	0.4(50)	<0.1	--
Enewetak	Distilled seawater	E-37	3/18/78	--	22(8)	0.3(70)	<0.1	--
Enewetak	Water truck	E-10	3/21/78	--	10(14)	5.4(22)	0.2(40)	--
Kwajalein	--	--	11/29/77	52(4)	80(3)	0.21(20)	<0.1	--
R.V. Liktanur[c]	--	--	10/75	--	90(40)	0.6(20)	<0.1	--
R.V. Liktanur	--	--	4/76	--	30(3)	0.33(18)	<0.1	--
R.V. Liktanur	--	--	4/76	--	45(10)	0.25(20)	0.03(90)	--
R.V. Liktanur	--	--	1/77	--	--	0.3(15)	<0.1	--

[a]Values in parentheses are the percent standard deviation of the counting error.

[b]From Fig. 1.

[c]Research vessel at sea; water is usually taken on at Kwajalein.

TABLE 4. Radionuclide concentrations in surface groundwater samples (9/10/78).

Atoll and island sampled[b]	Salinity, ppt	fCi/l (% σ)[a]							
		^{90}Sr	^{137}Cs	$^{239+240}Pu$		^{238}Pu		^{241}Am	
				Filtrate	Filter	Filtrate	Filter	Filtrate	Filter
Rongelap F-42	1.02	2440(5)	1040(2)	3(7)	9.8(7)	<0.7	<0.05	0.24(24)	7.3(5)
Utirik I-6	0.84	82(4)	6550(1)	0.2(22)	--	<0.02	--	<0.01	<0.04
Likiep L-37	0.22	312(12)	176(2)	lost	0.5(20)	lost	0.1(60)	lost	0.2(60)
Likiep L-37	0.87	125(3)	383(3)	<0.1	0.12(38)	<0.05	0.06(75)	0.1(50)	0.16(60)
Likiep L-2	0.28	205(4)	298(1)	<0.04	0.22(34)	<0.04	<0.02	--	0.13(50)
Likiep L-2	0.39	334(3)	41(3)	<0.07	0.1(80)	<0.03	<0.02	0.2(40)	<0.05
Ailuk A-51	0.6	143(2)	1160(2)	0.31(40)	1.1(20)	0.25(60)	<0.04	0.1(80)	0.8(30)
Ailuk A-51	0.45	144(4)	31(6)	0.28(34)	<0.04	0.14(70)	<0.02	<0.1	<0.1
Ailuk A-2	0.69	450(3)	251(4)	0.11(60)	0.2(60)	<0.05	<0.08	0.2(50)	0.5(50)
Mejit lake	0.76	111(4)	764(1)	1.5(30)	1.3(12)	<0.1	0.2(50)	0.13(60)	0.8(30)
Wotho M-4	0.45	33(6)	1180(2)	<0.1	<0.03	<0.1	<0.05	0.4(40)	0.2(60)
Ujelang J-18	--	28(6)	410(2)	0.12(36)	<0.05	<0.1	<0.1	<0.2	<0.2

[a]Values in parentheses are the percent standard deviation of the counting error.

[b]From Fig. 1.

TABLE 5. The ^{90}Sr in wet deposition at Mid-Pacific Islands; measured and predicted concentrations of ^{90}Sr in cistern water from the Marshall Islands and percent of Environmental Protection Agency drinking water guidelines.

Atoll or island	°N latitude	Longitude	Mean annual rainfall (1976-1978), cm	^{90}Sr in wet deposition[a]	^{90}Sr in cistern water Mean[b]	Predicted[c]	Percent of EPA guidelines
Ponope	6°58'	158°13'E	433	0.02	--	--	0.3
Majuro	7°5'	171°23'E	273	0.03	--	--	0.4
Koror	7°21'	134°31'E	308	0.04	--	--	0.5
Truk	7°28	151°51'E	319	0.03	--	--	0.4
Kwajalein	8°44'	167°40'E	--	--	0.05	0.04	0.6
Yap	9°31'	138°08'E	279	0.04	--	--	0.5
Ujelang	9°42'	160°55'E	--	--	0.09±0.01	0.05	1.1
Likiep	9°55'	169°07'E	--	--	0.06±0.01	0.06	0.9
Wotho	10°07'	165°58'E	--	--	0.09±0.02	0.06	1.1
Jemo	10°08'	169°33'E	--	--	--	0.06	--
Mejit	10°15'	170°54'E	--	--	0.05	0.06	0.6
Ailuk	10°18'	170°00'E	--	--	0.06±0.02	0.07	0.8
Ailinginae	11°05'	166°27'E	--	--	0.07	0.1	0.9
Taka	11°06'	169°38'E	--	--	--	0.11	-
Utirik	11°13'	169°48'E	--	--	0.10±0.01	0.12	1.3
Rongelap	11°15'	166°50'E	--	--	0.25±0.08	0.12	3.1
Rongerik	11°19'	167°26'E	--	--	--	0.13	--
Enewetak	11°21'	162°21'E	--	--	--	0.13	--
Bikini Isl.	11°34'	165°25'E	--	--	0.61±0.56	0.16	7.6
Eneu Isl.	11°34'	165°25'E	--	--	0.24±0.14	0.16	3
Bikar	12°12'	170°15'E	--	--	--	0.24	--
Guam Isl.	13°35'	144°55'E	246	0.04	--	--	0.5
Wake Isl.	19°17'	166°39'E	97	0.23	--	--	2.9
Hawaii Isl.	21°59'	159°21'W	64	0.32	--	--	4

[a]From Ref. 12.

[b]Average values from Tables 2 and 3.

[c]Predicted concentrations using Eq. (1) and Fig. 2.

TABLE 6. Measured and predicted average concentrations of ^{137}Cs and $^{239+240}Pu$ in cistern water supplies.

Atoll	^{137}Cs (pCi/l) Measured	^{137}Cs (pCi/l) Predicted	Percent of EPA guidelines	$^{239+240}Pu$ (fCi/l) Measured	$^{239+240}Pu$ (fCi/l) Predicted
Kwajalein	0.08	0.06	0.04	0.2	0.9
Ujelang	0.11	0.08	0.06	0.2	1.1
Likiep	0.06	0.09	0.03	0.1	1.3
Wotho	0.08	0.08	0.04	0.3	1.3
Jemo	--	0.09	--	--	1.3
Mejit	0.14	0.09	0.07	0.2	1.3
Ailuk	0.09	0.09	0.05	0.3	1.5
Ailinginae	0.17	0.15	0.09	2.5	2.2
Taka	--	0.15	--	--	2.4
Utirik	0.14	0.17	0.07	0.5	2.6
Rongelap	0.67±0.45	0.18	0.3	2.4±1.5	2.6
Rongerik	--	0.19	--	--	2.9
Enewetak	--	0.19	--	--	2.9
Bikini					
Bikini Island	1.9±2	0.23	1	6.3±7	3.5
Eneu Island	0.31±0.12	0.23	0.16	4.5±6.7	3.5
Bikar	--	0.35	--	--	5.3

TABLE 7. Average concentrations of radionuclides in Bikini cistern water.

Date sampled	Approximate population	Chlorinity, ppm	pCi/l		
			^{90}Sr	^{137}Cs	$^{239+240}Pu$
Bikini Island					
6/75	60	26.7	1.5	2	16.8×10^{-3}
1/77	140	16.3	0.34	1	6×10^{-3}
11/77	140	6.2	0.2	0.44	3.9×10^{-3}
11/78	0	20	0.25	1.45	2.4×10^{-3}
4/79	0	23	0.79	4.4	2.2×10^{-3}
Eneu Island					
1/77	--	17	0.5	--	0.9×10^{-3}
11/77	--	9.1	0.15	0.21	16.5×10^{-3}
11/73	--	--	0.16	0.27	1.7×10^{-3}
4/79	--	--	0.16	0.45	1.1×10^{-3}

TABLE 8. Maximum annual-dose rate in mrem/y for atolls of the Northern Marshall Islands assuming a 2 l/d intake of either cistern water or groundwater.

Atoll and island	Cistern water		Groundwater	
	Whole body	Bone marrow	Whole body	Bone marrow
Rongelap				
Rongelap	0.018	0.073	0.041	0.64
Enieatok	0.043	0.11	--	--
Utirik				
Utirik	0.0056	0.029	0.26	0.27
Likiep				
Likiep	0.0023	0.019	0.011	0.063
Rikuraru	0.0026	0.016	0.0067	0.072
Ailuk				
Ailuk	0.0031	0.015	0.024	0.056
Enijabro	0.0041	0.022	0.0099	0.12
Mejit				
Mejit	0.0053	0.016	0.03	0.055
Wotho				
Wotho	0.0034	0.025	0.047	0.053
Ujelang				
Ujelang	0.0043	0.026	0.016	0.022
Ailinginae				
Enibuck	0.0066	0.025	--	--
Kwajalein				
Kwajalein	0.0032	0.015	--	--
Bikini				
Bikini	0.075	0.22	--	--
Eneu	0.012	0.073	--	--

Note: The listed bone-marrow dose is actually somewhat overestimated because it includes the contribution from $^{239+240}Pu$ and ^{241}Am, which are calculated as mineral-bone doses. For the relative contributions of the radionuclides and the fraction of the total dose that is bone-marrow dose, see Table 11.

TABLE 9. The 30-y integral dose in mrem for atolls of the Northern Marshall Islands assuming a 2 l/d intake of either cistern water or groundwater.

Atoll and island	Cistern water		Groundwater	
	Whole body	Bone marrow	Whole body	Bone marrow
Rongelap				
Rongelap	0.41	1.9	0.93	17
Enieatok	0.97	2.8	--	--
Utirik				
Utirik	0.13	0.74	5.8	6.3
Likiep				
Likiep	0.051	0.49	0.25	1.6
Rikuraru	0.059	0.41	0.15	1.8
Ailuk				
Ailuk	0.07	0.39	0.53	1.4
Enijabro	0.093	0.56	0.22	3
Mejit				
Mejit	0.12	0.41	0.68	1.4
Wotho				
Wotho	0.077	0.64	1.1	1.3
Ujelang				
Ujelang	0.097	0.66	0.37	0.55
Ailinginae				
Enibuck	0.15	0.7	--	--
Kwajalein				
Kwajalein	0.071	0.38	--	--
Bikini				
Bikini	1.7	5.6	--	--
Eneu	0.28	1.9	--	--

Note: The listed bone-marrow dose is actually somewhat overestimated because it includes the contribution from $^{239+240}Pu$ and ^{241}Am, which are calculated as mineral-bone doses. For the relative contributions of radionuclides and the fraction of the total dose that is bone-marrow dose, see Table 11.

TABLE 10. The 50-y integral dose in mrem for atolls of the Northern Marshall Islands assuming a 2 l/d intake of either cistern water or groundwater.

Atoll and island	Cistern water		Groundwater	
	Whole body	Bone marrow	Whole body	Bone marrow
Rongelap				
Rongelap	0.56	2.7	1.3	24
Enieatok	1.3	3.9	--	--
Utirik				
Utirik	0.17	1.1	8	8.7
Likiep				
Likiep	0.071	0.7	0.34	2.3
Rikuraru	0.081	0.58	0.21	2.6
Ailuk				
Ailuk	0.096	0.57	0.73	2.1
Enijabro	0.13	0.8	0.31	4.3
Mejit				
Mejit	0.17	0.59	0.94	2
Wotho				
Wotho	0.11	0.92	1.5	1.8
Ujelang				
Ujelang	0.13	0.95	0.5	0.78
Ailinginae				
Enibuck	0.21	1.1	--	--
Kwajalein				
Kwajalein	0.098	0.54	--	--
Bikini				
Bikini	2.3	8	--	--
Eneu	0.38	2.9	--	--

Note: The listed bone-marrow dose is actually somewhat overestimated because it includes the contribution from $^{239+240}Pu$ and ^{241}Am, which are calculated as mineral-bone doses. For the relative contributions of the radionuclides and the fraction of the toal dose that is bone-marrow dose, see Table 11.

TABLE 11. Individual radionuclide contributions in mrem to the 30-y integral dose assuming a 2 l/d intake of either cistern water or groundwater.

Atoll and island	Radionuclide	Cistern water		Groundwater	
		Whole body	Bone marrow	Whole body	Bone marrow
Rongelap					
Rongelap	^{137}Cs	0.41	0.41	0.93	0.93
	^{90}Sr	--	1.4	--	15
	$^{239+240}Pu$	--	0.03	--	0.13
	^{241}Am	--	0.01	--	0.39
Enieatok	^{137}Cs	0.97	0.97	--	--
	^{90}Sr	--	1.8	--	--
	$^{239+240}Pu$	--	0.012	--	--
	^{241}Am	--	0.031	--	--
Utirik					
Utirik	^{137}Cs	0.13	0.13	5.8	5.8
	^{90}Sr	--	0.6	--	0.51
	$^{239+240}Pu$	--	0.005	--	0.002
	^{241}Am	--	0.01	--	0.001
Likiep					
Likiep	^{137}Cs	0.051	0.051	0.25	0.25
	^{90}Sr	--	0.43	--	1.4
	$^{239+240}Pu$	--	0.001	--	0.001
	^{241}Am	--	0.0031	--	0.0093
Rikuraru	^{137}Cs	0.059	0.059	0.15	0.15
	^{90}Sr	--	0.34	--	1.7
	$^{239+240}Pu$	--	0.002	--	0.002
	^{241}Am	--	0.0052	--	0.0047
Ailuk					
Ailuk	^{137}Cs	0.07	0.07	0.53	0.53
	^{90}Sr	--	0.3	--	0.89
	$^{239+240}Pu$	--	0.004	--	0.001
	^{241}Am	--	0.013	--	0.023

TABLE 11. (Continued.)

Atoll and island	Radionuclide	Cistern water		Groundwater	
		Whole body	Bone marrow	Whole body	Bone marrow
Enijabro	^{137}Cs	0.093	0.093	0.22	0.22
	^{90}Sr	--	0.47	--	2.8
	$^{239+240}Pu$	--	0.001	--	0.002
	^{241}Am	--	0.0052	--	0.026
Mejit					
Mejit	^{137}Cs	0.12	0.12	0.68	0.68
	^{90}Sr	--	0.29	--	0.68
	$^{239+240}Pu$	--	0.002	--	0.0013
	^{241}Am	--	0.0052	--	0.041
Wotho					
Wotho	^{137}Cs	0.077	0.077	1.1	1.1
	^{90}Sr	--	0.56	--	0.2
	$^{239+240}Pu$	--	0.003	--	0.004
	^{241}Am	--	0.0052	--	0.01
Ujelang					
Ujelang	^{137}Cs	0.097	0.097	0.37	0.37
	^{90}Sr	--	0.56	--	0.17
	$^{239+240}Pu$	--	0.004	--	0.002
	^{241}Am	--	0.0052	--	0.01
Ailinginae					
Enibuck	^{137}Cs	0.15	0.15	--	--
	^{90}Sr	--	0.43	--	--
	$^{239+240}Pu$	--	0.025	--	--
	^{241}Am	--	0.088	--	--
Kwajalein					
Kwajalein	^{137}Cs	0.071	0.071	--	--
	^{90}Sr	--	0.31	--	--
	$^{239+240}Pu$	--	0.0021	--	--
	^{241}Am	--	--	--	--

TABLE 11. (Continued.)

Atoll and island	Radionuclide	Cistern water		Groundwater	
		Whole body	Bone marrow	Whole body	Bone marrow
Bikini					
Bikini	^{137}Cs	1.7	1.7	--	--
	^{90}Sr	--	3.8	--	--
	$^{239+240}Pu$	--	0.063	--	--
	^{241}Am	--	0.052	--	--
Eneu	^{137}Cs	0.28	0.28	--	--
	^{90}Sr	--	1.5	--	--
	$^{239+240}Pu$	--	0.045	--	--
	^{241}Am	--	0.13	--	--

Note: The doses calculated for $^{234+240}Pu$ and ^{241}Am are for mineral bone; therefore, only a fraction of the listed doses for Pu and Am would be to the bone marrow.

TABLE 12. Maximum annual doses for consumption of 2 l/d of cistern water compared with the individual and population average Federal guidelines in mrem/y.

Atoll and island	Whole body	Bone marrow	Federal annual guidelines for the population	Federal annual guidelines for an individual
Bikini				
Bikini	0.075	0.22	170	500
Eneu	0.012	0.073	170	500
Rongelap				
Rongelap	0.018	0.073	170	500
Enieatok	0.043	0.11	170	500
Utirik				
Utirik	0.0056	0.029	170	500
Ailinginae				
Enibuck	0.0066	0.025	170	500
Other atolls[a]	0.0035 (0.00098)	0.02 (0.00045)	170	500

[a]Mean value of the atolls with the standard deviation in parenthesis.

TABLE 13. The 30-y integral doses for consumption of 2 l/d of cistern water compared with the 30-y Federal guidelines for whole-body exposure in mrem.

Atoll and island	Whole body	Bone marrow	Federal guidelines for 30-y whole-body doses
Bikini			
Bikini	1.7	5.6	5000
Eneu	0.28	1.9	5000
Rongelap			
Rongelap	0.41	1.9	5000
Enieatok	0.07	2.8	5000
Utirik			
Utirik	0.13	0.74	5000
Ailinginae			
Enibuck	0.15	0.7	5000
Other atolls[a]	0.08 (0.022)	0.49 (0.11)	5000

[a]Mean value of the other atolls with the standard deviation in parenthesis.

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