UCRL-LR-107036

An Updated Dose Assessment for Rongelap Island

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July 1994

Lawrence Livermore National Laboratory

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

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William L. Robison, Cynthia L. Conrado, and Kenneth T. Bogen, *An Updated Dose Assessment for Rongelap Island,* Lawrence Livermore National Laboratory, Livermore, CA, UCRL-LR-107036 (July 1994).

The authors regret that a typographical error went undetected throughout the review of this report. On page 7, Table 3, in the fourth column heading of Plutonium aerosol concentration, the heading under concentration (Bq m^{-3}) should be corrected to (μBq m^{-3}). We apologize for any inconvenience this error may have caused the readers.

Table 3. Resuspension data for high and low resuspension conditions on Bikini and Enewetak Atolls ($^{239+240}$Pu).

Location	Surface description	Dust aerosol (μg m^{-3})	Plutonium aerosol concentration (μBq m^{-3})	Suspended soil activity (Bq g^{-1})		Surface soil plutonium activity (Bq g^{-1})		Enhancement factor (EF)[a]		Personal enhancement factor (PEF)		Total enhancement factor (TEF)
Normal "background"												
Bikini	Coconut grove	18	2.2	0.12	+	0.30	=	0.40	×	1.1	=	0.44
Bikini	Stabilized bare soil	21	9.8	0.47	+	0.57	=	0.82	×	2.6	=	2.2
Enjebi[b]	Vegetated field	22	8.9	0.40	+	0.90	=	0.44				
Bikini	In and around house, light work	21	9.8	0.47	+	0.57	=	0.82	×	1.9	=	1.5
Unusual conditions												
Bikini	Field, freshly tilled	136	239	1.8	+	0.57	=	3.1	×	0.92	=	2.9
Enjebi[b]	Garden, freshly tilled		275			0.90		4.4				
Enjebi[b]	Garden, 1 wk. after tilled		113			0.90		2.6				
Bikini	Road with traffic	28	16	0.38	+	0.15	=	2.5	×	1.0	=	2.5
Enjebi[b]	Downwind of road		40			1.3		0.56				

[a] Calculated by assuming 34 μg m^{-3} sea spray that has been verified by measurement on Bikini.

[b] Enjebi Island, Enewetak Atoll.

UCRL-LR-107036
Distribution Category UC-902

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Manuscript date: July 1994

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Abstract

We have updated the radiological dose assessment for Rongelap Island at Rongelap Atoll using data generated from field trips to the atoll during 1986 through 1993. The data base used for this dose assessment is ten fold greater than that available for the 1982 assessment.

Details of each data base are presented along with details about the methods used to calculate the dose from each exposure pathway.

The doses are calculated for a resettlement date of January 1, 1995. The maximum annual effective dose is 0.26 mSv y^{-1} (26 mrem y^{-1}). The estimated 30-, 50-, and 70-y integral effective doses are 0.0059 Sv (0.59 rem), 0.0082 Sv (0.82 rem), and 0.0097 Sv (0.97 rem), respectively. More than 95% of these estimated doses are due to 137-Cesium (^{137}Cs). About 1.5% of the estimated dose is contributed by 90-Strontium (^{90}Sr), and about the same amount each by 239+240-Plutonium ($^{239+240}Pu$), and 241-Americium (^{241}Am).

Introduction

On March 1, 1954, a nuclear weapon test, code-named BRAVO, was conducted at Bikini Atoll in the northern Marshall Islands. The explosive yield of the detonation greatly exceeded expectations, with the result that radioactive material in the cloud was three-to-five times what was expected. Thus, despite the attention that was given to meteorology in the operational planning, moderate to heavy fallout was experienced at the Rongerik, Rongelap, Ailinginae, Ailuk, Taka, Mejit, and Utirik Atolls, located to the east of Bikini. Rongelap and Utirik were inhabited by Marshallese. A small number of Rongelap residents were visiting uninhabited Ailinginae, and a small detachment of U.S. military personnel were stationed on Rongerik. These people were removed from all four atolls as soon as evacuation resources could be deployed. The Rongelap evacuation commenced about 47 hours after the first arrival of fallout and was completed within a few hours. Most of the acute dose received by these residents was attributable to many short-lived radionuclides. In contrast, by the time they returned to their atoll three years later (June, 1957), many of these radionuclides had decayed. However, some radionuclides with intermediate half-lifes, such as 55-Iron (^{55}Fe), 65-Zinc (^{65}Zn), and 60-Cobalt (^{60}Co), did contribute to the dose people received in the first two or three years (Lessard et al., 1980a) after their return. Currently, the long-lived radionuclides, ^{137}Cs, ^{90}Sr, $^{239+240}Pu$, and ^{241}Am, contribute most of the dose to inhabitants of Rongelap Island from man-made sources.

In 1978, in anticipation of the termination of its role as trustee under the United Nations Trusteeship Agreement, the United States government decided to conduct an aerial survey of several atolls east of Bikini Atoll in the direction of the BRAVO fallout pattern to determine the external gamma-exposure rates. The survey, known as the Northern Marshall Islands Radiological Survey (NMIRS), was to be conducted using the USNS Wheeling and helicopters in which the EG&G gamma detectors had been mounted. Based on our work at Enewetak and Bikini Atolls indicating that the terrestrial food chain was potentially the most significant exposure pathway, we strongly recommended that sampling of soil, vegetation, marine species, and water be included as part of the survey to cover all exposure pathways. Consequently, the survey was expanded to include terrestrial and marine sampling using the same vessel to provide logistical and boat support, and limited on-board sample handling. The high cost of ship operation and the time required to do the aerial survey at each atoll were important factors influencing the extent of the sampling program.

The terrestrial and marine sampling was designed as a screening program. The goal was to acquire samples at as many islands at an atoll as possible in the time available to (1) provide data for a preliminary dose assessment at the islands and (2) identify those islands or atolls where additional sampling and analysis may be required (Robison et al., 1981a). A dose assessment was made based on the limited data from the screening survey to determine the dose people living on Rongelap Island would receive between 1978 and 2050 (Robison et al., 1982). Estimates of the dose Rongelap inhabitants received from 1957 through 1978 were reported by Lessard et al. (Lessard et al., 1980a).

Since the 1978 survey, we have collected and analyzed additional samples from Rongelap Atoll. This has resulted in an extensive expansion of the data base for both Rongelap and Kabelle Islands.

In 1985, the Rongelap people were relocated to an island at Kwajalein Atoll where they remain today. In this report we use data from the 1978 NMIRS and the larger amount of data developed from sampling trips to Rongelap Atoll from 1986 through 1993, to estimate the dose that people would receive if they were to resettle on Rongelap Atoll.

The doses are calculated assuming a resettlement date of 1995.

As noted below, we also have had access to and have found useful data from earlier surveys, for example, those done by the University of Washington (LRE) in 1959 and 1961 (Walker and Gessel, 1985).

Exposure Pathways

The radiological dose to inhabitants at a contaminated atoll occurs from both external and internal exposure. Each of these two categories can be broken down further into the following exposure pathways:

(1) External Exposure
- A. Natural Background Radiation
- B. Nuclear-Test-Related Radiation

(2) Internal Exposure
- A. Natural Background Radiation
- B. Nuclear-Test-Related Radiation
  1. Radionuclides in Terrestrial Foods
  2. Radionuclides Inhaled
  3. Radionuclides in Marine Foods
  4. Radionuclides in Drinking Water

The above internal exposure pathways are listed in descending order of their contribution to the total estimated radiological dose at the atolls (Robison et al., 1987). The terrestrial foods are of importance because of the uptake of ^{137}Cs by vegetation; these foods account for about 60% of the total estimated effective dose. The dose from the external gamma pathway is also primarily due to ^{137}Cs. Consequently, about 95% of the total estimated effective dose at Rongelap Island is due to ^{137}Cs. The contribution of the ^{90}Sr, $^{239+240}$Pu, and ^{241}Am is generally less than 5% of the total estimated effective dose, but does vary at different atolls and islands.

The external natural background radiation exposure in the northern Marshall Island Atolls is 3.5 μR h^{-1} or 0.22 mSv y^{-1} (22 mrem y^{-1}) due to cosmic radiation. The external background dose due to terrestrial radiation is very low in the Marshall Islands. The internal effective dose is about 2.2 mSv y^{-1} (220 mrem y^{-1}) for natural occurring radionuclides such as 40-Potassium (^{40}K), 210-Polonium (^{210}Po), and 210-Lead (^{210}Pb), that result from consumption of local and imported foods. The natural background dose is not included in the doses presented in this paper unless specifically stated.

Data Bases

External Exposure Measurements

The external exposure rates at Rongelap and Ailinginae Atolls were measured by EG&G as part of the aerial survey conducted in the 1978 NMIRS (Tipton and Meibaum, 1981). The average exposure rate on Rongelap Island as measured by EG&G in 1978 was about 4.5 μR h^{-1}. The EG&G external exposure contours for ^{137}Cs are shown in Figure 1. In 1988, we made a series of external gamma measurements at the two atolls with our *in-situ*

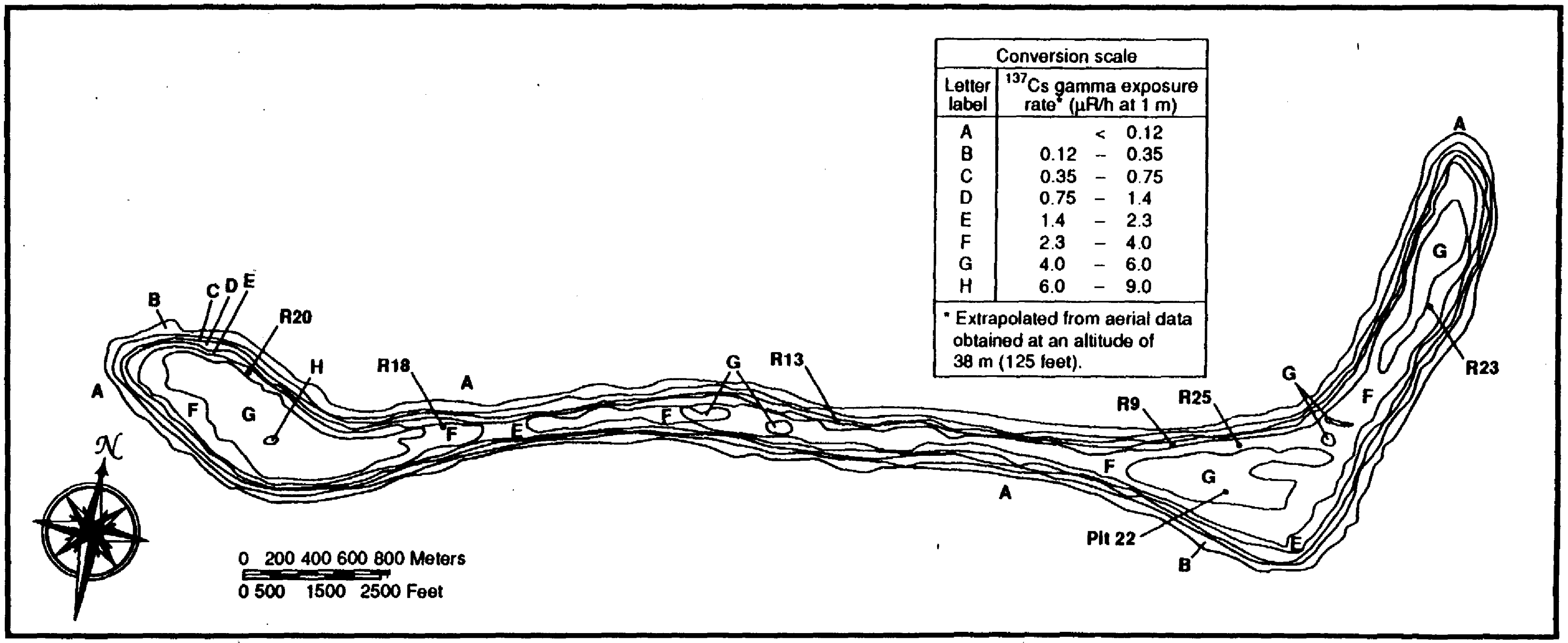

Figure 1. The locations of seven sites (R9, R13, R18, R20, R23, R25, and Pit 22) at Rongelap Island where LLNL made *in-situ* gamma measurements to compare with the EG&G contours developed from the aerial survey in 1978.

gamma-spectroscopy system and compared them with the EG&G aerial gamma measurement of 1978. As part of this process, an independent reviewer, Dr. Herwig Paretzke of the German Radiation Institute in Munich, Germany, participated in the measurements to evaluate our methodology and compare our results with the EG&G 1978 data. The results of the measurements made using our *in-situ* sodium iodide crystal spectrometer system and the EG&G data are listed in Table 1. EG&G's data were listed as ranges for each contour. Our locations were within the specified contour ranges.

In addition, in 1988, LLNL staff took more specific external gamma measurements of ^{137}Cs and ^{60}Co inside and outside of houses and other buildings as well as around the village area. These measurements could not be taken with the aerial-measurement system used in 1978. The buildings provide shielding so that the exposure rate is reduced compared to the exposure rate determined from open-air gamma measurements (McGraw and Lynch, 1973; Robison unpublished data from Bikini Island, 1987); based on measurements at Rongelap Island (Table 2) the reduction factor is about 2. Also, it is customary in the Marshall Islands to place crushed coral around the houses and the village area. This provides an additional shielding factor. The shielding by buildings and crushed coral must be considered when estimating the dose to the people living on the island. The results from our measurements inside the houses and in the surrounding area of the houses and the village are shown in Table 2.

The data presented here from both the 1978 aerial survey conducted by EG&G and from our own more specific measurements made in 1988, are decay corrected to 1995 and form the basis for our estimate of the external dose people would receive while living on Rongelap Island. The maximum effective dose occurs in the first year and is about 0.11 mSv y^{-1} (11 mrem y^{-1}).

Table 1. Comparison of the EG&G aerial gamma measurements with the LLNL *in-situ* gamma measurements for ^{137}Cs.

	^{137}Cs, μR h^{-1}	
Island/Site	LLNL[a]	EG&G aerial contours[a]
Rongelap		
R23	2.1	1.6–2.8
R25	3.5	1.6–2.8
Pit22	3.7	2.8–4.1
R20	2.6	1.6–2.8
R18	3.8	1.6–2.8
R9a	2.6	1.6–2.8
R9b	2.6	1.6–2.8
R13	1.7	1.6–2.8
Ailinginae		
C24	0.98	0.51–0.98
C23	1.5	0.98–1.5

[a] Decay corrected to 1995.

Table 2. External ^{137}Cs gamma exposure-rate measurements in and around the houses and village area of Rongelap Island.

Location	Number of sites	^{137}Cs, μR h^{-1} Median[a]	Mean[a]	Standard deviation
In house	12	0.79	0.83	0.32
Outside house	22	1.5	1.7	0.98
General village sites	16	2.2	2.4	0.85

[a] Decay corrected to 1995.

External Beta-Particle Exposure

The unshielded beta contribution to the external dose was estimated for Enjebi Island at Enewetak Atoll in 1980 (Crase et al., 1982). The average beta dose at 1-m height over open ground was 29% of the external gamma dose. The beta dose is delivered, for the most part, to the first centimeter of tissue, the so-called "shallow dose" and, therefore, should not be added to the external gamma dose in estimating the whole-body dose. More recent studies at Bikini Atoll using new, thinner thermoluminescent dosimeters (TLDs) indicate that the dose over open ground at 1-cm height is about three times that at 1-m height (Shingleton et al., 1987). Thus, the unshielded beta dose at 1-cm on Rongelap Island could be equal to, or slightly greater than, the external gamma dose. For some portion of one day, people do sit or lie on the ground where the 1-cm exposure may be relevant. However, for a significant part of the day, the eyes, upper body, and gonads are at 0.8 m or more in height above the ground surface.

Moreover, it is important to realize that the beta dose to skin, for a number of reasons, will be significantly less than that determined from the unshielded TLDs placed over open ground. The walls and floors of the houses and the crushed coral customarily placed around houses and the village area absorb most of the beta radiation. Because people spend a significant amount of their time in these areas, their exposure to beta particles is greatly reduced. In addition, any clothing, shoes, zories, *Pandanus* mats, or other coverings also greatly reduce exposure to beta radiation.

Airborne Radionuclide Concentrations

Airborne concentrations of $^{239+240}$Pu and ^{241}Am are estimated from data developed in resuspension experiments conducted at Enewetak Atoll in February 1977, and at Bikini Atoll in May 1978. We briefly describe the resuspension methodology here; more detail can be found in Shinn et al. (1989). The dose from ^{137}Cs and ^{90}Sr are orders of magnitude lower than that from $^{239+240}$Pu and ^{241}Am and, consequently, are not listed.

Our study conducted on Bikini Island in May of 1978, provides a more complete set of data than our preliminary studies on Enjebi Island at Enewetak Atoll in February of 1977. (Subsequent studies were conducted on Eneu Island at Bikini Atoll.) The Bikini Island study included (1) extensive soil sampling and *in-situ* gamma spectroscopy to determine isotope concentrations in soil and vegetation; (2) various air-sampling procedures to determine particle-size distribution, and radioactivity; and (3) micrometeorological techniques to determine aerosol fluxes.

Four simultaneous experiments were conducted: (1) a characterization of the normal (background) suspended aerosols and the contributions of 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 to provide 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 air samplers carried by volunteers during daily routines. Less complete studies similar to those of (1) and (2) had been performed previously on Enjebi Island and background studies similar to that of 1 were performed later on Eneu Island.

The "normal" or "background" mass loading (the mass of solid material per unit volume of air) measured by gravimetric methods for both atolls is approximately 55 $\mu g\ m^{-3}$. The Bikini experiments at Bikini Atoll show that about 34 $\mu g\ m^{-3}$ of this total is due to sea salt, which is present across the entire island as a result of ocean, reef, and wind actions. The mass loading due to terrestrial origins is, therefore, about 21 $\mu g\ m^{-3}$. The highest terrestrial mass loading observed was 136 $\mu g\ m^{-3}$ immediately after bulldozing.

Concentrations of $^{239+240}Pu$ in collected aerosols were determined in areas (1) with normal ground cover and conditions in coconut groves, (2) with high-activity conditions, i.e., areas being cleared by bulldozers and being tilled, and (3) with stabilized bare soil, i.e., cleared areas after a few days of weathering. The plutonium concentration in the collected aerosols is different from the plutonium concentration in surface soil for each of these situations. We have defined an enhancement factor (EF) as the $^{239+240}Pu$ concentration in the collected soil aerosol mass (corrected to sea-salt mass) divided by the $^{239+240}Pu$ concentration in surface-soil (0- to 5-cm).

The EF obtained for normal conditions (using standard, high-volume air samplers) is less than 1; the EF for the worst-case, high resuspension conditions is 3. The observed EF's at Bikini and Enewetak Atolls are summarized in Table 3. The EF of less than 1 (EF < 1) for the 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 other words, the particle size and density, and the corresponding radionuclide concentration of normally resuspended material, is different from that of a representative 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 Pu concentration than the soil. Similarly, the enhancement factor of 3 for high-resuspension conditions results from the increased resuspension of particle sizes with a higher plutonium concentration than that observed in the total 0- to 5-cm soil sample.

We have developed additional personal enhancement factors (PEF factors) from personal air sampler data. These data are normalized to the high-volume air sampler data for a particular condition and represent the enhancement that occurs around individuals due to their daily activities. These data are also summarized in Table 3. The total enhancement factor used to estimate the amount of suspended plutonium is the EF multiplied by the PEF. Consequently, the total enhancement factor (TEF) used for normal resuspension conditions is 1.5 (0.82 × 1.9) and for high resuspension conditions, 2.9 (3.1 × 0.92).

To calculate inhalation exposure, we assume that a person spends 1 h d^{-1} in high resuspension conditions (mass loading = 136 $\mu g\ m^{-3}$), 23 h d^{-1} under normal resuspension conditions (mass loading = 21 $\mu g\ m^{-3}$) and has a breathing rate of 23 m^3 per day (1.2 m^3 under high resuspension conditions and 21.6 m^3 under normal resuspension conditions).

The radionuclide concentrations in surface soil (0- to 5- cm) for Rongelap Island complete the information necessary for calculation of plutonium and americium intake through inhalation.

The median $^{239+240}Pu$ and ^{241}Am concentration in surface soil in the island interior region is a factor of 6 higher than the $^{239+240}Pu$ and ^{241}Am concentration in surface soil in the village and housing area (Table 4). We assume for the 1 h d^{-1} in high resuspension conditions, that the resuspended soil aerosol is based on the island interior value for Pu and Am concentration in surface soil and that a person breaths 1.2 m^3 of air during that 1 h period. The 23 h spent in normal resuspension conditions is broken down as follows:

- 7 h d^{-1} in non-occupational activity conditions in the island interior (island interior median Pu and Am concentrations in soil) in which 8.4 m^3 of air is breathed.
- 7 h d^{-1} in non-occupational activity in the village area (village median Pu and Am concentration in soil) in which 8.4 m^3 of air is breathed.
- 9 h d^{-1} in resting conditions in the village area (village median Pu and Am concentrations in soil) in which 4.8 m^3 of air is breathed.

Table 3. Resuspension data for high and low resuspension conditions on Bikini and Enewetak Atolls ($^{239+240}Pu$).

Location	Surface description	Dust aerosol ($\mu g\ m^{-3}$)	Plutonium aerosol concentration ($Bq\ m^{-3}$)	Suspended soil activity ($Bq\ g^{-1}$)		Surface soil plutonium activity ($Bq\ g^{-1}$)		Enhancement factor (EF)[a]		Personal enhancement factor (PEF)		Total enhancement factor (TEF)
Normal "background"												
Bikini	Coconut grove	18	2.2	0.12	+	0.30	=	0.40	×	1.1	=	0.44
Bikini	Stabilized bare soil	21	9.8	0.47	+	0.57	=	0.82	×	2.6	=	2.2
Enjebi[b]	Vegetated field	22	8.9	0.40	+	0.90	=	0.44				
Bikini	In and around house, light work	21	9.8	0.47	+	0.57	=	0.82	×	1.9	=	1.5
Unusual conditions												
Bikini	Field, freshly tilled	136	239	1.8	+	0.57	=	3.1	×	0.92	=	2.9
Enjebi[b]	Garden, freshly tilled		275			0.90		4.4				
Enjebi[b]	Garden, 1 wk. after tilled		113			0.90		2.6				
Bikini	Road with traffic	28	16	0.38	+	0.15	=	2.5	×	1.0	=	2.5
Enjebi[b]	Downwind of road		40			1.3		0.56				

[a] Calculated by assuming 34 $\mu g\ m^{-3}$ sea spray that has been verified by measurement on Bikini.
[b] Enjebi Island, Enewetak Atoll.

Table 4. The median concentration in Bq g^{-1} dry weight of ^{137}Cs, ^{90}Sr, $^{239+240}Pu$, and ^{241}Am in soil at Rongelap Island.

Soil depth, cm	No. of samples	$^{137}Cs^{a}$	No. of samples	$^{90}Sr^{a}$	No. of samples	$^{239+240}Pu$	No. of samples	^{241}Am
0–5 (Interior)	401	0.48 (0.45)	16	0.19 (0.12)	196	0.13 (0.11)	366	0.096 (0.099)
0–5 (village)	131	0.11 (0.19)	4	0.16 (0.11)	110	0.019 (0.031)	90	0.015 (0.024)
5–10	345	0.22 (0.29)	20	0.12 (0.18)	16	0.037 (0.092)	255	0.034 (0.069)
10–15	347	0.10 (0.16)	20	0.11 (0.15)	18	0.018 (0.036)	169	0.018 (0.026)
15–25	346	0.040 (0.082)	20	0.081 (0.089)	18	0.0073 (0.0097)	93	0.0070 (0.026)
25–40	340	0.013 (0.028)	21	0.052 (0.061)	19	0.0033 (0.0047)	41	0.0028 (0.0023)
40–60	302	0.0069 (0.024)	0	—	0	—	21	0.0014 (0.0049)
0–40	330	0.13 (0.10)	17	0.11 (0.080)	13	0.030 (0.024)	20	0.030 (0.028)

[a] Decay corrected to 1995. Number in parentheses is the standard deviation.

The basic equation for calculating the amount of Pu or Am inhaled is: Pu or Am inhaled = Cs × (TEF) × M × I = Bq d^{-1},

where Cs = the concentration of Pu or Am in surface soil in Bq μg^{-1}
M = the mass loading in $\mu g\ m^{-3}$
I = the inhalation rate in the $m^3\ d^{-1}$
(TEF) = the total enhancement factor for either high or normal resuspension conditions

The daily inhalation of $^{239+240}Pu$ and ^{241}Am based on the scenario described above is 0.10 mBq d^{-1} (0.037 Bq y^{-1}) and 0.078 mBq d^{-1} (0.028 Bq y^{-1}), respectively.

Radionuclides in Drinking Water

The drinking water pathway contributes a small portion of radionuclides to the total estimated dose at Rongelap Island. The major source of water used in cooking and for drinking is rainwater that is collected from the roofs of houses and other buildings and stored in cisterns. Two cistern and one ground water sample were collected and analyzed for ^{137}Cs, ^{90}Sr, $^{239+240}Pu$, and ^{241}Am as part of the NMIRS (Noshkin et al., 1981a). The source of radionuclides in the cistern water is generally vegetation that falls into the cisterns through openings in the top of the cisterns or from dust washed off of the roofs when it rains. If extreme drought conditions occur, then the freshest ground water available is used. Only one ground water sample was collected on Rongelap Island. The concentrations of radionuclides in both cistern water and ground water are listed in Tables 5 and 6. The collected rainwater has very low concentrations of ^{137}Cs and ^{90}Sr, while the ground water concentrations are higher; the concentration of transuranic radionuclides is similar in the ground water and cistern water.

For the dose estimates, we use an intake of 1 L d^{-1} of drinking water. We assume for the dose assessment that cistern water is available for 60% of the year and that ground water is used for 40% of the year. The people are very fond of soda (colas, orange soda, root beer, and others) and fruit drinks. These drinks are frequently available and account for some of the daily fluid intake. The total daily drinking fluid intake from all these sources is between 2 and 2.5 L d^{-1}. Water consumption from foods (soups etc.) are not included.

Radionuclides in Marine Foods

The concentrations of ^{137}Cs, ^{90}Sr, $^{239+240}Pu$ and ^{241}Am in marine foods are listed in Tables 5 and 6. Most of the data resulted from work

Table 5. Diet Model—Rongelap Island. Local and imported foods available for adults greater than 18 years.

Local Food	grams d^{-1}	kcal g^{-1}[a,b]	kcal d^{-1}	Specific activity in 1995 (Bq g^{-1} wet wt.) ^{137}Cs	^{90}Sr	$^{239+240}Pu$	^{241}Am	Bq d^{-1} ^{137}Cs	^{90}Sr	$^{239+240}Pu$	^{241}Am
Reef fish[d]	24.2	1.40	33.8	6.7×10^{-4}	2.4×10^{-5}	1.2×10^{-5}	1.4×10^{-6}	1.6×10^{-2}	5.9×10^{-4}	3.0×10^{-4}	3.3×10^{-5}
Tuna	13.9	1.40	19.4	6.0×10^{-4}[d]	2.4×10^{-5}[e]	3.0×10^{-7}[d]	1.4×10^{-6}[e]	8.4×10^{-3}	3.4×10^{-4}	4.1×10^{-6}	1.9×10^{-5}
Mahi Mahi	3.56	1.10	3.92	6.0×10^{-4}[d]	2.4×10^{-5}[e]	3.0×10^{-7}[d]	1.4×10^{-6}[e]	2.1×10^{-3}	8.7×10^{-5}	1.1×10^{-6}	4.9×10^{-6}
Marine crabs[f]	1.68	0.90	1.51	3.3×10^{-4}	4.9×10^{-5}	3.6×10^{-5}	4.1×10^{-6}	5.5×10^{-4}	8.3×10^{-5}	6.0×10^{-5}	6.8×10^{-6}
Lobster[f]	3.88	0.90	3.49	3.3×10^{-4}	4.9×10^{-5}	3.6×10^{-5}	4.1×10^{-6}	1.3×10^{-3}	1.9×10^{-4}	1.4×10^{-4}	1.6×10^{-5}
Clams[c,d,g]	4.56	0.80	3.65	4.2×10^{-5}	1.3×10^{-4}	3.9×10^{-4}	1.2×10^{-4}	1.9×10^{-4}	6.0×10^{-4}	1.8×10^{-3}	5.4×10^{-4}
Trochus[c,d,g]	0.10	0.80	0.08	4.2×10^{-5}	1.3×10^{-4}	3.9×10^{-4}	1.2×10^{-4}	4.2×10^{-6}	1.3×10^{-5}	3.9×10^{-5}	1.2×10^{-5}
Tridacna muscle[c,d,g]	1.67	1.28	2.14	4.2×10^{-5}	1.3×10^{-4}	3.9×10^{-4}	1.2×10^{-4}	7.1×10^{-5}	2.2×10^{-4}	6.4×10^{-4}	2.0×10^{-4}
Jedrul[c,d,g]	3.08	0.80	2.46	4.2×10^{-5}	1.3×10^{-4}	3.9×10^{-4}	1.2×10^{-4}	1.3×10^{-4}	4.1×10^{-4}	1.2×10^{-3}	3.7×10^{-4}
Coconut crabs[c,h]	3.13	0.70	2.19	8.9×10^{-2}	3.9×10^{-2}	7.2×10^{-5}	2.3×10^{-5}	2.8×10^{-1}	1.2×10^{-1}	2.3×10^{-4}	7.2×10^{-5}
Land crabs[c,i]	0.00	0.70	0.00	8.9×10^{-2}	3.9×10^{-2}	7.2×10^{-5}	2.3×10^{-5}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Octopus	4.51	1.00	4.51	4.3×10^{-4}[j]	2.4×10^{-5}[e]	1.2×10^{-5}[e]	1.4×10^{-6}[e]	1.9×10^{-3}	1.1×10^{-4}	5.6×10^{-5}	6.2×10^{-6}
Turtle	4.34	0.89	3.86	6.6×10^{-5}[k]	2.4×10^{-5}[e]	1.2×10^{-5}[e]	1.4×10^{-6}[e]	2.9×10^{-4}	1.1×10^{-4}	5.4×10^{-5}	6.0×10^{-6}
Chicken muscle	8.36	1.70	14.2	1.3×10^{-1}[ℓ]	1.3×10^{-4}[c]	2.5×10^{-6}[m]	3.3×10^{-6}[m]	1.1×10^{0}	1.1×10^{-3}	2.1×10^{-5}	2.8×10^{-5}
Chicken liver	4.50	1.64	7.38	8.8×10^{-2}[ℓ]	2.9×10^{-4}[c]	1.5×10^{-5}[m]	3.1×10^{-5}[m]	4.0×10^{-1}	1.3×10^{-3}	6.8×10^{-5}	1.4×10^{-4}
Chicken gizzard	1.66	1.48	2.46	5.3×10^{-2}[c]	3.2×10^{-4}[c]	9.6×10^{-6}[m]	1.0×10^{-5}[m]	8.9×10^{-2}	5.3×10^{-4}	1.6×10^{-5}	1.7×10^{-5}
Pork muscle	5.67	4.50	25.5	4.9×10^{-1}[ℓ]	9.0×10^{-5}[c]	1.3×10^{-6}[c]	9.1×10^{-7}[c]	2.8×10^{0}	5.1×10^{-4}	7.6×10^{-6}	5.2×10^{-6}
Pork kidney	NR	1.40	0.00	5.8×10^{-1}[ℓ]	1.5×10^{-4}[c]	1.3×10^{-5}[m]	2.4×10^{-5}[m]	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Pork liver	2.60	2.41	6.27	2.0×10^{-1}[ℓ]	1.5×10^{-4}[n]	3.4×10^{-5}[m]	1.3×10^{-5}[m]	5.3×10^{-1}	3.9×10^{-4}	8.8×10^{-5}	3.3×10^{-5}
Pork heart	0.31	1.95	0.61	5.1×10^{-1}[ℓ]	9.0×10^{-5}[o]	1.3×10^{-6}[o]	9.1×10^{-7}[o]	1.6×10^{-1}	2.8×10^{-5}	4.1×10^{-7}	2.8×10^{-7}
Bird muscle[e]	2.71	1.70	4.61	6.7×10^{-4}	2.4×10^{-5}	1.2×10^{-5}	1.4×10^{-6}	1.8×10^{-3}	6.6×10^{-5}	3.4×10^{-5}	3.8×10^{-6}
Bird eggs	1.54	1.50	2.31	1.7×10^{-4}[p]	3.7×10^{-5}[p]	1.2×10^{-5}[e]	1.4×10^{-6}[e]	2.7×10^{-4}	5.7×10^{-5}	1.9×10^{-5}	2.1×10^{-6}
Chicken eggs[q]	7.25	1.63	11.8	1.3×10^{-1}	1.3×10^{-4}	2.5×10^{-6}	3.3×10^{-6}	9.4×10^{-1}	9.7×10^{-4}	1.8×10^{-5}	2.4×10^{-5}
Turtle eggs	9.36	1.50	14.0	6.6×10^{-5}[r]	2.4×10^{-5}[e]	1.2×10^{-5}[e]	1.4×10^{-6}[e]	6.2×10^{-4}	2.3×10^{-4}	1.2×10^{-4}	1.3×10^{-5}
Pandanus fruit[ℓ]	8.66	0.60	5.20	2.5×10^{-1}	1.5×10^{-2}	1.6×10^{-6}	8.1×10^{-7}	2.1×10^{0}	1.3×10^{-1}	1.4×10^{-5}	7.0×10^{-6}
Pandanus nuts[s]	0.50	2.66	1.33	2.5×10^{-1}	1.5×10^{-2}	1.6×10^{-6}	8.1×10^{-7}	1.2×10^{-1}	7.3×10^{-3}	8.2×10^{-7}	4.0×10^{-7}
Breadfruit[ℓ]	27.2	1.30	35.3	1.3×10^{-1}	2.0×10^{-3}	6.0×10^{-7}	7.4×10^{-7}	3.5×10^{0}	5.5×10^{-2}	1.6×10^{-5}	2.0×10^{-5}
Coconut juice[ℓ]	99.1	0.11	10.9	3.2×10^{-2}	3.7×10^{-5}	9.8×10^{-7}	9.3×10^{-7}	3.2×10^{0}	3.6×10^{-3}	9.8×10^{-5}	9.2×10^{-5}
Coconut milk[t]	51.9	3.46	179	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	6.3×10^{0}	2.7×10^{-2}	8.6×10^{-5}	1.1×10^{-4}
Tuba/Jekero[t]	0.00	0.50	0.00	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Drinking coco meat[ℓ]	31.7	1.02	32.3	7.1×10^{-2}	3.3×10^{-4}	1.2×10^{-6}	1.4×10^{-6}	2.3×10^{0}	1.0×10^{-2}	3.9×10^{-5}	4.4×10^{-5}
Copra meat[ℓ]	12.2	4.14	50.3	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	1.5×10^{0}	6.3×10^{-3}	2.0×10^{-5}	2.5×10^{-5}
Sprout. coco[t]	7.79	0.80	6.23	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	9.4×10^{-1}	4.0×10^{-3}	1.3×10^{-5}	1.6×10^{-5}
Marsh. cake[t]	11.7	3.36	39.2	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	1.4×10^{0}	6.0×10^{-3}	1.9×10^{-5}	2.4×10^{-5}
Papaya	6.59	0.39	2.57	4.3×10^{-1}[u]	6.7×10^{-3}[v]	4.7×10^{-6}[w]	4.9×10^{-6}[u]	2.8×10^{0}	4.4×10^{-2}	3.1×10^{-5}	3.2×10^{-5}

Table 5. (Continued)

Local Food	grams d^{-1}	kcal g^{-1} [a,b]	kcal d^{-1}	Specific activity in 1995 (Bq g^{-1} wet wt.) ^{137}Cs	^{90}Sr	$^{239+240}Pu$	^{241}Am	Bq d^{-1} ^{137}Cs	^{90}Sr	$^{239+240}Pu$	^{241}Am
Squash	NR	0.47	0.00	2.1×10^{-1} [ℓ]	2.8×10^{-3} [v]	6.3×10^{-7} [v]	6.5×10^{-7} [w]	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Pumpkin[x]	1.24	0.30	0.37	2.1×10^{-1}	2.8×10^{-3}	6.3×10^{-7}	6.5×10^{-7}	2.6×10^{-1}	3.5×10^{-3}	7.8×10^{-7}	8.1×10^{-7}
Banana	0.02	0.88	0.02	1.2×10^{-2} [ℓ]	1.1×10^{-3} [u]	4.7×10^{-6} [y]	4.9×10^{-6} [y]	2.5×10^{-4}	2.3×10^{-5}	9.4×10^{-8}	9.8×10^{-8}
Arrowroot[ℓ]	3.93	3.46	13.6	2.0×10^{-1}	2.5×10^{-3}	2.6×10^{-5}	1.3×10^{-5}	8.0×10^{-1}	1.0×10^{-2}	1.0×10^{-4}	5.2×10^{-5}
Citrus	0.10	0.49	0.05	5.7×10^{-2} [ℓ]	2.0×10^{-3} [z]	6.0×10^{-7} [z]	7.4×10^{-7} [z]	5.7×10^{-3}	2.0×10^{-4}	6.0×10^{-8}	7.4×10^{-8}
Rainwater[aa]	313	0.00	0.00	1.2×10^{-5}	5.7×10^{-6}	1.1×10^{-7}	7.4×10^{-9}	3.6×10^{-3}	1.8×10^{-3}	3.5×10^{-5}	2.3×10^{-6}
Wellwater[aa]	207	0.00	0.00	2.6×10^{-5}	6.1×10^{-5}	4.7×10^{-7}	2.8×10^{-7}	5.5×10^{-3}	1.3×10^{-2}	9.8×10^{-5}	5.8×10^{-5}
Malolo[bb]	199	0.00	0.00	1.2×10^{-5}	5.7×10^{-6}	1.1×10^{-7}	7.4×10^{-9}	2.3×10^{-3}	1.1×10^{-3}	2.2×10^{-5}	1.5×10^{-6}
Coffee/Tea[bb]	228	0.00	0.00	1.2×10^{-5}	5.7×10^{-6}	1.1×10^{-7}	7.4×10^{-9}	2.6×10^{-3}	1.3×10^{-3}	2.5×10^{-5}	1.7×10^{-6}
Soil[ℓ, cc,dd]	0.10	0.00	0.00	2.8×10^{-1}	1.6×10^{-1}	6.7×10^{-2}	5.1×10^{-2}	2.8×10^{-2}	1.6×10^{-2}	6.7×10^{-3}	5.1×10^{-3}
Total Local	1322		547					31	0.47	0.012	0.0071
Fluids	1046		11								
Solids	276		536								

Imported food	grams d^{-1}	kcal g^{-1} [a,b]	kcal d^{-1}
Baked bread	30.3	2.75	83.3
Fried bread	72.0	4.25	306
Pancakes	59.5	2.18	130
Cake	2.64	3.27	8.63
Rice	234	1.10	257
Instant mashed potatoes	127	0.90	114
Sugar	65.2	3.85	251
Canned chicken	13.0	1.98	25.7
Corned beef	78.7	2.16	170
Spam	55.0	2.28	125
Canned mackerel	44.0	1.83	80.5
Canned sardines	42.5	2.14	91.0
Canned tuna	59.0	1.98	117
Canned salmon	NR	2.03	0.00
Other canned fish	NR	2.00	0.00
Other meat, fish, or poultry	NR	2.00	0.00
Carbonated drinks	338	0.40	135
Orange juice	188	0.44	82.6

Table 5. (Continued)

Imported food	grams d^{-1}	kcal/g^{-1} [a,b]	kcal d^{-1}
Tomato juice	99.5	0.19	18.9
Pineapple juice	178	0.55	97.6
Other canned juice	25.4	0.50	12.7
Evaporated milk	201	1.37	276
Powdered milk	72.9	1.37	99.9
Whole milk	0.00	0.68	0.00
Canned butter	0.00	7.16	0.00
Onion	0.00	0.45	0.00
Canned vegetables	NR	0.80	0.00
Baby food	NR	1.00	0.00
Cocoa	178	0.97	173
Ramen noodles	6.07	1.25	7.6
Candy	NR	4.00	0.00
Total Imported	2168		2661
Fluids	1280		895
Solids	888		1766
Total Local and Imported	3490		3208
Fluids	2326		906
Solids	1164		2302

NOTE: NR stands for no response.

a Data from Murai et al. (1958).

b Includes data from Watt and Merrill (1963), Burton (1965), Buchanan (1947), and Pennington (1976).

c Specific activity from Robison et al. (1982).

d Specific activity from Noshkin et al. (1981b); Robison et al. (1981b).

e Specific activity used is that of reef fish.

f Specific activity calculated using the ratio (Bq g^{-1} shellfish tissue wet weight versus Bq g^{-1} fish tissue wet weight) from Bikini Atoll (Robison et al., 1988).

g Data used is from *Hippopus hippopus* and *Tridacna squamosa*.

h Data used is from coconut crabs from Arbar Island on Rongelap Atoll.

i Specific activity used is that of coconut crab.

j Specific activity calculated using the ratio (Bq g^{-1} octopus tissue wet weight versus Bq g^{-1} fish tissue wet weight) from Bikini Atoll (Robison et al., 1988).

k Specific activity calculated using the ratio (Bq g^{-1} turtle tissue wet weight versus Bq g^{-1} fish tissue wet weight) from Bikini Atoll (Robison et al., 1988).

ℓ Specific activity is based on determinations from samples taken from Rongelap Island from the 1978 survey together with our most recent trips to Rongelap Island from 1986 through 1993.

m Specific activity is unpublished data from the 1978 NMIRS.
n Specific activity used is that of pork kidney.
o Specific activity used is that of pork muscle.
p Specific activity calculated using the ratio (Bq g^{-1} bird eggs wet weight versus Bq g^{-1} bird muscle wet weight) from Bikini Atoll (Robison et al., 1988).
q Specific activity used is that of chicken muscle.
r Specific activity used is that of turtle.
s Specific activity used is that of *Pandanus* fruit.
t Specific activity used is that of copra meat.
u Specific activity used is calculated using concentration ratios (Bq g^{-1} fruit wet weight versus Bq g^{-1} soil dry weight) from the other atolls taken on the 1978 survey.
v Specific activity used is calculated using concentration ratios (Bq g^{-1} fruit weight versus Bq g^{-1} soil dry weight) from Bikini and Eneu Islands at Bikini Atoll.
w Specific activity used is calculated using the same concentration ratio for $^{239+240}Pu$ and ^{241}Am when no data is available and assuming $^{239+240}Pu$ and ^{241}Am are the same.
x Specific activity used is that of squash.
y Specific activity used is that of papaya.
z Specific activity used is that of breadfruit.
aa Specific activity from Noshkin et al. (1981a).
bb Specific activity used is that of rainwater.
cc Specific activity is in Bq g^{-1} dry weight.
dd Specific activity used is calculated using the time distribution of 16 h d^{-1} in the village area versus 7 h d^{-1} in the interior of Rongelap Island.

Table 6. Diet Model—Rongelap Island. Imported foods unavailable (only local foods) for adults greater than 18 years.

Local Food	grams d^{-1}	kcal g^{-1} [a,b]	kcal d^{-1}	Specific activity in 1995 (Bq g^{-1} wet wt.) ^{137}Cs	^{90}Sr	$^{239+240}Pu$	^{241}Am	Bq d^{-1} ^{137}Cs	^{90}Sr	$^{239+240}Pu$	^{241}Am
Reef fish[d]	43.4	1.40	60.7	6.7×10^{-4}	2.4×10^{-5}	1.2×10^{-5}	1.4×10^{-6}	2.9×10^{-2}	1.1×10^{-3}	5.4×10^{-4}	6.0×10^{-5}
Tuna	36.0	1.40	50.4	6.0×10^{-4}[d]	2.4×10^{-5}[e]	3.0×10^{-7}[d]	1.4×10^{-6}[e]	2.2×10^{-2}	8.8×10^{-4}	1.1×10^{-5}	5.0×10^{-5}
Mahi Mahi	10.7	1.10	11.8	6.0×10^{-4}[d]	2.4×10^{-5}[e]	3.0×10^{-7}[d]	1.4×10^{-6}[e]	6.5×10^{-3}	2.6×10^{-4}	3.2×10^{-6}	1.5×10^{-5}
Marine crabs[f]	9.75	0.90	8.78	3.3×10^{-4}	4.9×10^{-5}	3.6×10^{-5}	4.1×10^{-6}	3.2×10^{-3}	4.8×10^{-4}	3.5×10^{-4}	4.0×10^{-5}
Lobster[f]	17.6	0.90	15.8	3.3×10^{-4}	4.9×10^{-5}	3.6×10^{-5}	4.1×10^{-6}	5.7×10^{-3}	8.7×10^{-4}	6.3×10^{-4}	7.2×10^{-5}
Clams[c,d,g]	29.1	0.80	23.2	4.2×10^{-5}	1.3×10^{-4}	3.9×10^{-4}	1.2×10^{-4}	1.2×10^{-3}	3.8×10^{-3}	1.1×10^{-2}	3.4×10^{-3}
Trochus[c,d,g]	0.12	0.80	0.10	4.2×10^{-5}	1.3×10^{-4}	3.9×10^{-4}	1.2×10^{-4}	5.1×10^{-6}	1.6×10^{-5}	4.6×10^{-5}	1.4×10^{-5}
Tridacna muscle[c,d,g]	5.72	1.28	7.32	4.2×10^{-5}	1.3×10^{-4}	3.9×10^{-4}	1.2×10^{-4}	2.4×10^{-4}	7.6×10^{-4}	2.2×10^{-3}	6.8×10^{-4}
Jedrul[c,d,g]	9.69	0.90	8.72	4.2×10^{-5}	1.3×10^{-4}	3.9×10^{-4}	1.2×10^{-4}	4.1×10^{-4}	1.3×10^{-3}	3.7×10^{-3}	1.1×10^{-3}
Coconut crabs[c,h]	12.5	0.70	8.73	8.9×10^{-2}	3.9×10^{-2}	7.2×10^{-5}	2.3×10^{-5}	1.1×10^{0}	4.8×10^{-1}	9.0×10^{-4}	2.9×10^{-4}
Land crabs[c,i]	0.00	0.70	0.00	8.9×10^{-2}	3.9×10^{-2}	7.2×10^{-5}	2.3×10^{-5}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Octopus	24.5	1.00	24.5	4.3×10^{-4}[j]	2.4×10^{-5}[e]	1.2×10^{-5}[e]	1.4×10^{-6}[e]	1.1×10^{-2}	6.0×10^{-4}	3.1×10^{-4}	3.4×10^{-5}
Turtle	8.88	0.89	7.90	6.6×10^{-5}[k]	2.4×10^{-5}[e]	1.2×10^{-5}[e]	1.4×10^{-6}[e]	5.9×10^{-4}	2.2×10^{-4}	1.1×10^{-4}	1.2×10^{-5}
Chicken muscle	15.6	1.70	26.5	1.3×10^{-1}[ℓ]	1.3×10^{-4}[c]	2.5×10^{-6}[m]	3.3×10^{-6}[m]	2.0×10^{0}	2.1×10^{-3}	3.9×10^{-5}	5.2×10^{-5}
Chicken liver	8.84	1.64	14.5	8.8×10^{-2}[ℓ]	2.9×10^{-4}[c]	1.5×10^{-5}[m]	3.1×10^{-5}[m]	7.8×10^{-1}	2.5×10^{-3}	1.3×10^{-4}	2.7×10^{-4}
Chicken gizzard	1.66	1.48	2.46	5.3×10^{-2}[c]	3.2×10^{-4}[c]	9.6×10^{-6}[m]	1.0×10^{-5}[m]	8.9×10^{-2}	5.3×10^{-4}	1.6×10^{-5}	1.7×10^{-5}
Pork muscle	6.96	4.50	31.3	4.9×10^{-1}[ℓ]	9.0×10^{-5}[c]	1.3×10^{-6}[c]	9.1×10^{-7}[c]	3.4×10^{0}	6.3×10^{-4}	9.3×10^{-6}	6.3×10^{-6}
Pork kidney	NR	1.40	0.00	5.8×10^{-1}[ℓ]	1.5×10^{-4}[c]	1.3×10^{-5}[m]	2.4×10^{-5}[m]	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Pork liver	3.35	2.41	8.07	2.0×10^{-1}[ℓ]	1.5×10^{-4}[n]	3.4×10^{-5}[m]	1.3×10^{-5}[m]	6.8×10^{-1}	5.0×10^{-4}	1.1×10^{-4}	4.3×10^{-5}
Pork heart	0.31	1.95	0.61	5.1×10^{-1}[ℓ]	9.0×10^{-5}[o]	1.3×10^{-6}[o]	9.1×10^{-7}[o]	1.6×10^{-1}	2.8×10^{-5}	4.1×10^{-7}	2.8×10^{-7}
Bird muscle[e]	13.2	1.70	22.4	6.7×10^{-4}	2.4×10^{-5}	1.2×10^{-5}	1.4×10^{-6}	8.8×10^{-3}	3.2×10^{-4}	1.6×10^{-4}	1.8×10^{-5}
Bird eggs	11.4	1.50	17.1	1.7×10^{-4}[p]	3.7×10^{-5}[p]	1.2×10^{-5}[e]	1.4×10^{-6}[e]	2.0×10^{-3}	4.2×10^{-4}	1.4×10^{-4}	1.6×10^{-5}
Chicken eggs[q]	20.6	1.63	33.6	1.3×10^{-1}	1.3×10^{-4}	2.5×10^{-6}	3.3×10^{-6}	2.7×10^{0}	2.7×10^{-3}	5.2×10^{-5}	6.8×10^{-5}
Turtle eggs	117	1.50	176	6.6×10^{-5}[r]	2.4×10^{-5}[e]	1.2×10^{-5}[e]	1.4×10^{-6}[e]	7.7×10^{-3}	2.9×10^{-3}	1.5×10^{-3}	1.6×10^{-4}
Pandanus fruit[ℓ]	31.5	0.60	18.9	2.5×10^{-1}	1.5×10^{-2}	1.6×10^{-6}	8.1×10^{-7}	7.8×10^{0}	4.6×10^{-1}	5.1×10^{-5}	2.5×10^{-5}
Pandanus nuts[s]	1.00	2.66	2.66	2.5×10^{-1}	1.5×10^{-2}	1.6×10^{-6}	8.1×10^{-7}	2.5×10^{-1}	1.5×10^{-2}	1.6×10^{-6}	8.1×10^{-7}
Breadfruit[ℓ]	93.1	1.30	121	1.3×10^{-1}	2.0×10^{-3}	6.0×10^{-7}	7.4×10^{-7}	1.2×10^{1}	1.9×10^{-1}	5.6×10^{-5}	6.9×10^{-5}
Coconut juice[ℓ]	167	0.11	18.3	3.2×10^{-2}	3.6×10^{-5}	9.8×10^{-7}	9.3×10^{-7}	5.4×10^{0}	6.1×10^{-3}	1.6×10^{-4}	1.6×10^{-4}
Coconut milk	60.9	3.46	211	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	7.4×10^{0}	3.2×10^{-2}	1.0×10^{-4}	1.2×10^{-4}
Tuba/Jekero[t]	0.00	0.50	0.00	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Drinking coco meat[ℓ]	90.4	1.02	92.2	7.1×10^{-2}	3.3×10^{-4}	1.2×10^{-6}	1.4×10^{-6}	6.4×10^{0}	3.0×10^{-2}	1.1×10^{-4}	1.3×10^{-4}

Table 6. (Continued)

Local Food	grams d^{-1}	kcal g^{-1} [a,b]	kcal d^{-1}	Specific activity in 1995 (Bq g^{-1} wet wt.) ^{137}Cs	^{90}Sr	$^{239+240}$Pu	^{241}Am	Bq d^{-1} ^{137}Cs	^{90}Sr	$^{239+240}$Pu	^{241}Am
Copra meat[l]	35.7	4.14	148	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	4.3×10^{0}	1.8×10^{-2}	5.9×10^{-5}	7.3×10^{-5}
Sprout. coco[t]	61.2	0.80	48.9	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	7.4×10^{0}	3.2×10^{-2}	1.0×10^{-4}	1.3×10^{-4}
Marsh. cake[t]	0.00	0.76	0.00	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Papaya	13.5	0.39	5.26	4.3×10^{-1}[u]	6.7×10^{-3}[v]	4.7×10^{-6}[w]	4.9×10^{-6}[u]	5.7×10^{0}	9.1×10^{-2}	6.3×10^{-5}	6.6×10^{-5}
Squash	NR	0.47	0.00	2.1×10^{-1}[l]	2.8×10^{-3}[v]	6.3×10^{-7}[v]	6.5×10^{-7}[w]	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Pumpkin[x]	2.72	0.30	0.82	2.1×10^{-1}	2.8×10^{-3}	6.3×10^{-7}	6.5×10^{-7}	5.7×10^{-1}	7.7×10^{-3}	1.7×10^{-6}	1.8×10^{-6}
Banana	0.29	0.88	0.26	1.2×10^{-2}[l,]	1.1×10^{-3}[u]	4.7×10^{-6}[y]	4.9×10^{-6}[y]	3.6×10^{-3}	3.3×10^{-4}	1.4×10^{-6}	1.4×10^{-6}
Arrowroot[l]	47.4	3.46	164	2.0×10^{-1}	2.5×10^{-3}	2.6×10^{-5}	1.3×10^{-5}	9.7×10^{0}	1.2×10^{-1}	1.2×10^{-3}	6.3×10^{-4}
Citrus	0.10	0.49	0.05	5.7×10^{-2}	2.0×10^{-3}[z]	6.0×10^{7}[z]	7.4×10^{-7}[z]	5.7×10^{-3}	2.0×10^{-4}	6.0×10^{-8}	7.4×10^{-8}
Rainwater[aa]	315	0.00	0.00	1.2×10^{-5}	5.7×10^{-6}	1.1×10^{-7}	7.4×10^{-9}	3.7×10^{-3}	1.8×10^{-3}	3.5×10^{-5}	2.3×10^{-6}
Wellwater[aa]	215	0.00	0.00	2.6×10^{-5}	6.1×10^{-5}	4.7×10^{-7}	2.8×10^{-7}	5.7×10^{-3}	1.3×10^{-2}	1.0×10^{-4}	6.0×10^{-5}
Malolo[bb]	0.00	0.00	0.00	1.2×10^{-5}	5.7×10^{-6}	1.1×10^{-7}	7.4×10^{-9}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Coffee/Tea[bb]	0.00	0.00	0.00	1.2×10^{-5}	5.7×10^{-6}	1.1×10^{-7}	7.4×10^{-9}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Soil[l, cc, dd]	0.10	0.00	0.00	2.8×10^{-1}	1.6×10^{-1}	6.7×10^{-2}	5.1×10^{-2}	2.8×10^{-2}	1.6×10^{-2}	6.7×10^{-3}	5.1×10^{-3}
Total Local	1541		1392					78	1.5	0.031	0.013
Fluids	696		18								
Solids	845		1374								

NOTE: NR stands for no response.

[a] Data from Murai et al. (1958).
[b] Includes data from Watt and Merrill (1963), Burton (1965), Buchanan (1947), and Pennington (1976).
[c] Specific activity from Robison et al. (1982).
[d] Specific activity from Noshkin et al. (1981b); Robison et al. (1981b)
[e] Specific activity used is that of reef fish.
[f] Specific activity calculated using the ration (Bq g^{-1} shellfish tissue wet weight versus Bq g^{-1} fish tissue wet weight) from Bikini Atoll (Robison et al., 1988).
[g] Data used is from *Hippopus hippopus* and *Tridacna squamosa*.
[h] Data used is from coconut crabs from Arbar Island on Rongelap Atoll.
[i] Specific activity used is that of coconut crab.
[j] Specific activity calculated using the ratio (Bq g^{-1} octopus tissue wet weight versus Bq g^{-1} fish tissue wet weight) from Bikini Atoll (Robison et al., 1988).
[k] Specific activity calculated using the ratio (Bq g^{-1} turtle tissue wet weight versus Bq g^{-1} fish tissue wet weight) from Bikini Atoll (Robison, et al., 1988).

l Specific activity is based on determinations from samples taken from Rongelap Island from the 1978 survey together with our most recent trips to Rongelap Island from 1986 through 1993.

m Specific activity is unpublished data from the 1978 NMIRS.

n Specific activity used is that of pork kidney.

o Specific activity used is that of pork muscle.

p Specific activity calculated using the ratio (Bq g^{-1} bird eggs wet weight versus Bq g^{-1} bird muscle wet weight) from Bikini Atoll (Robison et al., 1988).

q Specific activity used is that of chicken muscle.

r Specific activity used is that of turtle.

s Specific activity used is that of *Pandanus* fruit.

t Specific activity used is that of copra meat.

u Specific activity used is calculated using concentration ratios (Bq g^{-1} fruit wet weight versus Bq g^{-1} soil dry weight) from the other atolls taken on the 1978 survey.

v Specific activity used is calculated using concentration ratios (Bq g^{-1} fruit weight versus Bq g^{-1} soil dry weight) from Bikini and Eneu Islands at Bikini Atoll.

w Specific activity used is calculated using the same concentration ratio for $^{239+240}Pu$ and ^{241}Am when no data is available and assuming $^{239+240}Pu$ and ^{241}Am are the same.

x Specific activity used is that of squash.

y Specific activity used is that of papaya.

z Specific activity used is that of breadfruit.

aa Specific activity from Noshkin et al. (1981a).

bb Specific activity used is that of rainwater.

cc Specific activity is in Bq g^{-1} dry weight.

dd Specific activity used is calculated using the time distribution of 16 h d^{-1} in the village area versus 7 h d^{-1} in the interior of Rongelap Island.

conducted at Rongelap Atoll by Dr. V. Noshkin; the sources of the data are identified in the table footnotes. The data in the tables have been decay corrected from the date of the reported results to our target date of 1995.

Radionuclides in Soil

The median concentration of ^{137}Cs, ^{90}Sr, $^{239+240}Pu$, and ^{241}Am in surface soil for interior and village areas, and soil profiles on Rongelap Island are listed in Table 4. The decrease in activity with depth is exponential with about 80% of the activity in the top 15 cm of the soil column.

We have included in the diet model, 100 mg/d of surface soil that may contaminate the food during preparation or on the hands of the people where it might be ingested. Consequently, for the Imports Available diet, surface soil accounts for 56% on the $^{239+240}Pu$ daily intake, and 72% for the ^{241}Am daily intakes. For the Imports Unavailable diet, soil ingestion accounts for 22% and 39% for the $^{239+240}Pu$ and ^{241}Am daily intakes. The daily intake of ^{137}Cs and ^{90}Sr via soil ingestion is negligible compared to the other foods. In Tables 5 and 6, the mean surface soil concentrations for ^{137}Cs, ^{90}Sr, $^{239+240}Pu$, and ^{241}Am are presented to account for the time distribution spent in the village versus the interior of the island. We assume people spend 16 h d^{-1} in the village, 1 h d^{-1} on the beach, and 7 h d^{-1} in the interior of Rongelap Island. More detailed results showing mean, median, ranges and other statistical information for the village and the interior of Rongelap Island are listed in Appendix A.

The majority of ^{241}Am in soil profiles below 10 cm are under the minimum detection limits. The values for ^{241}Am presented in this report are based on only a small number of the total samples collected and analyzed since we do not report values below the minimum detection limit. Therefore, the statistics presented would be much lower if we had real values for the samples that gave us minimum detection limits. For the soil depths of 10–15 cm, 15–25 cm, 25–40 and 40–60 cm the percent below the minimum detection limit are approximately 50%, 70%, 80%, and greater than 80%.

Radionuclides in Terrestrial Foods

The mean concentrations of radionuclides in food crops grown on Rongelap Island are listed in Tables 5 and 6. The numbers of samples that were averaged to derive each of the mean values, as well as the median and range of values, are listed in Appendix B. The distribution of our sampling sites on Rongelap Island is shown in Figure 2.

The concentrations of ^{137}Cs in foods from Rongelap Island, based on all the data from 1986 through 1993, are compared in Table 7 with the adjusted values used in the 1982 preliminary assessment (Robison et al., 1982) that was based on the 1978 NMIRS.

The reason for adjusting the 1978 data is outlined below. During the 1978 NMIRS, U.S. personnel conducting the survey collected all coconut, *Pandanus*, breadfruit, other vegetation, and soil samples. All of the coconuts collected on Rongelap Island (and the other islands) were assumed to be drinking coconuts. The ^{137}Cs concentration of 0.20 Bq g^{-1} (5.5 pCi g^{-1}) in these coconut samples was used for the drinking coconut meat value in the dose assessment. A value for copra meat was estimated from this "assumed" drinking coconut meat value and was taken as 0.28 Bq g^{-1} (7.6 pCi g^{-1}).

As we progressed with our program from 1979 to the present, we have had Marshallese assistants select and classify the coconuts as drinking or copra coconuts. We found that we could differentiate between drinking coconuts and copra coconuts, as selected by the Marshallese staff, by measuring the dry to wet ratio of the coconut meat. If the coconut meat dry to wet ratio is greater than 0.45, then the coconuts fall into the copra class and if the ratio is less than 0.45, they fall into the drinking coconut class.

When we apply these criteria to the coconuts collected in 1978, we find that most of the coconuts collected by U.S. personnel in 1978 were really copra coconuts; only three of the seventeen coconut samples collected were drinking coconuts. Consequently, the concentration of 0.20 Bq g^{-1} (5.5 pCi g^{-1}) used in the 1982 dose assessment was much too high for the drinking coconut class because the ^{137}Cs concentration is higher in copra coconuts than in drinking coconuts.

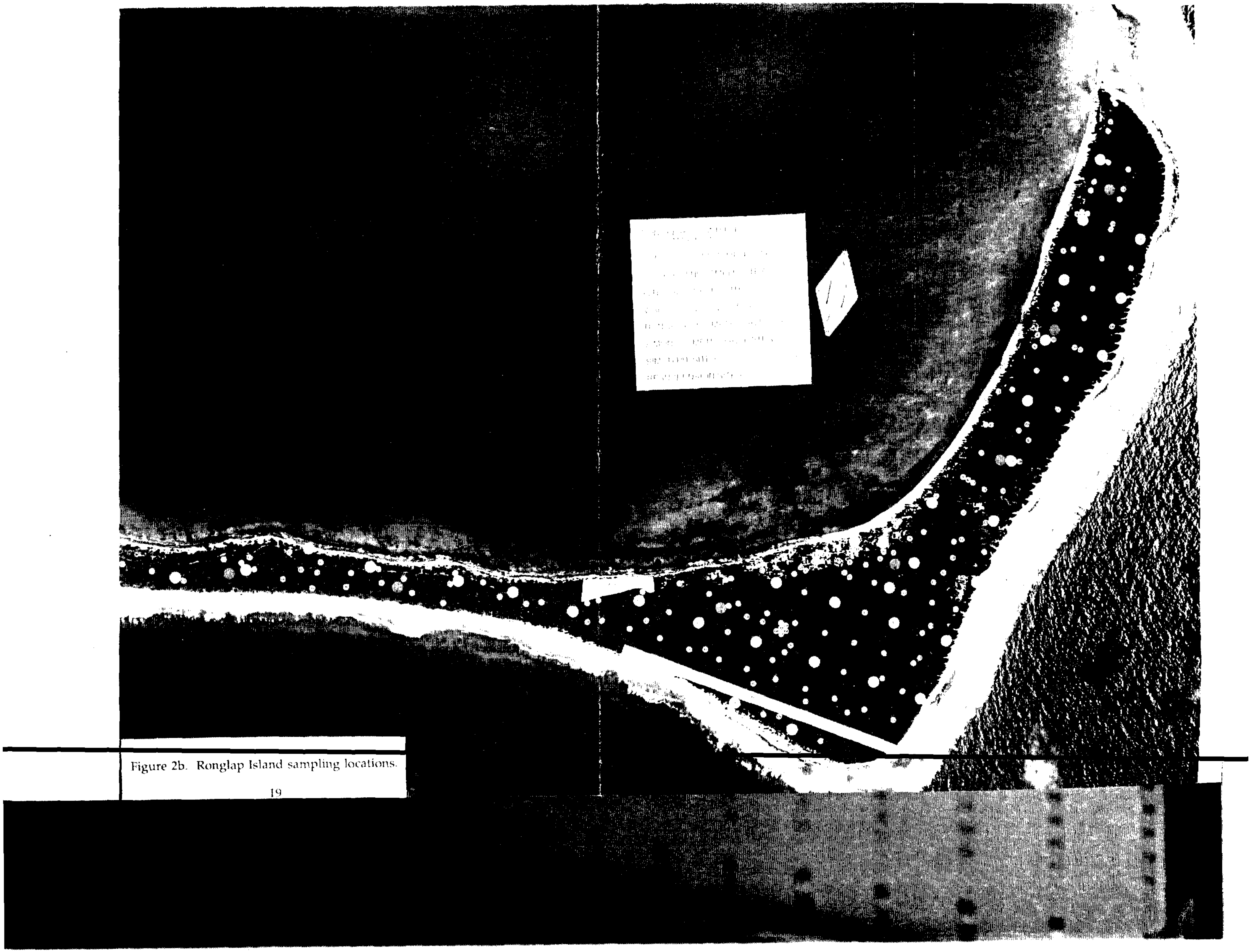

Figure 2b. Ronglap Island sampling locations.

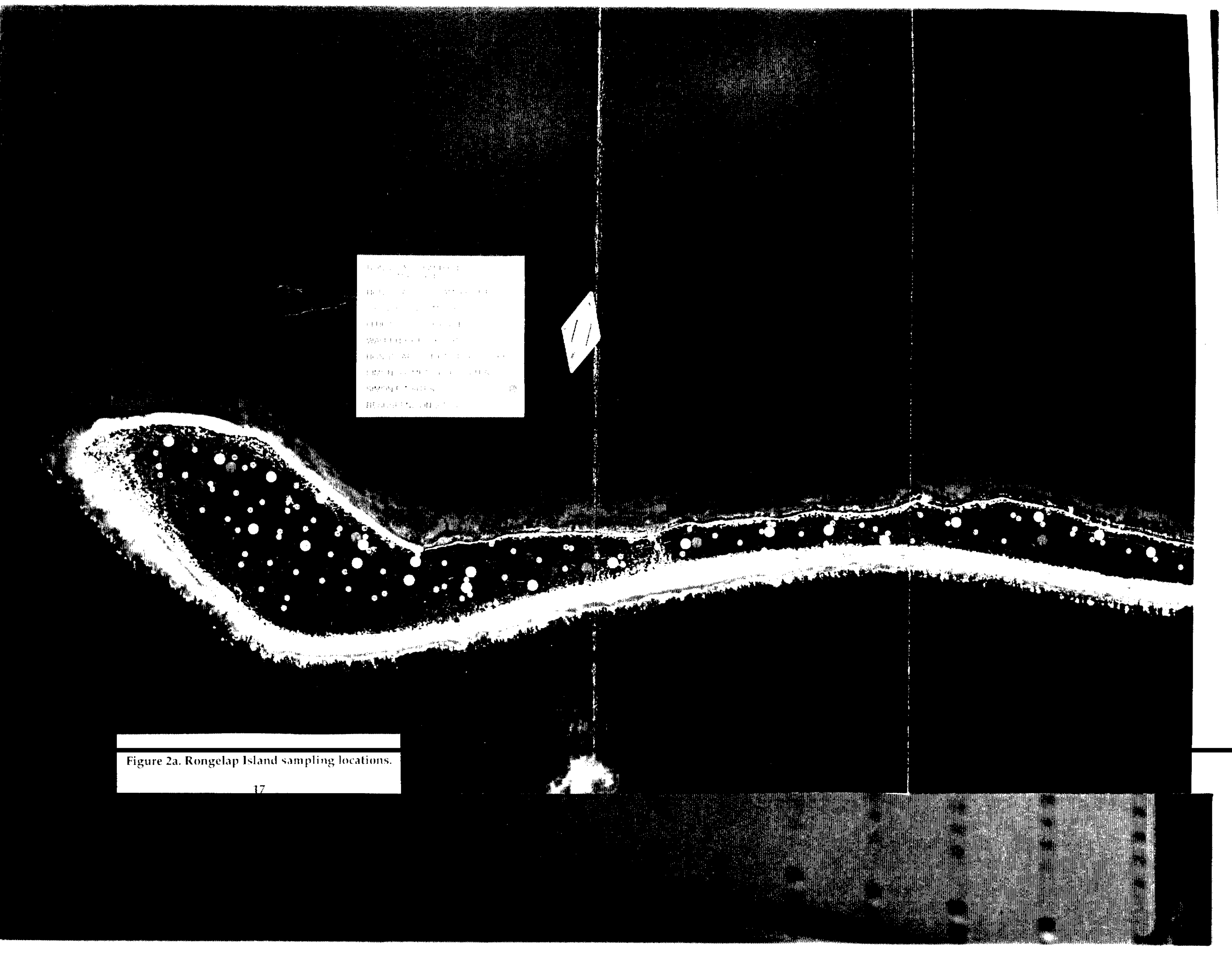

Figure 2a. Rongelap Island sampling locations.

Table 7. Cesium-137 concentration in Bq g^{-1} wet weight in Rongelap Island vegetation (decay corrected to 1995).

Time period	Drinking coconut meat	Drinking coconut fluid	Copra meat	*Pandanus*	Breadfruit
1978 (NMIRS)	0.065 (3)[a]	—	0.16 (14)	0.27 (16)	0.068 (1)
1986–1993	0.071 (433)	0.032 (427)	0.12 (108)	0.25 (116)	0.13 (40)

[a] Number of samples in parentheses.

The comparison in Table 7 is based on the readjustment of the class of coconuts collected in 1978. The results for samples collected in 1978 and those collected from 1986 through 1993 are very similar for all food products even though there was a very limited sampling in 1978.

Diet

The estimated average intake of local and imported foods used in the dose assessment is a very important parameter; radiological dose will scale directly with the total intake of ^{137}Cs, which is proportional to the quantity of locally grown foods that are consumed. Therefore, a reasonable estimate of the average daily consumption rate of each food item is essential. Our laboratory, and independent committees, in concert with local government authorities, with the legal representatives of the people, and with Peace Corps representatives, and anthropologists have endeavored to establish and document pertinent trends, cultural influences, and economic realities —with the hope that our estimates may be soundly based.

The diet model we use for estimating the intake of local and imported foods is presented in Tables 5 and 6. The basis of this diet model was the survey of the Ujelang community in 1978 by the Micronesian Legal Services Corporation (MLSC) staff and a Marshallese school teacher on Ujelang (Robison et al., 1980). The results were presented for women, men, teenagers, and children. Adult intake exceeded that of teenagers and children, and the intake of local food was about 20% greater for women than for men. The higher intake attributed to women is unexplained and certainly questionable. It is indicative of the acknowledged uncertainty in dietary estimates. Nevertheless, we believe that the MSLC survey provides a reasonable basis for estimating dietary intake. Pending the availability of empirical data, we have chosen to use the higher (female) diet as our diet model rather than attempt further speculative refinement.

Our choice of this diet model is supported by other considerations. The estimated intake of coconut, which dominates the potential dose to people, is higher in the Brookhaven National Laboratory (BNL) diet than in our diet model; this difference arises in part from the fact that the BNL estimates were for food prepared rather than for food actually consumed. A more detailed comparison of the Ujelang Diet Survey with higher dietary intake estimated by the BNL is presented in Robison et al. (1980). A comparison of the estimated body burdens from our dose model using the MLSC diet and from the BNL A and B diets against actual whole-body measurements of the Rongelap and Utirik people made by another BNL team shows that the MLSC diet predicts observed body burdens more closely than does the BNL diet (Robison, 1983; Miltenberger et al., 1980a; Lessard et al., 1980a, 1980b). In fact, predictions of body burdens and doses using our diet model are very close to the whole-body measurements of the population, as is illustrated in Figure 3. The "local-foods only" diet (imported foods unavailable) and the BNL A and B diets lead to body burdens greatly in excess of those observed by direct whole-body measurements.

Further support of our diet model is found in other estimates of coconut consumption. The current estimate of consumption of coconut meat

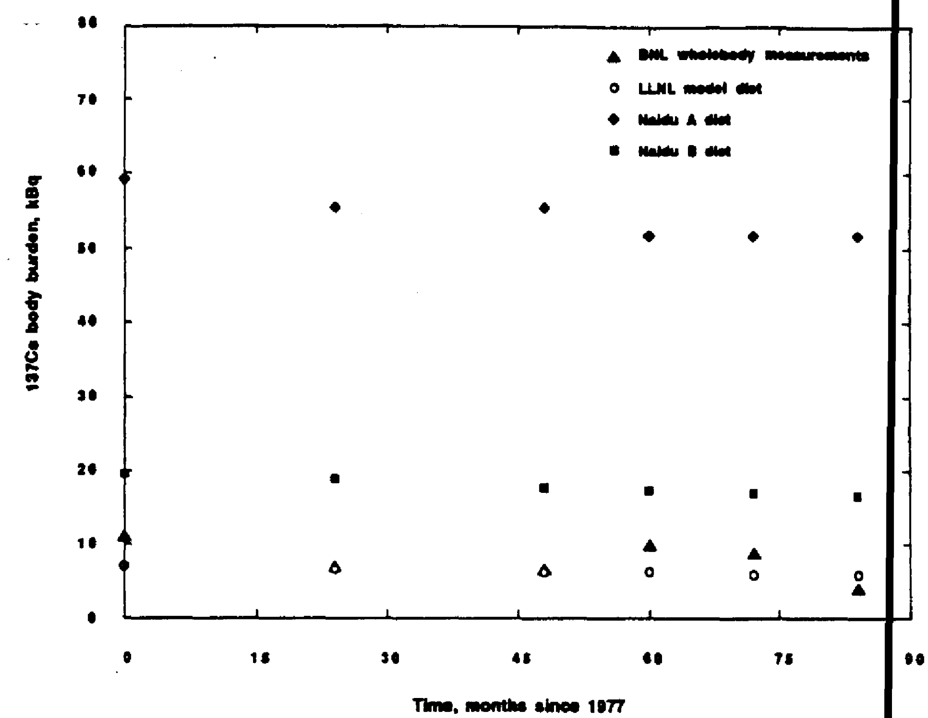

Figure 3. Comparison of ^{137}Cs body burdens estimated using various diet models with actual whole body measurements at Rongelap Island.

and fluid in our diet model of about 1 to 1.5 coconuts per day, per person, averaged over a year is consistent with estimates of an average of 0.5 and 1.0 coconuts per day, per person, made by two Marshallese officials with considerable experience in living habits at atolls other than Majuro Atoll (DeBrum, 1985).

Based on data published by Mary Murai in 1954, the average intake of coconut products was drinking coconut fluid, 95 mL d^{-1}; copra meat, 48 g d^{-1}; and drinking coconut meat, 10 g d^{-1}; however, sprouting coconut was not mentioned (Murai, 1954). The total intake is essentially the same as the results of the Ujelang Survey. It might be noted that consumption of local foods in 1954 was higher than today.

Moreover, the Bikini Atoll Rehabilitation Committee (BARC) asked for a survey on coconut consumption by the Bikini community (Bikini Atoll Rehabilitation Committee, 1986). The result of the limited survey was that coconut consumption was about one-third of that indicated in the MLSC diet listed in Table 5. Similarly, 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 (Domnick and Seelye, 1967). 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. Data from Eneu Island show that an average drinking coconut contains 325 mL of fluid (standard deviation equals 125 mL), so that even if the entire average coconut use of 0.5 per day were all drinking nuts, the average intake would be about 160 g d^{-1}. This is in agreement with the results from the MLSC survey at Ujelang.

Experience at Enewetak Atoll also supports our model. In past years, coconuts have been brought to Enewetak Atoll from Ujelang Atoll. Sufficient quantities have been available for the average consumption rate to have been 1 coconut per day, per person, if all coconuts were consumed. However, all the coconuts were not consumed, a significant number were fed to pigs or left to decay, and thus the average coconut consumption rate has been less than 1 coconut per person per day (Wilson, 1985). In short, the average coconut consumption rate in our diet model appears to be somewhat higher than in other sources of information we have found, except the BNL report.

Another way to evaluate the general validity of a proposed diet model is to determine the total daily intake in terms of mass and calories. A summary of the grams per day (g d^{-1}) intake of solid foods plus milk products and liquids in our diet model compared with average U.S. diets is listed in Table 8. Also listed are the average kilocalories per day (kcal d^{-1}) intake for the diet model when imported foods are both available and unavailable, and for the U.S. population from three different sources (Yang and Nelson, 1986; Abraham et al., 1979; Rupp, 1980). The average food intake reported for Japan by Hisamatsu et al. (1987) and by the Japanese Ministry of Health and Welfare is 1253 g d^{-1} and 1352 g d^{-1}, respectively (Hisamatsu et al., 1987).

The intake of about 1440 g d^{-1}, including milk products (1164 g solids + 274 g milk) in our diet model when imported foods are available, is higher by about 200 to 400 g d^{-1} than the results from the U.S. and Japanese surveys that also include milk and milk products. The 3208 kcal d^{-1} in the diet model exceeds the U.S. average by a little more than 1000 kcal d^{-1}. The average recommended allowances for caloric intake range from 2000 to 3200 kcal d^{-1}, and individual recommended allowances from 1600 to 4000 kcal d^{-1} (Dietary Standard for Canada, 1964; FAO, 1957; Joint FOA,WHO/UNU, 1985; ICRP, 1975; NAS, 1980).

This comparison shows that our diet model, based upon the MLSC survey at Ujelang Atoll, is not seriously at variance with the U.S. and Japanese data for g d^{-1} intake or for total daily calories consumed.

The calculation of body burden, dietary intake, and calorie intake for the "Imported Foods Unavailable" diet (Figure 3 and Table 8) is based upon the assumption that no imported foods are available; that is, people consume only local foods for their entire lifetime. Our observation is that in the Marshall Islands of today this is unrealistic. The demand for imported foods is present, they are considered staples in the diet, and suppliers and commercial transport are also available. Even though resupply schedules may be somewhat erratic,

Table 8. Comparison of the average adult diet model for the Northern Marshall Islands with the average adult diet for the United States.

	Average adult diet model for the Northern Marshall Islands		Average adult diet for the United States		
	Imports available	Imports unavailable	Yang and Nelson (1986)	Abraham et al. (1979)	Rupp (1980)
Food intake, g d^{-1}	1164	845	1066	—	1232
Fluid intake, g d^{-1}	2326	696	1526	—	1351
Caloric intake, kcal d^{-1}	3208	1392	1853	1925	—

inventories of imported foods are expected to be such that the total absence of imported foods from the diet is most unlikely.

A few general conclusions can be drawn from evaluating all of the available data on dietary habits in the Marshall Islands.

1. Coconut consumption is the major source of ^{137}Cs intake in the diet model; the diet model does predict the ^{137}Cs body burden observed in actual whole-body counting of the adult population for two atolls. Consequently, the ^{137}Cs intake in the model is very close to reality — at least at these atolls.

2. The dietary habits are, to a degree, atoll-specific and should be generalized from one atoll to another only when supporting atoll-specific data are unavailable.

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 data are needed to improve the precision of the dose assessment for each resettlement situation.

Dose Methodology

To predict the effective dose to a population on Rongelap Island, we calculated both the potential external and internal effective dose from the available data and information. The sources of exposure and methods of calculation are different for external and internal exposure.

External Exposure

Estimates of external exposure include both gamma and beta radiation. The method of calculation for each is described below.

Gamma Radiation

The external exposure calculations for gamma radiation are based on measurements made on Rongelap Island in 1978 and 1988, and decay corrected to 1995. The following arbitrary distribution of time was used to develop the average external exposure for ^{137}Cs for a 1995 resettlement:

1. Nine h d^{-1} are spent in the house where the exposure rate is 0.83 $\mu R\ h^{-1}$ (see Table 2).

2. Six h d^{-1} around the house and village area where the exposure rate is assumed to be 2.0 $\mu R\ h^{-1}$ (weighted average of outside house and general village sites).

3. Seven h d^{-1} in the interior region of the island where the average exposure is 3.0 $\mu R\ h^{-1}$ (Tipton and Meibaum, 1981).

4. Two h d^{-1} on the beach or lagoon where the exposure is 0.089 $\mu R\ h^{-1}$, based on EG&G data (Tipton and Meibaum, 1981).

Although the selection of this particular time distribution is arbitrary, general discussions with Marshallese people and observations made while we have been in the islands make the selection reasonable.

The external exposure rates in $\mu R\ h^{-1}$ are converted to equivalent dose rates in tissue using a factor of 0.0075 Sv per Roentgen (0.75 rem per Roentgen) and assuming a quality factor of 1.0 for gamma radiation (UNSCEAR, 1972; ICRP, 1973; ICRU, 1985). Several researchers have evaluated the conversion of exposure doses in air to absorbed dose in specific organs (Kerr, 1980; O'Brien and Sanna, 1976). These conversion factors range from 0.0049 to 0.0075 Sv per Roentgen (0.49 to 0.75 rem per Roentgen), depending on the organ. We have chosen the conversion factor for testes, one of the higher factors, and used it for the whole body and bone marrow. A result of this choice is that the whole-body doses listed in this report can be used to estimate genetic effects based on gonad dose. Based on the conversion factor of 0.0075 Sv in tissue per Roentgen exposure in air, the conversion factor to mSv y^{-1} from $\mu R\ h^{-1}$ is 0.066.

The resultant contributions of ^{137}Cs to the annual average effective dose in the first year of occupancy of various island areas described in the above scenario are:

1. Inside houses—0.022 mSv y^{-1} (2.2 mrem y^{-1}).
2. Elsewhere in the housing and village area—0.031 mSv y^{-1} (3.1 mrem y^{-1}),

3. Island interior—0.059 mSv y^{-1} (5.9 mrem y^{-1}).

4. Beaches and lagoon—0.50 μSv y^{-1} (0.050 mrem y^{-1}).

The average external effective dose rate attributable to such a living pattern in 1995 on Rongelap Island is about 0.11 mSv y^{-1} (11 mrem y^{-1}). The natural external background effective dose rate is about 0.22 mSv y^{-1} (22 mrem y^{-1}).

Beta Radiation

It is impossible to predict precisely what the beta dose to the skin will be, but it is clear that the "shallow dose" due to both beta particles and external gamma exposure will be only slightly greater than the dose estimated for external gamma whole-body exposure. This higher "shallow dose" will occur primarily to the most exposed parts of the body, usually the arms, lower legs, and feet. The skin is a much less sensitive organ to radiation than other parts of the body; for example, the weighting factor for stochastic risk recommended by the ICRP for skin is 0.01, compared with 0.20 for gonads, 0.12 for red bone marrow, colon, stomach, and lungs, and 0.05 for breast, bladder, liver, and thyroid (ICRP, 1990). Consequently, the beta contribution to the total effective dose is extremely small.

Internal Exposure

Cesium-137

The conversion from the intake of ^{137}Cs to the effective dose for the adult is based upon the ICRP methods described in ICRP Publications 30, 56, 61 (ICRP, 1979, 1990, 1991b), which are based on Leggett's model (Leggett, 1986). We have combined the ICRP model for charged-particle emissions for the beta-particle emissions ($\bar{E}$ = 0.51 meV) from ^{137}Cs and the methods of Leggett et al. (1984), and Cristy and Ekerman (1987a and 1987b) for the photon emission (E = 0.66 meV), associated with ^{137}Cs decay (^{137m}Ba) to generate the final dose conversion factors. The biological half-life of ^{137}Cs is determined as a function of mass (i.e., age) by the methods described in the Leggett model. In a separate report, we estimated the comparative doses between adults and children (Robison and Phillips, 1989). The results indicate that the estimated integral effective dose for adults due to ingestion of ^{137}Cs and ^{90}Sr can be used as a conservative estimate for intake beginning in infancy. In this report we calculate only the doses to adults.

Strontium-90

Several models have been developed over the years to estimate the cycling and retention of ^{90}Sr in the body as a function of age to calculate age-dependent dose conversion factors. We have previously used both the model developed at Environmental Measurement Laboratory (EML) (Rivera, 1967; Bennett, 1973, 1977, 1978; Klusek, 1979) and that of Papworth and Vennart (1973, 1984). The two models give very similar results, with the biggest difference in results occurring for persons between the ages of 5 and 15 y. Both models are empirical models based on measurements of ^{90}Sr in the diet and corresponding measurements of ^{90}Sr in autopsy bone samples. The retentions and turnover rates, and discrimination factors in the models are determined by regression analysis or equation solution fitting of the observed data. No particular correlation is made with bone compartments, as outlined by the ICRP (1972, 1979, 1990), in the EML model, but Papworth and Vennart's model does include the two compartments of compact and cancellous bone.

A more recent model developed by Leggett et al. (1982) is based on the structure and function of bone compartments as generally outlined in the ICRP model (ICRP, 1972, 1979, 1990). The bone is assumed to be composed of a structural component associated with bone volume, which includes the compact cortical bone, a large portion of the cancellous (trabecular) bone, and a metabolic component associated with bone surfaces. In effect, three compartments are then identified: two within the bone volume and one within the bone surface. The bone volume is associated with mechanical structure and integrity of the bone, and the bone surface is involved with the metabolic regulation of extracellular calcium. Much use is made of general data about age-dependent bone formation within these compartments and, consequently, this model is not as dependent on radionuclide-specific data as the other models.

We will not discuss further details of these models, but refer the reader to the original articles and their associated references for additional discussion and clarification (Leggett et al., 1982; Cristy et al., 1984). Doses listed in this paper are calculated from the Leggett model.

Transuranic Radionuclides ($^{239+240}$Pu and ^{241}Am)

Ingestion. We calculated the effective dose from ingestion of transuranic radionuclides ($^{239+240}$Pu and ^{241}Am) by ICRP methods (ICRP, 1979, 1986, 1988). The amount of ingested plutonium or americium crossing the gut wall to the blood (i.e., the gut-transfer factor) is assumed to be 10^{-3} for plutonium and americium in vegetation, and 10^{-4} and 10^{-3} for the fraction of Pu and Am, respectively, ingested via soil. Of the fraction of plutonium or americium reaching the blood, 45% is assumed to go to bone and 45% to the liver (ICRP, 1986, 1988). The biological half-life is 50 y in bone and 20 y in liver for both elements (ICRP, 1986). The quality factor is 20 for the alpha particles from ^{239}Pu, ^{240}Pu, and ^{241}Am.

Inhalation. The effective dose from inhalation for the transuranic radionuclides is based on the intake determined from the assumptions discussed in the section on Airborne, Respirable Radionuclide Concentrations of this paper and ICRP dose methodology (ICRP, 1979, 1986, 1990). The $^{239+240}$Pu and the ^{241}Am are considered class W particles, and the quality factor is 20. Other parameters are described in the ICRP method previously discussed for the ingestion of transuranic radionuclides. The activity-median aerodynamic diameter (AMAD) is assumed to be 1 µm. This is a conservative approach in that measurements at Bikini Atoll indicate the AMAD is between 1.5 and 2.4 µm.

The potential effective dose from the inhalation pathway for ^{137}Cs and ^{90}Sr at the atoll are insignificant compared with the transuranic radionuclides. For example, the annual limit of intake (ALI) listed in ICRP publication 61 (ICRP, 1991b) is 10^6 Bq (2.7×10^7 pCi) for ^{137}Cs, 5.9×10^5 Bq (1.6×10^7 pCi) for ^{90}Sr, and 3×10^2 Bq (8.1×10^3 pCi) for each $^{239+240}$Pu and ^{241}Am. When combined with the surface soil concentration of the radionuclides, the potential effective dose from ^{137}Cs and ^{90}Sr is about 3 orders of magnitude less than that from $^{239+240}$Pu and ^{241}Am.

The same conclusion can be reached by looking at the recent publication of the National Radiological Protection Board in England (Kendall et al., 1986). The effective dose per unit intake for inhalation (in Sv Bq^{-1})* is 5.7×10^{-8} for ^{90}Sr, 7.7×10^{-9} for ^{137}Cs, 1.1×10^{-4} for $^{239+240}$Pu, and 1.2×10^{-4} for ^{241}Am. Again, the effective dose per unit intake is 3 to 4 orders of magnitude lower for ^{137}Cs and ^{90}Sr than for transuranic radionuclides. Thus, the doses via inhalation are so small for ^{137}Cs and ^{90}Sr that they are not listed in the tables.

Polonium-210, Lead-210

The estimated effective dose from ingestion of natural ^{210}Po and ^{210}Pb is based on new ICRP data and methods (Eckerman, 1993). The weighted committed effective dose per unit intake of activity for ^{210}Po is 2.3×10^{-6} Sv Bq^{-1}. The corresponding weighted committed effective dose for ^{210}Pb is 1.5×10^{-6} Sv Bq^{-1}.

Body Weights and Biological Half-Life of ^{137}Cs

Data from BNL have been summarized to determine the body weights of the Marshallese people (Conard et al., 1958, 1959, 1960, 1963, 1975; McCraw, 1980; Miltenberger et al., 1980b). The average body weights of adult males are listed in Table 9. The average adult male body weight is 72 kg for Bikini, 71 kg for Enewetak, 63 kg for Rongelap, and 69 kg for Utirik; thus, they are very near the 70 kg value of reference man (ICRP, 1975). (The lower body weight for Rongelap could be because of age distribution.) We have used 70 kg as the average male 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 13 Utirik females, 66 kg for 41 Bikini females, and 54 kg for 83 Rongelap females. The weighted average for females is 60 kg.

The average biological half-life for the long-term compartment for ^{137}Cs in adults is

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* 1 Sv = 1 Joule kg^{-1} ≡ 100 rem; 1 Bq = 1 disentegration sec $^{-1}$ ≡ 27 pCi.

Table 9. Body weights of Marshallese adult males in kilograms.[a]

Atoll	Number	Mean	Standard deviation	Minimum	Maximum
Utirik	9	69	12.9	54.5	92.7
Bikini	50	72	11.7	52	100.5
Rongelap	87	63	9.4	47.5	86.8
Enewetak[b]	130	71	14	37	126
Total	276	69[c]	—	37	126

a Conard et al. (1958, 1959, 1960, 1963, 1975); Mittenberger et al. (1980b); McCraw (1980).

b Personal communications, E.T. Lessard and R. Miltenberger, Brookhaven National Laboratory, Upton, NY (1979).

c Weighted mean.

listed as 110 d in ICRP (1979, 1990) and NCRP (1977). This is consistent with data obtained by BNL on the half-time of the long-term compartment in Marshallese (Miltenberger et al., 1981; Miltenberger and Lessard, 1987). A summary of BNL data presented in Figure 4 shows that the distribution of biological half-life in 23 Marshallese adult males can be considered lognormal with a median of 115 d, a mean of 119 d, and a range of 76–178 d. In our dose model for ^{137}Cs, we used the 110-d half-life because it is based on a much larger sample population and the difference between it and the 115-d half-life observed in 23 Marshallese males is minimal. The half-time in the long-term compartment for 21 females in the BNL study was 83 d (range 63–126 d). We have not made a separate calculation based on the shorter biological half-life and the smaller body mass for females. These two parameters are offsetting to a degree, and the dose to females would be somewhat less than the males.

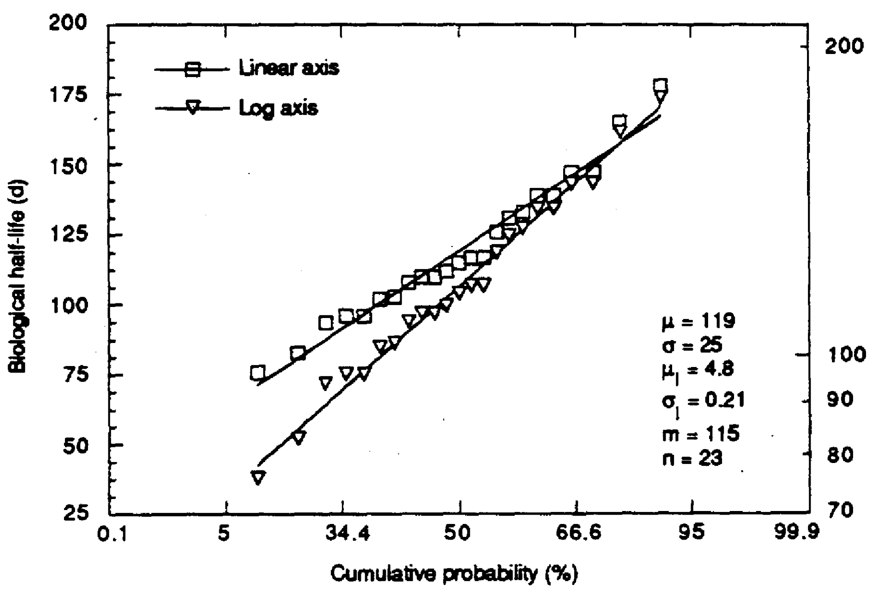

Figure 4. Probability plot of the biological half-life for ^{137}Cs in Marshallese males.

Results

The effective dose is listed in both Sieverts (Sv) or (milliSieverts (mSv)) and in rem (or mrem) in this report. This is done intentionally because we have used the rem as the unit of dose in our earlier publications concerning the Marshall Islands (Robison et al., 1980, 1982; USAEC, 1973). In addition, the Marshallese Communities, the Republic of the Marshalls Government, and U.S. agencies and committees are familiar with these publications, doses, and units. Thus, the previous dose estimates (and units) serve as a reference point for updated dose estimates presented here. The effective dose in rem or mrem can be converted to Sv or mSv by dividing by 100, and pCi can be converted to Becquerels (Bq) by dividing by 27.

The purpose of this paper is to present our estimates of the potential radiological doses people might receive if they were to resettle Rongelap Island at Rongelap Atoll and to document the scientific and technical basis for the estimates. To place the magnitude of the estimated doses in perspective, we have compared them to current guidelines adopted by several Federal agencies. We acknowledge, and even emphasize, that there is a legitimate question as to which, if any, of the current guidelines are applicable at Rongelap, Enewetak, and Bikini Atolls in the Marshall Islands, where the islands are already contaminated and people wish to return and live at "home." Nevertheless, such guidance does provide a reference point for radiation doses that lead to a very minimal risk, and may provide useful insight for those who must decide on future actions.

The National Council on Radiation Protection and Measurements (NCRP, 1987b) and the International Commission on Radiological Protection (ICRP, 1990) have recently recommended an average annual effective dose rate of 1 mSv y^{-1} (100 mrem y^{-1}) to the general public for continuous exposure resulting from operating nuclear industries. The Department of Energy (DOE) has recently adopted this guidance for its operating nuclear facilities. Consequently, we will use 1 mSv y^{-1} (100 mrem y^{-1}) for our comparison with doses estimated for Rongelap Island.

The estimated maximum annual and integral effective dose for people resettling Rongelap Island are calculated using our diet model, the average radionuclide concentrations in foods, the average biological removal rates and depositions for the radionuclides in organs or the whole body, and the average external dose rates. The maximum annual effective dose rate is defined as the dose rate in that year after the Rongelap people return (we have used 1995 as the start date), when the sum of the internal dose and the external gamma dose is at maximum. In other words, using the average value of all parameters in the dose model and our diet model, the annual effective dose for any other year would be less than the maximum annual effective dose we present. The 30-, 50-, and 70-y integral effective doses are calculated with year 1 being 1995.

Doses are presented for two cases: imported foods available (IA) and imported foods unavailable (IUA). The doses listed under the case "IUA" are calculated assuming no imported foods are available, and that only local foods are consumed over the entire lifetime of the people's residence on Rongelap Island. As noted in the Data Base Section on Diet, our observations lead us to conclude that the latter case is unrealistic over any extended period of time and highly conservative. Nevertheless, it is presented here so that the reader may apply different assumptions or use the results of future observations to develop an apportioned dose estimate. In our model for IA, we have assumed that 60% of the diet will be made up of imported foods, and even this may be low. Imported foods seem now to be established in the diet and the culture.

The maximum annual organ equivalent dose and the effective dose when imported foods are available and unavailable are listed in Table 10. The maximum annual organ equivalent dose rates for IA range from 0.23 to 0.31 Sv y^{-1} (23 to 31 mrem y^{-1}) from all exposure pathways. About 0.11 mSv (11 mrem) of this dose is from external gamma exposure, while most of the remainder is from ingestion pathways. The maximum effective dose rate is 0.26 mSv y^{-1} (26 mrem y^{-1}).

The 30-, 50-, and 70-y integral effective dose for residents of Rongelap Island for IA, are

Table 10. The maximum annual organ equivalent dose and effective dose in mSv y^{-1} for Rongelap Island residents.

	Weight factor	External gamma	Dose equivalent rate, mSv y^{-1}			
			Internal		Total[a]	
			Ingestion[a]	Inhalation	Organ[b]	Effective
Imported Foods Available						
Bone marrow	0.12	.11	0.17	0.00077	0.28	0.26 mSv (26 mrem) (~0.15 mSv y^{-1} of the total is from ingestion)
Bone surface	0.01	.11	0.19	0.0086	0.31	
Gonads	0.20	.11	0.15	0.00011	0.26	
Lung	0.12	.11	0.14	0.0012	0.25	
Breast	0.05	.11	0.12	0.000023	0.23	
Thyroid	0.05	.11	0.14	0.000023	0.25	
Liver	0.05	.11	0.15	0.0018	0.26	
Colon	0.12	.11	0.15	0.000025	0.26	
Stomach	0.12	.11	0.14	0.000023	0.25	
Bladder	0.05	.11	0.15	0.000023	0.26	
Esophagus	0.05	.11	0.14	0.000023	0.25	
Skin	0.01	.11	0.12	0.000023	0.23	
Remainder	0.05	.11	0.15	0.000029	0.26	
Imported Foods Unavailable						
Bone marrow	0.12	0.11	0.43	0.00077	0.54	0.48 mSv (48 mrem)
Bone surface	0.01	0.11	0.47	0.0086	0.59	
Gonads	0.20	0.11	0.38	0.00011	0.49	
Lung	0.12	0.11	0.34	0.0012	0.45	
Breast	0.05	0.11	0.30	0.000023	0.41	
Thyroid	0.05	0.11	0.35	0.000023	0.46	
Liver	0.05	0.11	0.36	0.0018	0.47	
Colon	0.12	0.11	0.38	0.000025	0.49	
Stomach	0.12	0.11	0.36	0.000023	0.47	
Bladder	0.05	0.11	0.38	0.000023	0.49	
Esophagus	0.05	0.11	0.35	0.000023	0.46	
Skin	0.01	0.11	0.29	0.000023	0.40	
Remainder	0.05	0.11	0.37	0.000029	0.48	

[a] The total dose may vary in the second decimal place due to rounding.
[b] Rounded to two significant figures.

listed in Table 11. The doses are presented by pathway and radionuclide so the contribution of each pathway and nuclide can be evaluated. The 30-, 50-, and 70-y integral effective doses are 0.0059 Sv (0.59 rem), 0.0082 Sv (0.82 rem), and 0.0097 Sv (0.97 rem), respectively. The same information for the local foods only diet (IUA) are listed in Table 12.

The doses calculated in this report are less than those calculated in 1982 (Robison et al., 1982) because of the concentration now used for drinking coconut and copra meat versus that used in 1982 (see discussion on page 16), and because the internal gamma dose calculation now accounts for shielding by buildings, etc. In 1982 we used the average open-air gamma exposure with no adjustments for shielding and the amount of time people spent in various locations.

Since that time, we have made specific measurements inside and outside of houses and around the village area to define more precisely the average external effective dose a resident would receive. The comparative results of the 1982 estimated effective dose and the effective dose estimated in this report are listed in Table 13.

The effective doses presented here for Rongelap Island could be reduced even further based on experiments conducted at Bikini Atoll; the use of high-potassium fertilizer at Bikini has reduced the ^{137}Cs uptake in food crops by about 90 to 95%. Consequently, it is possible to reduce the ^{137}Cs doses from ingestion listed in Table 11 and 12 by a similar amount if some mitigating, salutary measures are implemented.

Discussion

Comparison of Estimated Doses to Adopted Guidelines and to Background Doses

The maximum annual effective dose for Rongelap Island in 1995, using average values for parameters in the dose model, is 0.26 mSv y^{-1} (26 mrem y^{-1}) when imported foods are available. By way of comparison, the current guideline adopted by most government agencies for the average annual effective dose to a population is 1 mSv y^{-1} (100 mrem y^{-1}). The 30-y integral effective dose for Rongelap Island is 0.0059 Sv (0.59 rem). The guideline for 30-y integral effective dose based on the 1 mSv (100 mrem) annual standard, is 0.030 Sv (3.0 rem).

Additional perspective can be obtained by comparing these estimated doses for Rongelap Island with natural background doses in the United States. The average annual effective dose from natural background sources in the

Table 11. The 30-, 50-, and 70-y integral effective dose for Rongelap Island residents when imported foods are available (IA).

	Integral effective dose, Sv (rem)		
	30 y	50 y	70 y
External	0.0024 (0.24)	0.0033 (0.33)	0.0039 (0.39)
Internal			
Ingestion			
^{137}Cs	0.0033 (0.33)	0.0045 (0.45)	0.0053 (0.53)
^{90}Sr	8.7×10^{-5} (0.0087)	1.3×10^{-4} (0.013)	1.5×10^{-4} (0.015)
$^{239+240}Pu$	1.3×10^{-5} (0.0013)	3.3×10^{-5} (0.0033)	6.0×10^{-5} (0.0060)
^{241}Am	1.4×10^{-5} (0.0014)	3.3×10^{-5} (0.0033)	5.7×10^{-5} (0.0057)
Inhalation			
$^{239+240}Pu$	2.9×10^{-5} (0.0029)	7.0×10^{-5} (0.0070)	1.3×10^{-4} (0.013)
^{241}Am	1.9×10^{-5} (0.0019)	4.5×10^{-5} (0.0045)	7.8×10^{-5} (0.0078)
Total[a]	0.0059 (0.59)	0.0082 (0.82)	0.0097 (0.97)

[a] The total dose may vary in the second decimal place due to rounding.

Table 12. The 30-, 50-, and 70-y integral effective dose for Rongelap Island residents for a diet when imported foods are unavailable (IUA; i.e., only local foods.)

	Integral effective dose , Sv (rem)		
	30 y	50 y	70 y
External	0.0024 (0.24)	0.0033 (0.33)	0.0039 (0.39)
Internal			
Ingestion			
^{137}Cs	0.0081 (0.81)	0.011 (1.1)	0.013 (1.3)
^{90}Sr	2.7×10^{-4} (0.027)	4.0×10^{-4} (0.040)	4.8×10^{-4} (0.048)
$^{239+240}Pu$	5.1×10^{-5} (0.0051)	1.3×10^{-4} (0.013)	2.3×10^{-4} (0.023)
^{241}Am	2.5×10^{-5} (0.0025)	6.0×10^{-5} (0.0060)	1.0×10^{-4} (0.010)
Inhalation			
$^{239+240}Pu$	2.9×10^{-5} (0.0029)	7.0×10^{-5} (0.0070)	1.3×10^{-4} (0.013)
^{241}Am	1.9×10^{-5} (0.0019)	4.5×10^{-5} (0.0045)	7.8×10^{-5} (0.0078)
Total[a]	0.011 (1.1)	0.015 (1.5)	0.018 (1.8)

[a] The total dose may vary in the second decimal place due to rounding.

Table 13. Comparison of the doses estimated in 1982 based on the 1978 NMIRS data, to those in this report for the case of imported foods available.

	Previous Estimates (1998[a])	Current estimates (1995)
Maximum annual effective dose	0.37 mSv (37 mrem)	0.26 mSv (26 mrem)
30-y integral effective dose	0.0089 Sv (0.89 rem)	0.0059 Sv (0.59 rem)
50-y integral effective dose	0.012 Sv (1.2 rem)	0.0082 Sv (0.82 rem)
70-y integral effective dose	0.013 Sv (1.3 rem)	0.0097 Sv (0.97 rem)

[a] Doses are decay corrected to 1995 for comparison with the current dose estimates.

United States is about 3 mSv y^{-1} (300 mrem y^{-1}); the breakdown by source is given in Table 14 (NCRP, 1987a). The world-wide average background effective dose is 2.4 mSv y^{-1} (240 mrem y^{-1}) with some areas over 10 mSv y^{-1} (1000 mrem y^{-1}) (UNSCEAR, 1972, 1988). Note the major contribution is from radon; only in the last few years has the extent and magnitude of this source been addressed and average dose estimates determined. There is still some uncertainty in the current estimate of 2 mSv y^{-1} (200 mrem y^{-1}).

Exposure to radon is essentially insignificant in the Marshall Islands because the concentration of the parent radionuclide, Radium-226 (^{226}Ra), in coral soil is very low (USAEC, 1973), the concentration of radon in the air is very much lower than over continental land masses, (Larson and Bressan, 1980; Robison, 1987), and the open, outdoor lifestyle in the

Table 14. Annual effective dose from natural background in the United States.[a]

Source of radiation	Effective dose mSv (mrem)
Cosmic radiation	0.27 (27)
Cosmogenic radionuclides	0.01 (1)
Terrestrial radiation	0.28 (28)
Inhaled radionuclides (radon)	2 (200)
Radionuclides in the body	0.40 (40)
Total	3 (300)

[a] Data from NCRP (1987a).

Marshall Islands. Thus, most of the natural background in the Marshall Islands is due to external cosmic radiation and internal dose from naturally occurring radionuclides in local foods. The external dose from terrestrial radiation is very low.

The effective dose rate from cosmic radiation in the Marshall Islands is about 0.22 mSv y^{-1} (22 mrem y^{-1}) (USAEC 1973; Gudiksen et al., 1976). An additional 0.18 mSv y^{-1} (18 mrem y^{-1}) results from intake of naturally occurring ^{40}K. A reassessment of ^{210}Po and ^{210}Pb in local fresh and imported foods shows that ingestion of these radionuclides, associated with the quantities of different foods defined in our diet model, leads to a committed effective dose rate (and because of equilibrium conditions the annual effective dose as well) of 2.0 mSv y^{-1} (200 mrem y^{-1}). Unlike the majority of dose from man-made radionuclides, which is derived from ^{137}Cs associated with terrestrial foods, 87% and 74% of ^{210}Po and ^{210}Pb, respectively, in the total diet is derived from the local and imported aquatic foods, including seabirds. A detailed report on the ^{210}Po and ^{210}Pb concentrations in Marshallese foods and the resulting dose rate calculations can be found in Noshkin et. al (1993).

Radiation dose guidelines are established without the inclusion of natural background doses. Thus, the mean maximum annual effective dose at Rongelap Island of 0.26 mSv y^{-1} (26 mrem y^{-1}) is 26% of the current guideline of 1 mSv y^{-1} (100 mrem y^{-1}) (Table 15) as recommended by the NCRP and ICRP (NCRP, 1987b; ICRP, 1990).

Table 15. Adopted guidelines for the general public, natural background doses in the United States and Marshall Islands, and estimated doses from man-made sources at Rongelap Island.

		Population average effective dose rate mSv y^{-1} (mrem y^{-1})
Adopted annual guideline		1 (100)
Rongelap Island: man-made sources		0.26 (26)
U.S. natural background		3 (300)
Marshall Island natural background		2.4 (240)
Cosmic	0.22 (22)	
Cosmogenic	0.01 (1)	
Terrestrial	0.01 (1)	
^{210}Po (diet)[a]	1.8 (180)	
^{40}K (diet)	0.18 (18)	
^{210}Pb (diet)[a]	0.20(20)	
Rongelap Island: natural background plus man-made sources		2.66 (266)
U.S. 30-y integral dose guideline		0.05 Sv[b] (5 rem[b])
Rongelap: man-made sources (30-y integral dose)		0.0059 (0.59 rem)

[a] The source of these estimated doses are discussed in Noshkin et al. (1993).
[b] Whole-body equivalent dose.

Similarly, the mean 30-y integral effective dose of 0.0059 Sv (0.59 rem) estimated for Rongelap Island is only 12% of the 0.05 Sv (5 rem) Federal guidance for the general public for a 30-y period (EPA, 1987; FRC, 1960a,b). It is 20% of 0.03 Sv (3 rem), which is the equivalent of 1 mSv y^{-1} (100 mrem y^{-1}) summed over 30 y.

In view of the fact that there is some question as to whether such guidance is really relevant for a situation such as the Marshall Islands, it is useful to develop other reference criteria. For perspective, the annual effective background dose in the United States is compared in Table 15 to the total maximum annual effective dose, including natural and man-made sources, at Rongelap Island. The total maximum annual effective dose at Rongelap Island of 2.66 mSv (266 mrem) is 89% of the annual background effective dose of 3 mSv (300 mrem) in the United States.

Relative Contributions of Exposure Pathways

The relative contribution of each of the exposure pathways is presented in Table 16. The dose from the terrestrial food-chain pathway accounts for about 60% of the total estimated 30-y integral effective dose; ^{137}Cs accounts for about 96% of this dose and ^{90}Sr for about 2%. Any procedure that would either block the uptake of ^{137}Cs into food crops and/or eliminate it from the soil column would substantially reduce the potential exposure of the Rongelap people living on Rongelap Island.

The external gamma exposure is next in significance and contributes about 40% of the 30-y integral effective dose. The primary source of exposure from the external gamma pathway is ^{137}Cs. In the first year, 1995, ^{137}Cs contributes more than 99% of the 0.11 mSv y^{-1} (11 mrem y^{-1}) external gamma dose rate; ^{60}Co accounts for less than 0.08%. By the year 2000, ^{137}Cs will essentially account for all of the external gamma dose rate. The annual external effective dose rates, the cumulative effective dose, and the contributions of ^{137}Cs and ^{60}Co are listed in Appendix C.

The inhalation pathway is potentially the most significant exposure pathway for the transuranic radionuclides. For this pathway, $^{239+240}Pu$ and ^{241}Am are about 3 to 4 orders of magnitude more significant than ^{137}Cs, ^{90}Sr, or ^{60}Co. The transuranic radionuclides contribute less through the ingestion pathway.

The ingestion dose calculation for Pu and Am includes a 100 mg d^{-1} consumption of surface soil every day of one's life. We feel this model probably overestimates the annual intake of soil, but chose it as a conservative approach to the problem. We also used the current recommended ICRP gut-transfer factor of 10^{-3} for organically bound transuranic radionuclides.

Table 16. The 30-, 50-, and 70-y integral effective dose for the various exposure pathways (IA).

Exposure pathway	Effective integral equivalent dose, Sv (rem)		
	30 y	50 y	70 y
Terrestrial food	0.0034 (0.34)	0.0047 (0.47)	0.0056 (0.56)
External gamma	0.0024 (0.24)	0.0033 (0.33)	0.0039 (0.39)
Marine food	1.6×10^{-5} (0.0016)	3.5×10^{-5} (0.0035)	6.0×10^{-5} (0.0060)
Cistern and ground water	5.1×10^{-6} (0.00051)	7.8×10^{-6} (0.00078)	1.0×10^{-5} (0.0010)
Inhalation	4.8×10^{-5} (0.0048)	1.2×10^{-4} (0.012)	2.0×10^{-4} (0.020)
Total[a]	0.0059 (0.59)	0.0082 (0.82)	0.097 (0.97)

[a] The total dose may vary in the second decimal place due to rounding.

However, data indicate that Pu bound to soil probably has a much lower gut-transfer factor of about 10^{-4} to 10^{-5} (Gilbert et al., 1989; Harrison et al., 1989). ICRP also recognizes a different gut transfer factor for Pu that is not organically bound (ICRP, 1990). Consequently, we used a gut transfer factor of 10^{-4} for Pu bound to soil. All Am was assumed to have a gut transfer factor of 10^{-3}. It is noted that the 10^{-3} gut transfer factor is considered to have a considerable margin of safety built in (ICRP, 1986, 1990).

The estimated effective dose from Pu based on the concentrations in food, soil, and air are very similar to those calculated by BNL based on the analysis of Pu in urine of the Rongelap people (Sun, 1992). These two very independent methods are in excellent agreement on the magnitude of the dose from the transuranic radionuclides as shown in Table 17. The estimated average committed effective dose for 50-y residence from Pu based on environmental data and models is 0.26 mSv (26 mrem), or 0.10 mSv (10 mrem), for the 50-y integral effective dose. We have assumed that a person is in a high-resuspension condition (1 h d^{-1}) everyday of his life, which is probably excessive, and that a person consumes 100 mg of soil every day. The value of 40 mrem committed effective dose from urine analyses is based on the detection limit of the analytical method used for analyzing Pu in urine. The median value for Pu in the urine of all the people analyzed is below this detection limit value. In other words, the actual median committed effective dose people receive is below the detection limit value of 40 mrem committed effective dose. People have been living on Rongelap Island for about 28 y subsequent to the fallout from BRAVO. Consequently, both methods indicate that the effective committed dose from Pu at Rongelap Island is below 40 mrem for residence between 30 and 50 y.

In the long term, of course, as the ^{137}Cs, ^{90}Sr, and ^{60}Co disappear, the transuranic radionuclides will be the only source of exposure. The total estimated effective dose from $^{239+240}Pu$ and ^{241}Am radionuclides, based on the inhalation and imported food available diet scenario discussed previously, is about 0.08 mSv (8 mrem) over 30 y, 0.18 mSv (18 mrem) over 50 y, and about 0.33 mSv (33 mrem) over 70 y.

From the marine pathway, the reef fish in particular, and the pelagic fish, are a key source, and a favorite source, of protein in the Marshallese diet. It is fortunate that the ^{137}Cs and ^{90}Sr concentrations are very low in the marine foods (Tables 5 and 6). Consequently, the marine pathway is a minor contributor to the total estimated dose from man-made radionuclides, but not necessarily for naturally occurring radionuclides.

The roof-catchment water (i.e., cistern water) contributes in a very minor way to the estimated dose listed in Table 16. If ground water is consumed, then the doses will go up because there is more ^{137}Cs and ^{90}Sr in the ground water than in the cistern water; however, ground water generally is used only in cases of extreme drought. In our dose calculations, we assume 40% of the water intake is from ground water and 60% is cistern water. The actual use of ground water over several years is probably much less than this.

The maximum annual intake (MAI) of ^{137}Cs, ^{90}Sr, $^{239+240}Pu$, and ^{241}Am for Rongelap Island can be compared to the annual limit of intake (ALI) recommended by the ICRP to determine the

Table 17. The average committed effective dose from Pu and Am at Rongelap Island in mSv (mrem).

	Method		
	Environmental (LLNL)[a]		Urine Analysis (BNL)
	Committed effective dose	50-y integral effective dose	Committed effective dose
Pu	0.26 (26)	0.10 (10)	0.4[b] (40)
Am	0.23 (23)	0.078 (7.8)	No estimate

[a] Two significant figures are given only to show the slight difference between Pu and Am.

[b] Based on the detection limit. The actual mean dose is something below this number.

significance of the four radionuclides via the ingestion pathway (Table 18). The MAI for Rongelap is the maximum annual intake that would occur based on the model described previously. For example, the intake of ^{137}Cs would be less in any year after 1995 decreasing exponentially by the 30-y radioactive half-life (i.e., 2.3% per year). The ALI for occupational workers as defined by the ICRP, is that annual intake of each radionuclide that would lead to an effective dose of rate 20 mSv y^{-1} (2000 mrem y^{-1}). In Table 18, we have reduced the ICRP ALI for occupational exposure by a factor of 20 to correspond to the adopted annual guideline of 1 mSv y^{-1} (100 mrem y^{-1}) effective dose rate for the public. As indicated in Table 18, the MAI on Rongelap for ^{137}Cs is about 22% of the adjusted ALI; it would of course decrease with each succeeding year. On the other hand, ^{90}Sr, $^{239+240}Pu$, and ^{241}Am are only 0.57%, 0.22%, and 0.17% of the ALI, respectively.

Mitigation of Food-Chain Dose

We have conducted many experiments at Bikini Atoll to evaluate methods to mitigate the ^{137}Cs dose from the terrestrial food chain. The experiments at Eneu Island at Bikini Atoll using potassium-rich fertilizers (16N-16P-16K) or KCl, show a reduction greater than 10 fold in the concentration of ^{137}Cs in coconut meat and fluid; the ^{137}Cs concentrations in foods grown without potassium-rich fertilizer range from 0.74 to 1.5 Bq g^{-1} (20 to 40 pCi g^{-1}) wet weight, while the ^{137}Cs concentrations in foods grown using potassium-rich fertilizer are less than 0.074 Bq g^{-1} (2 pCi g^{-1}) (Robison and Stone, 1992). A replicate experiment was conducted on Eneu Island two years after the initial experiment, and the results corroborate the initial findings. Concurrent with the replicate experiment on Eneu Island, we began a similar experiment on Bikini Island where the ^{137}Cs concentrations in soil, coconut, breadfruit, and other local foods are about 8 to 10 times higher than at Eneu Island. The results of that experiment through August 1988 show that we have reduced the ^{137}Cs concentration in coconut meat and fluid from a range of 5.6 to 11 Bq g^{-1} (150 to 300 pCi g^{-1}) wet weight to about 0.56 to 0.74 Bq g^{-1} (15 to 20 pCi g^{-1}) wet weight. In those trees where the initial concentration was between 1.9 to 3.7 Bq g^{-1} (50 to 100 pCi g^{-1}) wet weight, the potassium treatment has reduced the ^{137}Cs concentration to less than 0.37 Bq g^{-1} (10 pCi g^{-1}).

Table 18. Comparison of the maximum annual intake (MAI) on Rongelap Island with the adjusted ICRP annual limit on intake (ALI) for ^{137}Cs, ^{90}Sr, $^{239+240}Pu$, and ^{241}Am.

Nuclide	MAI on Rongelap[a] Imported foods available (Bq)	Imported foods unavailable (Bq)	Adjusted ICRP ALI[b] (Bq)	MAI as a fraction of the ALI when imported foods are available
^{137}Cs	1.1×10^4	2.8×10^4	5.0×10^4	0.22
^{90}Sr	1.7×10^2	5.5×10^2	3.0×10^4	0.0057
$^{239+240}Pu$ (ingestion)	4.4	11	2.0×10^3	0.0022
^{241}Am (ingestion)	2.6	4.7	1.5×10^3	0.0017
$^{239+240}Pu$ (inhalation)	0.037	0.037	15	0.0025
^{241}Am (inhalation)	0.028	0.028	15	0.0019

a Maximum annual intake based on data and models described in text. This value becomes less each year, declining exponentially with the 30-y half-life of ^{137}Cs (2.3% per year).

b The ICRP ALI (ICRP, 1991b) is divided by 20 to adjust the ALI, which is based on an effective dose of 20 mSv y^{-1} (2000 mrem y^{-1}), to a general population ALI based on an effective dose of 1 mSv y^{-1} (100 mrem y^{-1}) (ICRP, 1991a; NCRP, 1987b).

The ^{137}Cs concentrations in drinking coconut meat and fluid on Rongelap Island are about 20% of those on Eneu Island, and about 2% of those on Bikini Island. However, treatment of coconuts and other food crops on Rongelap Island with potassium-rich fertilizers should reduce the ^{137}Cs uptake to about 10% of current levels and reduce the estimated dose from the terrestrial food chain by a similar amount. Thus, the estimated maximum annual effective dose and 30-y integral effective dose for Rongelap, including both internal and external exposure, would then be about 0.12 mSv (12 mrem) and 0.0026 Sv (0.26 rem), respectively.

If a reasonable agricultural program is implemented that includes periodic use of fertilizer, the dose from ^{137}Cs through the food chain will be greatly reduced, and the growth and productivity of some plants and food crops will be enhanced.

Environmental Half-Life of ^{137}Cs

There are natural processes operating at the atolls that also will reduce the estimated doses presented in this paper. For example, ^{137}Cs is found in the ground water 3 to 4 m below the soil surface. The only way for the ^{137}Cs to get to the ground water is by transfer down the soil column during rainy seasons when sufficient rainfall occurs to produce a recharge of the ground water lens. This is the most likely mechanism for loss of ^{137}Cs from the island. Another possibility is the resuspension process that creates airborne soil and humic particles. This process is very limited, however, on a vegetated island (Shinn et al., 1989). In any case, the sum of all processes that result in the loss of ^{137}Cs from the atoll soil system, and/or make it unavailable for uptake in plants can be defined in terms of an environmental half-life ($T_{1/2}$ environmental), analogous to half-life for the natural radioactive decay ($T_{1/2}$ radiological). The net loss of ^{137}Cs from the environment is, therefore, a sum of two components: the loss by radioactive decay and the loss by environmental processes. Thus, an effective decay constant, λ_e, can be defined, which is equal to $\lambda_{radiological} + \lambda_{environmental}$, where the decay constant $\lambda = 0.693/T_{1/2}$. The significance of the environmental half-life is shown in Figure 5,

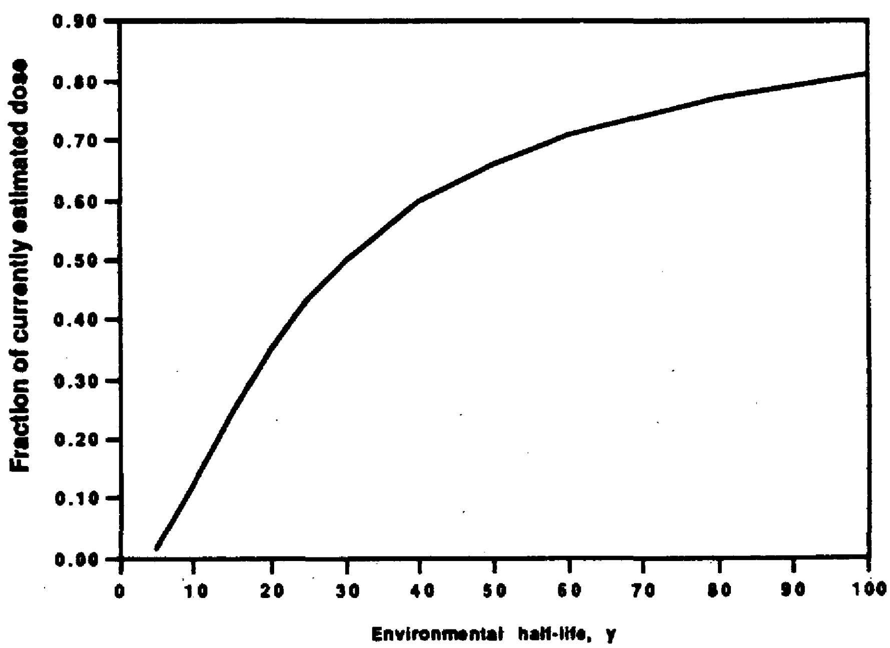

Figure 5. Percentage reduction in estimated doses to residents of Rongelap Island as a function of the environmental half-life.

where the reductions in the estimated ingestion doses in this paper are shown as a function of the environmental half-life. For example, if the environmental half-life of ^{137}Cs is equal to its radiological half-life of 30 y, then the estimated ingestion doses would be 50% of what we present in this paper.

The problem, of course, is in determining $\lambda_{environmental}$. We are in the process of evaluating data from Enewetak and Bikini Atolls that we have accumulated since 1978. We also have data from samples collected at Rongelap Atoll from 1986 to 1993 from specific trees first sampled in 1959 and 1961. These data will provide at least a limited retrospective look at the environmental half-life over this 30-y period.

Although we have not completed our analysis of these data and cannot at this time incorporate an actual environmental half-life in our dose assessment, the net result must be to reduce the total dose received from internal and external exposures.

Uncertainty and Interindividual Variability in Estimated Rongelap Doses

The doses presented above were calculated using arithmetic mean values for each of the parameters in the dose models, such as body weight, residence time of radionuclides in the body, radionuclide concentrations in food and soil, dietary intake (in g d^{-1}), and fractional deposition of radionuclides in body compartments. The distributions for some of these parameters are shown in the following figures; both log and linear probability plots are given on each graph. Figures 6 and 7 show the distribution of body weights for Marshallese females and males, respectively; Figures 8 and 9 the dietary intakes; Figures 10, 11, 12, and 13 the Pu and Am concentrations in soil; and, Figures 14 and 15 the ^{137}Cs concentrations in drinking coconut meat and fluid. Most of these data are lognormally distributed.

Estimated dose is a function of distributed quantities reflecting either *uncertainty* (i.e., lack of knowledge concerning "the true" value) or *interindividual variability* (which hereafter will be referred to simply as "variability," i.e., heterogeneity in values pertaining to different people), or both. To characterize such uncertainty and variability in estimated dose, it is necessary to distinguish these attributes systematically as each or both may pertain to each input variate (Bogen and Spear, 1987; Nazaroff et al., 1987; IAEA, 1989; Bogen, 1990; NRC, 1993). Below, doses to potential Rongelap residents are recalculated using this approach to obtain predicted dose as a function of several distributed input variates (summarized in Table 19), here all are assumed to be uncorrelated. Only uncertainty and variability in predicted doses due to ingested ^{137}Cs, external gamma-ray exposure, and Am+Pu inhalation doses were considered here. Non-^{137}Cs-related ingestion doses (^{90}Sr, ^{241}Am, and $^{239+240}Pu$) are comparatively negligible on Rongelap (see Table 11). For this uncertainty/variability analysis, the complex, multicompartment physiological model used above to calculate internal adult dose as a function of ingested ^{137}Cs (Leggett, 1986; ICRP, 1990, 1991a) was replaced by the following single-compartment model:

$$q_{ij}(t_i) = FBR_{ij}\, e^{-\lambda t_i} \quad \text{at any time } t_i,\ 0 \le t_i \le t, \qquad (1)$$

$$q_{ij}'(u) = -(\beta K + \lambda)\, q_i(u) \quad \text{for any time } u,\ t_i \le u \le t, \qquad (2)$$

$$q_{ij}(u) = FBR_{ij}\, e^{-\lambda t_i}\, e^{-(\beta K + \lambda)u} \quad \text{for any time } u,\ t_i \le u \le t, \qquad (3)$$

in which: $q_{ij}(u)$ is the activity, in Bq kg^{-1} body weight, of ^{137}Cs in the whole body at any time u following ingestion of an activity R_{ij} (in Bq kg^{-1} body weight) of ^{137}Cs contained in a food item of type j at time t_i, prime ($'$) denotes differentiation with respect to time, λ is the radiological decay rate of ^{137}Cs, $K = \text{Ln}(2)H^{-1}$ is the biological loss rate of ^{137}Cs from the dominant "slow" compartment of a reference adult, F is fraction of ingested dose input to the slow compartment, B represents a dietary-dose-model bias (i.e., a dose-estimation uncertainty factor) associated with R_{ij} and β is a factor representing uncertainty associated with H. Henceforth, angle brackets ($\langle\ \rangle$) denote mathematical expectation only with respect to uncertainty and an overbar denotes expectation only with respect to interindividual variability.

Daily intakes R_{ij} in Bq kg^{-1} d^{-1} of ^{137}Cs in local food items of type j were assumed to be

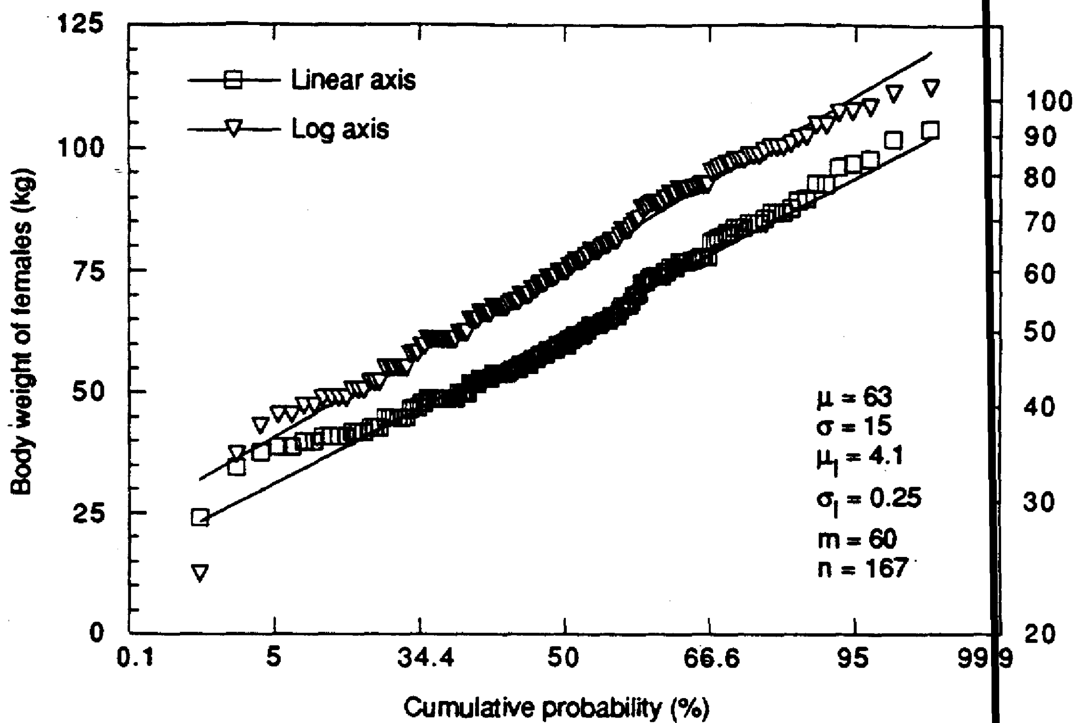

Figure 6. Probability plot for the body weights of 167 adult Marshallese females.

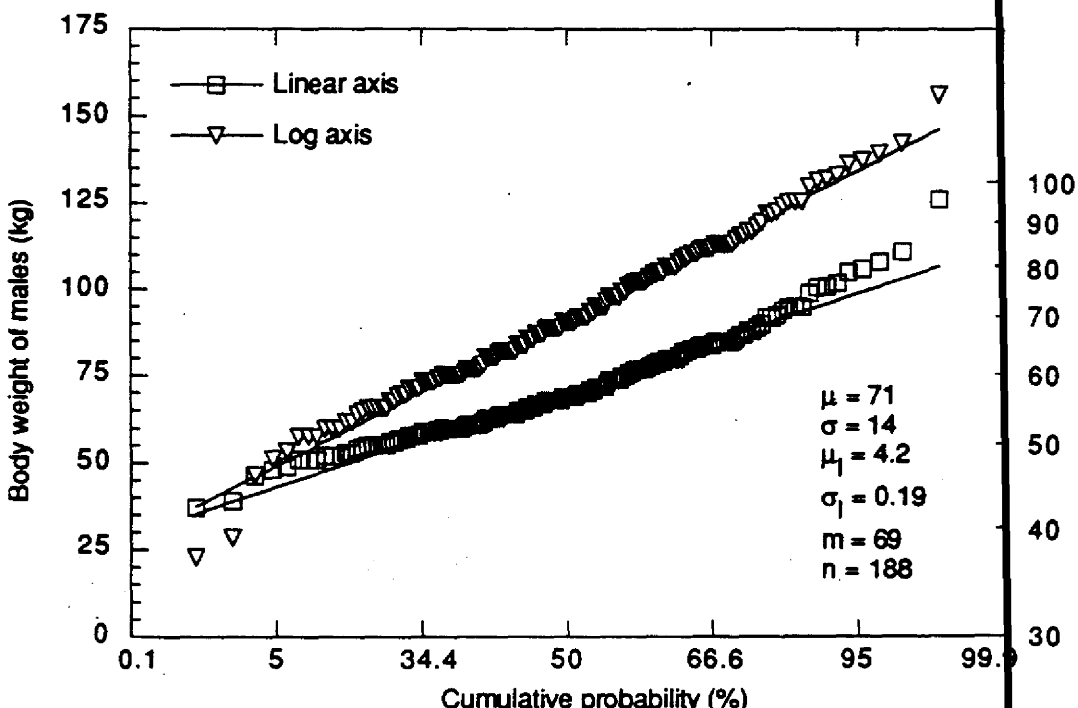

Figure 7. Probability plot for the body weights of 188 adult Marshallese males.

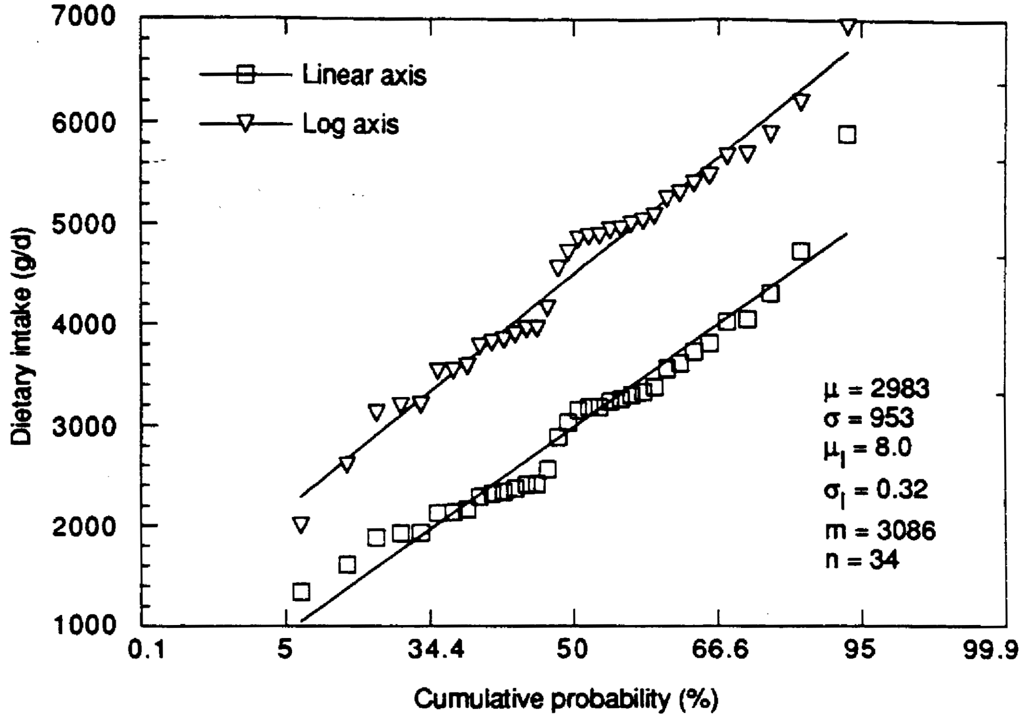

Figure 8. Probability plot of the dietary intake of 34 Marshallese females.

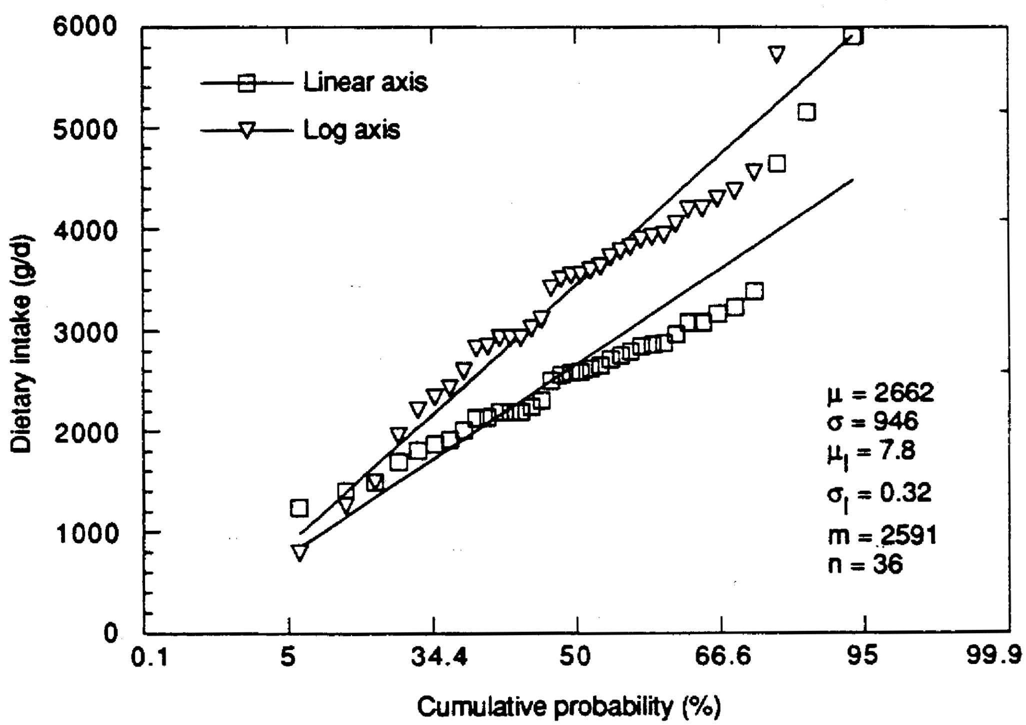

Figure 9. Probability plot of the dietary intake of 36 Marshallese males.

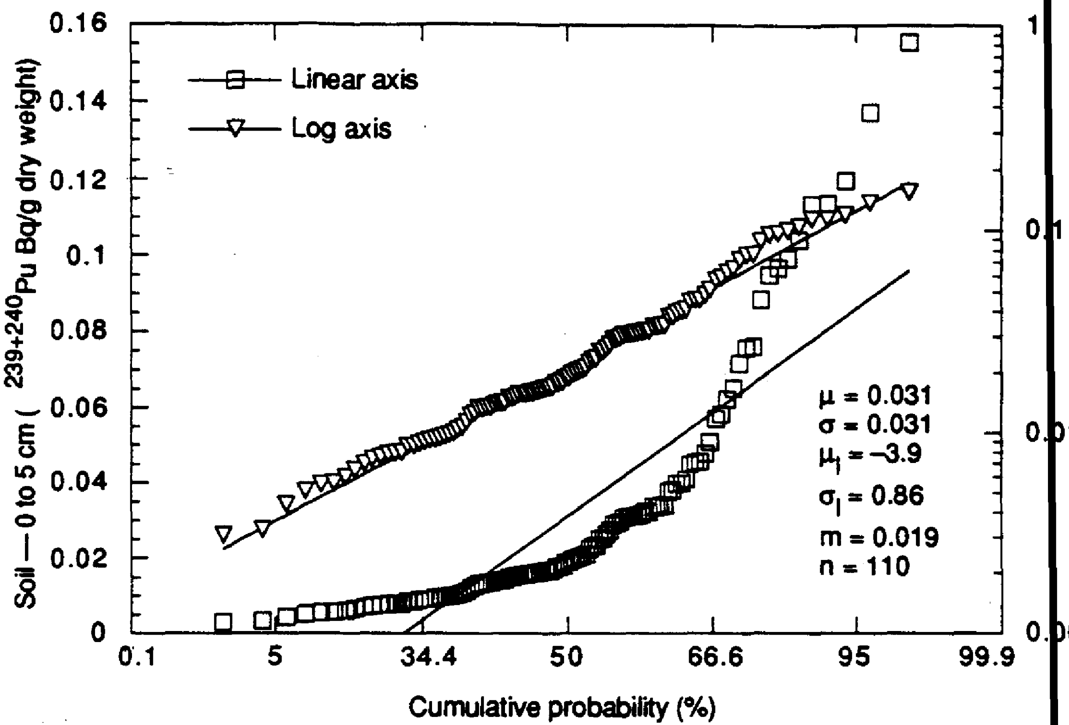

Figure 10. Probability plot of $^{239+240}$Pu concentration in the top 0 to 5 cm of soil in the village area of Rongelap Island.

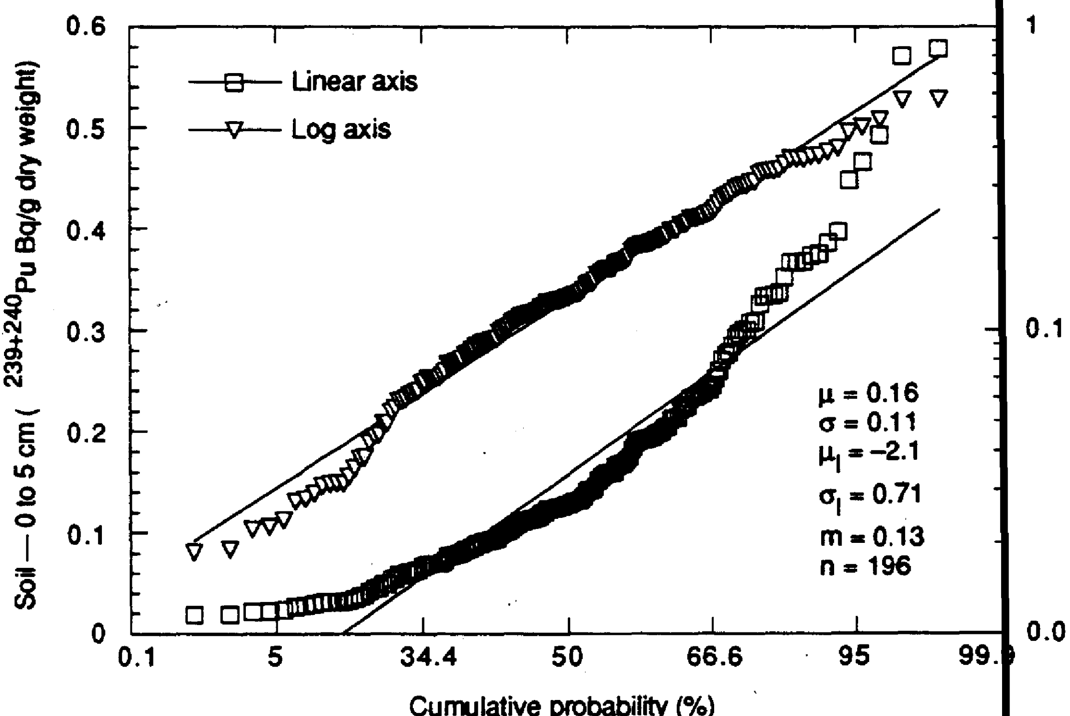

Figure 11. Probability plot of $^{239+240}$Pu concentration in the top 0 to 5 cm of soil in the interior of Rongelap Island.

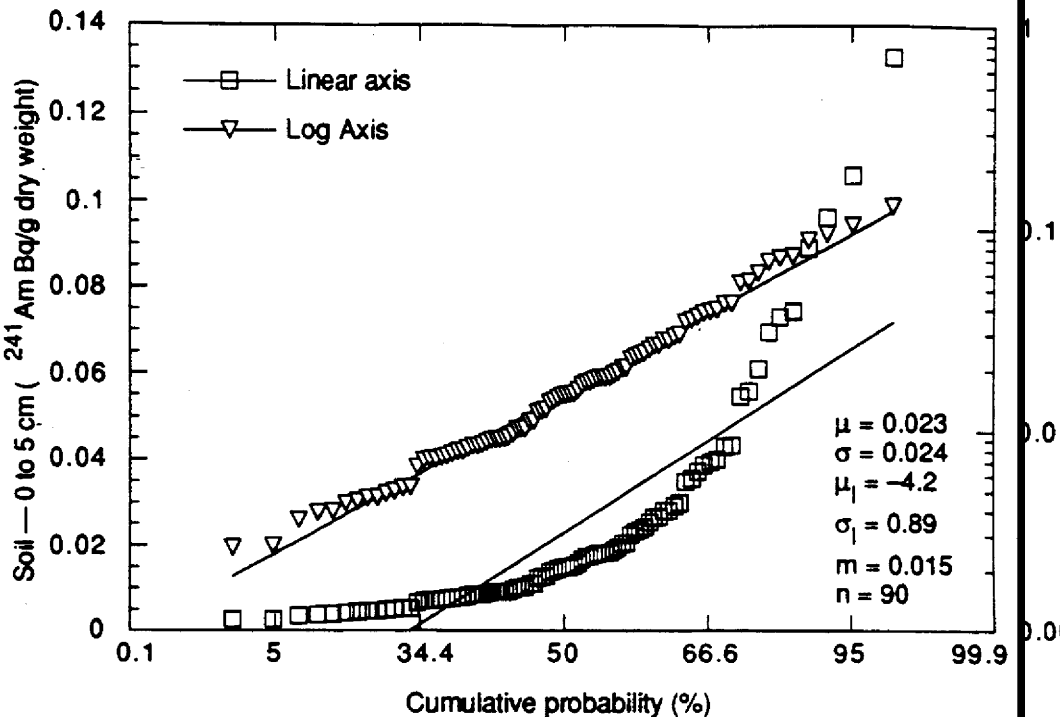

Figure 12. Probability plot of ^{241}Am concentration in the top 0 to 5 cm of soil in the village area of Rongelap Island.

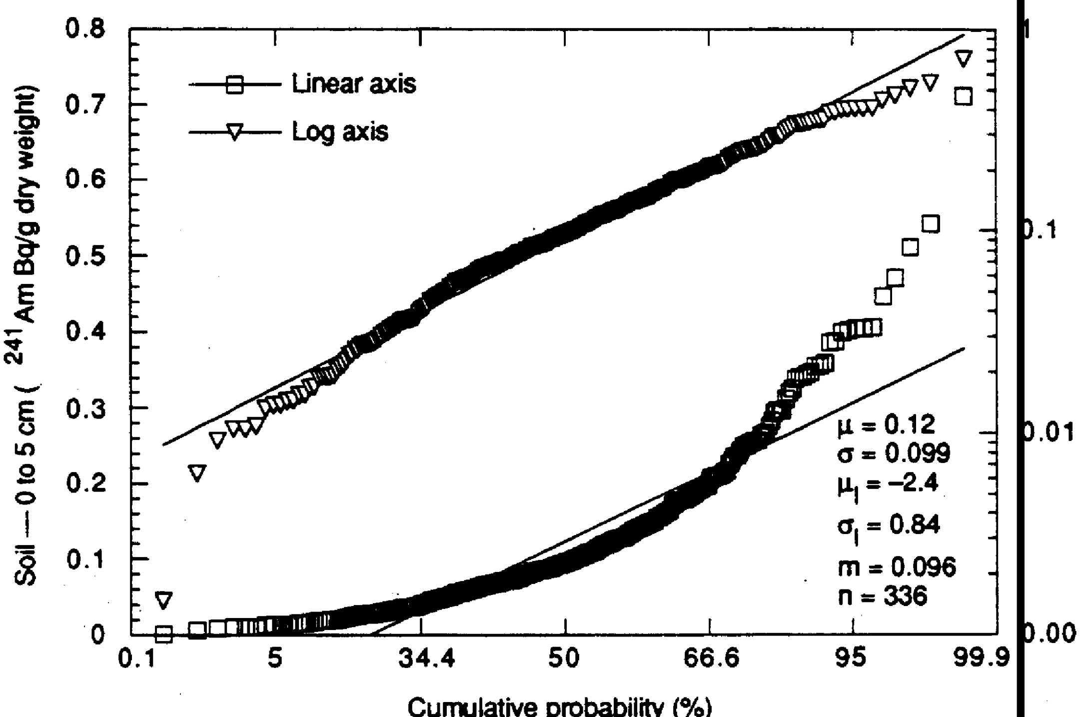

Figure 13. Probability plot of ^{241}Am concentration in the top 0 to 5 cm of soil in the interior of Rongelap Island.

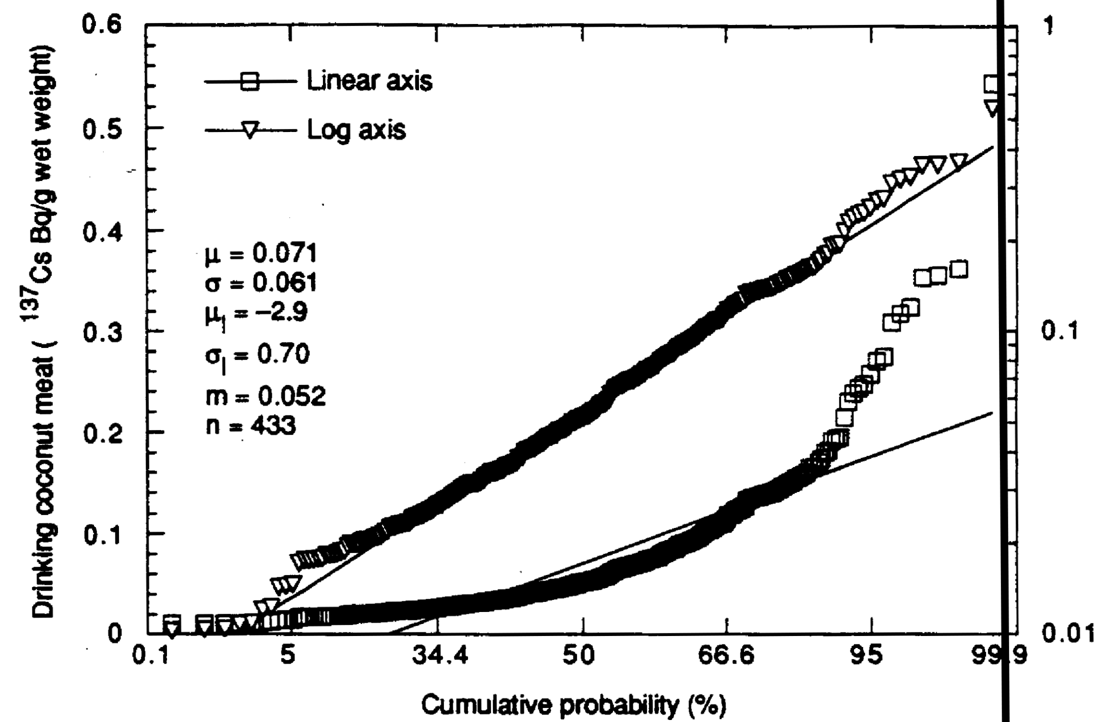

Figure 14. Probability plot of ^{137}Cs concentration in drinking coconut meat on Rongelap Island.

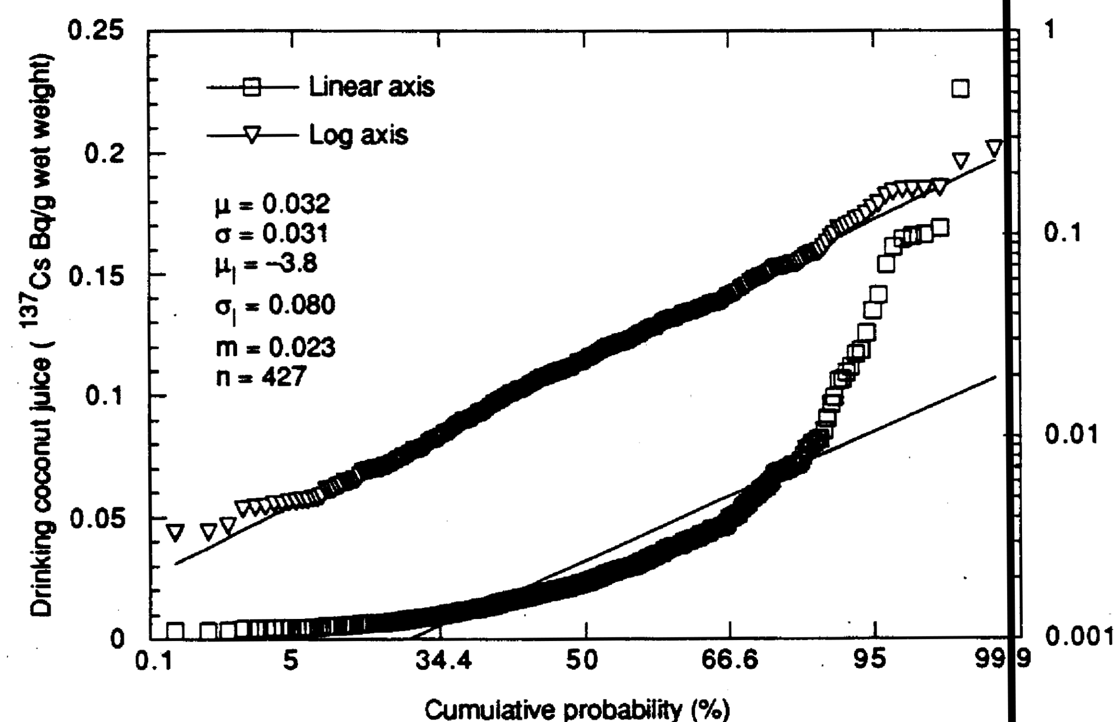

Figure 15. Probability plot of ^{137}Cs concentration in drinking coconut fluid on Rongelap Island.

Table 19. Parameters used in analysis of uncertainty and variability in estimated dose and cancer risk to hypothetical Rongelap residents.

Parameters[a]	Symbol	Variate type[b]	Value or distribution model[c]	Unit
Unit-conversion factor	c	C	2.431×10^{-4}	$cSv\ kg\ Bq^{-1}\ y^{-1}$
Radiological decay rate of ^{137}Cs	λ	C	0.0230	y^{-1}
Faction input to slow compartment	F	UV	$U(2\overline{F}-1, 1)$	unitless
Variability expectation of F	$\overline{F}$	U	U(0.855, 0.945)	unitless
Biological half-life of slow compartment	H	V	$LN\left(\overline{Ln(H)} - \left(s^2_{Ln(H)}/2\right), s_{Ln(H)}\right)$	y
Population-average value of H	$\overline{H}$	C	110/365	y
Uncertainty associated with H	β	U	U(0.9, 1.107)	unitless
SD of Ln(H)-variability	$s_{Ln(H)}$	C	0.275	unitless
Population-average value of R	$\overline{R}$	U	$N\left(\overline{\langle R\rangle}, \overline{\langle R\rangle} g_R\right)$	Bq/kg–y
Expected value of $\overline{R}$	$\overline{\langle R\rangle}$	C	0.447×365	Bq/kg–y
Annual dietary intake of ^{137}Cs	R	UV	$LN\left(\overline{Ln(R)} - \left(s^2_{Ln(R)}/2\right), s_{Ln(R)}\right)$	Bq/kg–y
CV of $\langle R\rangle$ variability	g_R	V	0.9821	unitless
SD of Ln(R) variability	$s_{Ln(R)}$	C	0.8217	unitless
CV in R due to dietary sampling uncertainty	γ_R	C	0.034	unitless
Uncertainty (model bias) associated with R	B	U	LN(-1.463, 0.8639)	unitless
Uncertainty risk per unit dose	W	U	LN(-7.970, 0.5409)	cSv^{-1}

[a] SD = standard deviation, CV = SD/mean

[b] C = constant, U = uncertainty, V = interindividually variable (i.e., heterogeneous), UV = both uncertain and heterogeneous.

[c] U (a,b) = uniformly distributed between a and b, LN (a,b) = lognormally distributed with geometric mean e^a and geometric SD e^b, N(a,b) = normally distributed with mean a and SD b.

obtained from independent random samples of such items collected n_j days per year from among the possible selections of the type available on Rongelap. The corresponding cumulative dose $D(t)$ from all major exposure routes was estimated as:

$$D(t) = D_x(t) + D_{\text{in}}(t) + \int_0^t \sum_j \sum_{i=1}^{n_j} \frac{365}{n_j} c q_{ij}(u)\, du \tag{4}$$

where c is a unit-conversion constant, where $D_x(t)$ and $D_{\text{in}}(t)$ are approximations of adult external-gamma dose (modeled as interindividually variable) and Am+Pu inhalation dose (modeled deterministically), respectively, and where Eq. (4) was evaluated using Monte-Carlo methods (see Appendix D).

Variability in $D_x(t)$ was modeled using data from Table 3 and assumptions stated above (Dose Methodology, External Exposure, Gamma Radiation) concerning average times spent in the house, house surroundings, village area, island interior and beach/lagoon areas, and corresponding mean exposure rates. From these assumptions, it was estimated that household and house-area exposures would typically account for ~64% of total external gamma dose, with a coefficient of variation (CV), i.e., the standard deviation divided by the arithmetic mean, with respect to interindividual variability equal to ~45%. The remainder of external gamma dose was assumed to be equal to the corresponding population-average value, reflecting an expected interindividual averaging over commonly frequented island areas. Accordingly, external gamma dose was modeled as $D_x(t) = (0.36 + Y)\overline{D_x(t)}$, where Y is a lognormally distributed variability factor with expectation 0.64 and geometric standard deviation (SD_g) = 1.536.

Variability in the fraction, F, of ingested ^{137}Cs input to the dominant biological compartment was assumed to be uniformly distributed between an uncertain lower bound ranging between 0.71 and 0.89, and an upper bound of 1. Thus, uncertainty in $\overline{F}$ was assumed to be uniformly distributed within ± 5% of an assumed expected value of 0.9, and variability of $\langle F \rangle$ was assumed to be uniformly distributed between 0.8 and 1. These assumptions approximately characterize the empirical data on the value of F obtained for 17 individuals reported by Schwartz and Dunning (1982).

Interindividual variability in the biological half-time, H, of the dominant slow compartment was modeled as lognormally distributed based on the data pertaining to 23 Marshallese males indicating a median of 115 d and SD_g = 1.23 as shown in Figure 4. For the present analysis, however, it was assumed that $\overline{H}$ = 110 d and that SD_g = 1.32 for H, based, respectively, on the ICRP (1979) reference mean value (used earlier) and on data reviewed by Schwartz and Dunning (1982) indicating slightly greater variability associated with the parameter among 53 individuals from whom measurements were available. A geometric mean (GM) value of H (105.9 d) consistent with the values selected for $\overline{H}$ and SD_g was obtained using the method of moments. Uncertainty pertaining to H was represented by the independent factor β assumed to be uniformly distributed (between 0.9 and 1.107), such that the true value of H pertaining to any specific individual was taken to lie within 10% of the expected value for that individual.

The population-average value of expected annual intake, $\overline{\langle R \rangle}$, of total ^{137}Cs activity in the LLNL model diet for hypothetical Rongelap residents as of 1995 (assuming imports are available) was taken to be 365 × 0.447 Bq kg^{-1} y^{-1} for a reference adult, based on the analysis of food consumption survey data for 34 adult Ujelang females discussed above. Interindividual variability in corresponding expected daily intakes, $\langle R_{ij} \rangle$ was modeled using the empirical distribution of average daily uptakes in Bq kg^{-1} calculated from the food-survey data for these same 34 adult Ujelang females, which was here multiplicatively scaled to have the expected daily population average value of (31.3 Bq d^{-1})(70 kg^{-1}), where 31 Bq d^{-1} was taken (see Table 20) to be 99% of the mean daily dose. This scaled empirical distribution does not significantly differ from a lognormal distribution having an expected value, GM, and SD_g of 0.447 Bq kg^{-1} d^{-1}, 0.319 Bq kg^{-1} d^{-1}, and SD_g = 0.8217, respectively (see Figure 16); p>0.15 using Stephen's modified Kolmolgorov-Smirnov, Cramer-von-Mises, or

Table 20. Diet model—Rongelap Island for adults.

Local Food	Intake: local foods only[a] (g d^{-1})	Intake: local + imported[b] (g d^{-1})	^{137}Cs activity[c] Mean (Bq g^{-1})	^{137}Cs activity[c] SD/Mean (%)	^{137}Cs Intake[d] Local only Mean (Bq d^{-1})	^{137}Cs Intake[d] Local only SD/Mean (%)	^{137}Cs Intake[d] Imports available Mean (Bq d^{-1})	^{137}Cs Intake[d] Imports available SD/Mean (%)
Coconut								
Milk	60.9	51.9	0.12	83[e]				
Meat	90.4	31.7	0.071	86				
Copra meat	35.7	12.2	0.12	83				
Juice	167	99.1	0.032	97				
Total	354		0.066	90	23.5	90		
Total		195	0.067	91			13.2	91
Pork								
Heart[f]	0.31	0.31	0.51	40				
Muscle[g]	6.96	5.67	0.49	58				
Liver[h]	3.35	2.60	0.20	36				
Total	10.6		0.40	51	4.24	51		
Total		8.58	0.40	51			3.46	51
Chicken								
Muscle	15.6	8.36	0.13	58[i]				
Liver	8.84	4.50	0.089	36[j]				
Gizzard	1.66	1.66	0.053	36[j]				
Total	26.1		0.11	49	2.90	49		
Total		14.5	0.11	49			1.57	49
Breadfruit	93.1	27.2	0.13	52	11.9	52	3.48	52
Pandanus								
fruit & nuts	32.5	9.16	0.25	92	8.00	92	2.26	92
Sprouting Coconut	61.2	7.79	0.12	83	7.41	83	0.943	83
Papaya	13.5	6.59	0.43	92[k]	5.75	92	2.80	92
Arrowroot	47.4	3.93	0.20	95	9.71	95	0.805	95

Table 20 Continued.

Local Food	Intake: local foods only[a] (g d-1)	Intake: local + imported[b] (g d-1)	^{137}Cs activity[c] Mean (Bq g-1)	^{137}Cs activity[c] SD/Mean (%)	^{137}Cs Intake[d] Local only Mean (Bq d-1)	^{137}Cs Intake[d] Local only SD/Mean (%)	^{137}Cs Intake[d] Imports available Mean (Bq d-1)	^{137}Cs Intake[d] Imports available SD/Mean (%)
Pumpkin	2.72	1.24	0.21	48	0.568	48	0.259	48
Marsh Cake	0	11.7	0.12	83[e]	0	0	1.42	83
Coco Crab	12.5	3.13	0.089[l]	53[m]	1.12	53	0.279	53
Total	654		0.11		75.1	2.7		
Total		289	0.11				30.5	3.5
% of Grand Total[a,b]	42	22			96.4		96.8	

[a] From Table 6.

[b] From Table 5.

[c] Derived from information in Tables 5 and B-1 and from an analysis of data on ^{137}Cs activity in pig and coco-crab meat on Rongelap. SD = standard deviation. Means and SDs for totals listed under Coconut, Pork and Chicken were calculated using subitem-specific intake weights.

[d] Totals for ^{137}Cs intake differ slightly from those listed in Tables 5 and 6 due to corresponding differences in significant digits used.

[e] Assumed to equal that of copra meat.

[f] Based on data from four animals. For comparison, the SD/Mean for 19 samples of pork heart from nine different Marshall Islands (including those from Rongelap) is 47%.

[g] Based on data from seven animals. For comparison, the SD/Mean for 28 samples of pork muscle from nine different Marshall Islands (including those from Rongelap) is 34%.

[h] Based on data from six animals.

[i] Assumed to equal that of pork muscle.

[j] Assumed to equal that of pork liver. For comparison, the SD/Mean for 29 samples of pork liver from nine different Marshall Islands (including those from Rongelap) is 49%.

[k] Assumed to equal that of *pandanus* fruit/nuts.

[l] Derived from activities measured in coconut crabs from Arbar Island on Rongelap Atoll.

[m] Based on data from nine coconut crabs from the southern half of Rongelap Atoll.

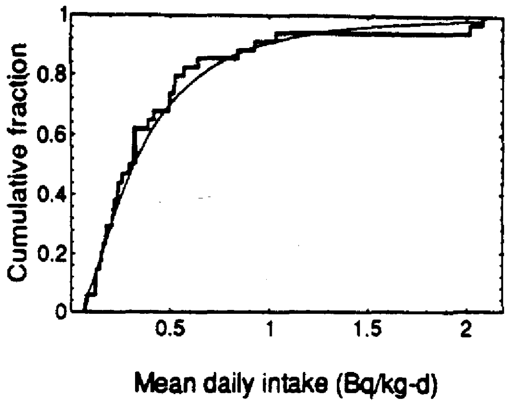

Figure 16. Sample distribution of interindividual variability in daily intake of ^{137}Cs per unit body weight based on survey data for 34 adult Ujelang females (bold), fit to a lognormal distribution (light) with mean = 0.447 Bq kg^{-1} d^{-1} and a geom. stand. dev. = 2.274.

Watson tests (Stephens, 1970; Pearson and Hartley, 1972). We used this lognormal distribution as the basis of our model of variability in $\langle R \rangle = 365\langle R_{ij} \rangle$ for a hypothetical Rongelap population of arbitrary size N. The distribution has a corresponding CV with respect to modeled variability equal to $g_R = 0.9821$.

Uncertainty due to random dietary sampling associated with daily ^{137}Cs intake for any given individual about that individual's mean daily level (presumed constant for each individual) was estimated under the assumptions stated above that food imports are available and that local foods of type j are randomly and independently sampled n_j times per year from among Rongelap sources, using LLNL-model-diet assumptions discussed previously, along with the information summarized in Table 20 about predicted amounts and measured inter-sample variability of ^{137}Cs in different food items local to Rongelap. For this analysis, the activities associated with the items listed in this table (accounting for ~99% of ^{137}Cs intake associated with local foods) were scaled to correspond to an assumption that these items comprise 100% of the local-food diet. Each corresponding CV, $\gamma_{R_{ij}} = \sigma_{R_{ij}} / \langle R_{ij} \rangle$, with respect to presumed dietary sampling error was assumed to be the measured value appearing in column 6 of Table 20, and was assumed to pertain to every individual in the modeled exposed population. The local food items appearing in Table 20 were divided into three types (and the indicated corresponding sampling periods were assumed): pork-related items ($n_1 = 12$ y^{-1}), chicken-related items ($n_2 = 52$ y^{-1}), and other items ($n_3 = 182.5$ y^{-1}).

Model-uncertainty (i.e., misspecification error) was estimated directly from the data shown in Figure 3 relating LLNL model-diet predictions assuming imported foods are available, and corresponding BNL measurements of whole-body dose among different samples of Marshallese people tested during the period 1977-1983. The mean of the six measured- to predicted-burden ratios shown is 1.25 ± 0.37 (differing insignificantly from 1, p > 0.16 by T-test). Based on these data, an uncertainty-CV of ~40% was assumed, and model uncertainty for the LLNL model diet assuming imported foods are available, was characterized as a corresponding lognormally distributed factor B with expectation 1 and $SD_g = 1.47$.

Predicted population risk I (here taken as the number of fallout-induced cancer fatalities) necessarily depends on the size, N and age distribution of the population involved in any Rongelap resettlement. To reasonably estimate I, it was assumed that $N = 500$ in a 1995 resettlement, wherein 40% of this population would be exposed for 70 y (i.e., be present upon birth) and the remainder (of adults of 40-y average age) for 30 y. Calculation of I was by the method of Bogen and Spear (1987), treating I as compound-Poisson-distributed with an uncertain parameter (population-average dose), here approximated as $500W\overline{D(\text{Lifetime})}$, where W is an uncertain risk-per-unit dose conversion factor and $\overline{D(\text{Lifetime})}$ was assumed to be the weighted functional (not stochastic) average of $\overline{D(70)}$ and $\overline{D(30)}$ using 0.4 and 0.6 as the respective weights. For this purpose, $\overline{D(70)}$ was taken to be $1.63\overline{D(30)}$ based on the corresponding LLNL/ICRP model predictions (Table 11). Based on the BEIR V (NRC, 1990) prediction of total cancer (leukemia + nonleukemia) fatalities for males and females likely to be caused by chronic low-LET radiation exposure and associated analysis of statistical and model-related errors, the uncertain factor W was taken to be approximately lognormally distributed with expectation 0.0004 cSv^{-1} and $SD_g = 0.864$.

Based on the analysis of interindividual variability in expected dose, it was calculated that the expected value of 30-y integral population-average dose, $\overline{\langle D(30)\rangle}$ is ~0.58 cSv, and that the chance that $\langle D(30)\rangle > 2.0$ cSv is ~1%, e.g., indicating that 2 cSv is the 30-y dose most likely to be incurred by the fifth highest exposed among 500 hypothetical Rongelap residents (Figure 17). The predicted relationship between cumulative exposure time t and interindividual variability in $\langle D(t)\rangle$ (Figures 18 and 19) indicates that the lower and upper 95% confidence limits on $\langle D(t)\rangle$ variability are ~2-fold below and ~2.5-fold above, respectively, the population-average expected-value function $\overline{\langle D(t)\rangle}$. The calculated interindividual variability in expected maximum 1-y dose is shown in Figure 20, contrasted to variability in that dose estimated assuming a hypothetical LLNL-type local-foods-only diet with twice the local calorie intake shown in Table 20. Such a local-foods-only diet implies a nearly 5-fold greater expected dose due to ^{137}Cs ingestion than predicted by the LLNL imports-available diet. The distribution corresponding to the LNL imports-available model diet (bold curve in Figure 20) has a mean of 0.25 mSv, and has 50th, 95th, 99th and 99.8th percentile values of 0.21, 0.52, 0.87, and 1.3 mSv, respectively. The maxima of expected annual doses under this dietary scenario are estimated to occur during the 2nd and 3rd years of residence for 66% and 33% of residents, respectively. The distribution corresponding to the local-foods-only diet with twice the local calorie intake indicated in Table 20 (light curve in Figure 20) has a mean of 0.83 mSv, and has 50th, 95th, 99th and 99.8th percentile values of 0.61, 2.2, 3.9 and 5.8 mSv, respectively, with maximal doses predicted to occur during the 2nd, 3rd and 4th years of residence for 44.5%, 53%, and 2.5% of residents, respectively. Note that a 99.8th percentile dose indicated in Figure 20 corresponds to the most likely value of the greatest maximum 1-y dose predicted assuming a 1995 resettlement population of 500 (NRC, 1993). The results summarized in Figure 20 indicate that 99.5% of hypothetical 1995 Rongelap resettlers would never receive a 1-y dose greater than 1 mSv if imported foods were routinely consumed, but that ~25% would receive maximum 1-y doses greater than 1 mSv if only local foods were consumed at twice the caloric intake rate indicated in Table 20.

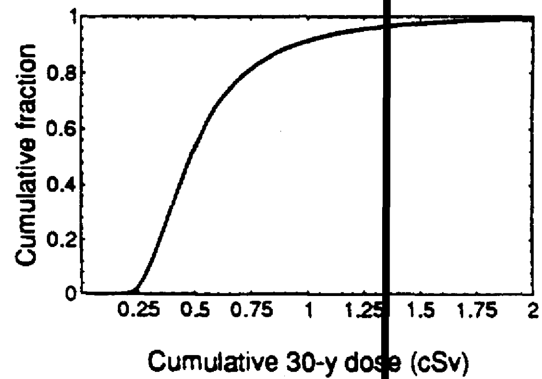

Figure 17. Estimated distribution of interindividual variability in expected 30-y dose corresponding to hypothetical residence on Rongelap Island starting in 1995. This distribution has a mean of 0.58 cSv and 50th, 95th and 99th percentile values of 0.48, 1.2 and 2.0 cSv, respectively.

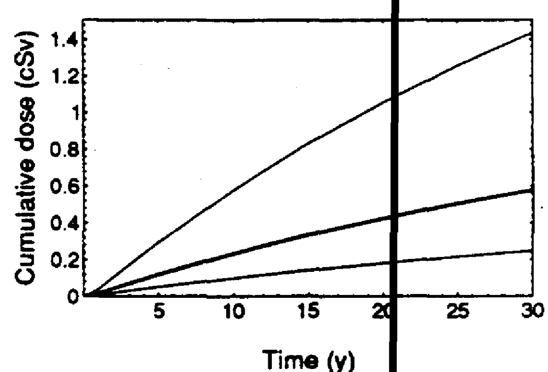

Figure 18. Population-average expected dose from hypothetical residence on Rongelap Island starting in 1995 (middle curve) and corresponding two-tail 95% confidence limits on interindividual variability in expected dose, as a function of residence time.

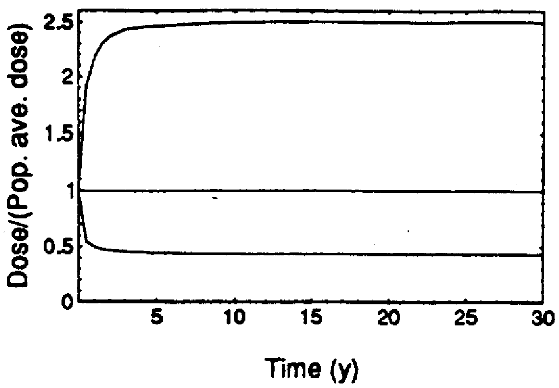

Figure 19. Two-tail 95% confidence limits on interindividual variability in expected dose from hypothetical residence on Rongelap Island starting in 1995 as ratios of the corresponding population-average value of this dose (horizontal line) at specified residence times.

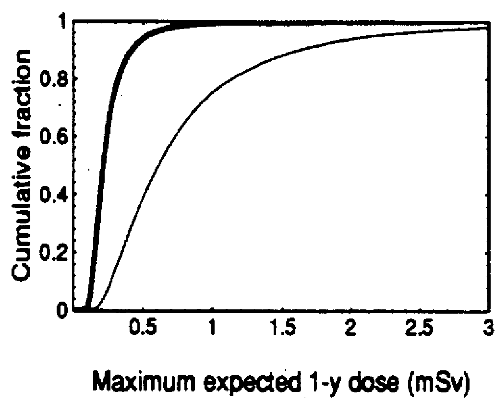

Figure 20. Estimated distributions of interindividual variability in the lifetime maximum of expected annual doses corresponding to hypothetical residence on Rongelap Island starting in 1995. Distributions corresponding to the LLNL imports-available model diet (bold curve) and a hypothetical local-foods-only diet assuming twice the local caloric intake shown in Table 20 (light curve) are shown.

From the analysis of uncertainty in population-average dose, the relationship between cumulative exposure time t and the 95% confidence limits of $\overline{D(t)}$ uncertainty shown in Figure 21 was calculated. Figure 22 illustrates how uncertainty in $\overline{D(t)}$ is predicted to become effectively independent of time after ~5 y of Rongelap residence, by which time residual uncertainty is derived solely from $\overline{F}$, B and β, and is characterized by confidence limits within a factor of 2 of $\langle \overline{D(t)} \rangle$. In particular, the chance that $\overline{D(30)}$ > 1.0 cSv is ~1% (Figure 23). Based on the hypothetical Rongelap-resettlement scenario described (in Methods) involving 500 people starting in 1995, the characterization of uncertainty in population-average dose implies the population-average lifetime dose $\overline{D(\text{Lifetime})}$ shown in Figure 24, which in turn implies an expected population risk of < 0.1 cases and an 87% chance (i.e., it is more likely than not) that zero cancers will arise as a result of fallout-related exposures on Rongelap.

As described above, the results of this uncertainty/variability analysis correspond to the LLNL model diet assuming imports are available. The results of the LLNL/ICRP-based assessment of predicted dose (Tables 11 and 12) indicate that total dose could be higher by a factor of ~1.85 if only local foods were assumed to be available. It is not clear, however, how a local-foods-only assumption would best be reflected in an analysis of uncertainty/variability of the type conducted here, because this assumption is substantially at odds with data on measured vs. LLNL model-diet-predicted (assuming imports available) whole-body ^{137}Cs burdens summarized in Figure 3. This discrepancy would be even greater if a hypothetical local-foods-only diet were assumed that is calorically more realistic than the corresponding LLNL local-only model diet (e.g., if total local-only calories were increased by a factor of two). As discussed above in reference to Figure 18, a local-foods-only diet that assumed twice the caloric intake of the corresponding LLNL model diet results in approximate 5-fold increase in expected dietary dose and 3.3-fold increase in expected maximum 1-y dose to potential 1995 Rongelap resettlers.

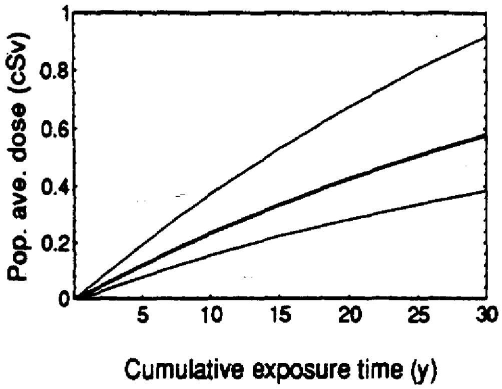

Figure 21. Population-average expected dose from hypothetical residence on Rongelap Island starting in 1995 (middle curve) and corresponding two-tail 95% confidence limits on uncertainty in population-average dose, as a function of residence time.

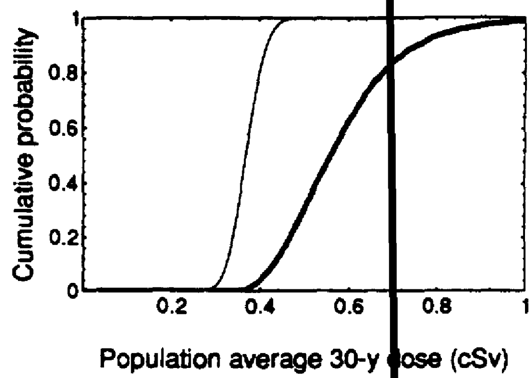

Figure 23. Estimated distribution characterizing uncertainty in population-average 30-y dose corresponding to hypothetical residence on Rongelap Island starting in 1995 (bold curve), contrasted with that for that component (*X*) of the latter distribution reflecting random dietary sampling only (light curve--see Appendix D). The former (bold) distribution has a mean of 0.58 cSv and 50th, 95th and 99th percentile values of 0.56, 0.84 and 1.0 cSv, respectively.

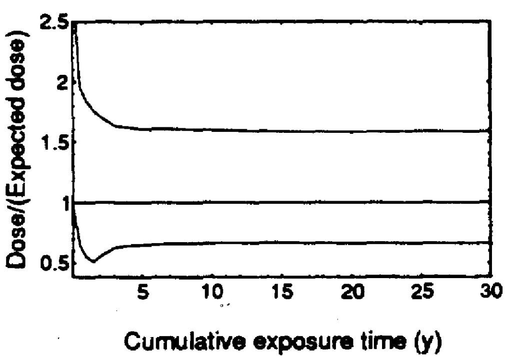

Figure 22. Two-tail 95% confidence limits on uncertainty in population-average dose from hypothetical residence on Rongelap Island starting in 1995 as ratios of the corresponding expected value of this dose (horizontal line) at specified residence times.

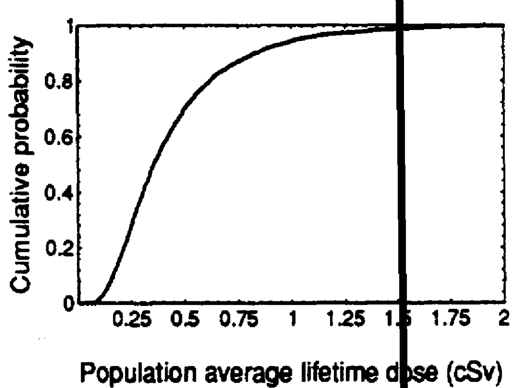

Figure 24. Estimated distribution of uncertainty in population-average lifetime dose corresponding to hypothetical residence of 500 people on Rongelap Island starting in 1995, assuming 40% incur a 70-y exposure (i.e., commencing at birth) and 60% incur a 30-y exposure. This distribution has a mean and 50th and 95th percentile values of 0.45, 0.36 and 1.0 cSv, respectively.

Remedial Actions

Significant reductions in dose can be achieved at atolls contaminated with different levels of radioactivity in the Marshall Islands. We list here five measures to achieve such reductions at Rongelap Island with reference to the effectiveness of the measures and associated monetary and environmental impacts.

1. Remove the surface soil (0 to 30 cm) in the area where the village will be established and for 10 to 15 m around each of the sites where houses will be built to minimize the external gamma and beta and alpha exposure in the areas where people spend most of their time. The additional cost to remove 15 to 20 cm of soil from the relatively small area included around each house and the village area would be minimal, compared with the overall costs of resettlement, since scraping and clearing is required to begin construction and resettlement. There would essentially be no adverse environmental effects from such an action.

2. Place a 10-cm layer of crushed coral around the village site and in a 5-to 10-m radius around each house to provide some additional reduction in any beta and gamma rays emanating from the soil subsequent to the soil removal and greatly reduce exposure to any residual beta radiation. This should be acceptable, as it is common practice in Marshallese villages to use crushed coral around homes for both appearance and dust suppression. The combination of the soil removal and application of crushed coral can significantly reduce the external exposure and provide small reductions in internal exposure.

3. Treat the entire agricultural area of the island, where coconut, breadfruit, and *Pandanus* fruit are growing, with potassium chloride (KCl) or complete fertilizer (nitrogen, phosphorus, and potassium) to reduce the uptake of ^{137}Cs into food crops. A high-potassium fertilizer can also be used in any family-type gardening for the same reason. The potential reduction in estimated dose from the food chain can be 90% or more. This salutary plan, coupled with the soil removal and addition of crushed coral in the housing and village areas, could reduce the total estimated 30-y, integral effective dose at Rongelap Island from 0.0059 Sv (0.59 rem) to about 0.0026 Sv (0.26 rem). Furthermore, growth rate and productivity of some food crops will be increased if a complete fertilizer consisting of nitrogen, phosphorus, and potassium is used to supply the needed potassium for blocking the uptake of ^{137}Cs into plants. The ^{137}Cs, ^{90}Sr, $^{239+240}$Pu, and ^{241}Am are still in the soil although the ^{137}Cs uptake into foods is greatly reduced.

4. Design adequate water catchment systems so that fresh water will always be available, even during extended dry periods, thus avoiding use of the contaminated ground water. Although the reduction in the estimated dose from the ground-water pathway (it contributes less than 0.05% of the estimated dose) is very much less than for the external gamma and terrestrial food pathways, it is not an expensive proposition to expand somewhat the water catchment systems that will be a necessary part of any housing and community design. Again, apart from radiological considerations, this measure should be found acceptable because of the obvious community benefits of expanded and improved water catchment systems. Consequently another potential source of exposure, albeit very low, can essentially be eliminated.

5. Of course, excavation of the top 30 to 40 cm of soil over the whole island also will reduce effectively the potential effective dose, both external and internal. This option, however, would entail environmental cost, as well as high dollar cost. The removal of the top 30 to 40 cm of soil would carry with it the removal of essentially all of the organic material—material that has taken decades, if not centuries, to develop and that contains all of the nutrients and water-retention capacity of the coral soil. This would obviously require removing all the mature coconut, breadfruit, *Pandanus*, lime, and other trees that supply food, windbreak, and shade at the island. This option would thus necessitate a very long-term commitment to rebuild the soil and revegetate the island. Such a commitment would, in turn, seem to suggest a continuous infusion of effort and expertise, the availability of which does not now seem assured.

We have not addressed the matter of the disposal of the very large quantity of removed soil and vegetation, but recent experiences at other locations indicate that this would present a formidable problem of both acceptance and cost.

Acknowledgments

We appreciate very much the excellent support of Marshall Stuart, Henry Jones, and John Rehder in the field phase of the project. The continued superb effort by Marshall Stuart, John Rehder, Mike Granillo, Steve Hall, and Henry Jones in processing the thousands of samples collected in this project has been outstanding. Kai Wong, Jim Brunk and Terry Jokela have done an excellent job analyzing thousands of samples in our analytical facilities, and Mark Mount has played a key role in the quality control phases of our analytical efforts and the dose assessment. Carol Stoker, Steve Kehl, Leina Boone, and James Johnson were a tremendous help in the organization, retrieval, reduction, and evaluation of the data resulting from the analysis of thousands of samples collected at the atoll. Everyone has been essential to the completion of this project and we thank them.

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Appendix A

Radionuclide concentration summary of all soil-profile samples collected during the 1978 NMIRS and from 1986 through 1993.

Table A-1. Cesium-137 radionuclide concentration summary for all soil profiles taken in the village area during the 1978 NMIRS together with our recent trips from 1986 through 1993 on Rongelap Island.

Soil depth (cm)	N[a]	Bq g^{-1} dry wt. Minimum	Maximum	Median	Mean	SD	Mean of logs	SD of logs
00–05	131	1.2×10^{-2}	1.4×10^{0}	1.1×10^{-1}	1.7×10^{-1}	1.9×10^{-1}	-2.2×10^{0}	8.6×10^{-1}
05–10	22	1.7×10^{-2}	4.8×10^{-1}	1.4×10^{-1}	1.8×10^{-1}	1.2×10^{-1}	-2.0×10^{0}	7.7×10^{-1}
10–15	21	3.0×10^{-2}	3.7×10^{-1}	1.2×10^{-1}	1.4×10^{-1}	1.0×10^{-1}	-2.2×10^{0}	7.5×10^{-1}
15–25	22	1.3×10^{-2}	1.8×10^{-1}	5.7×10^{-2}	7.7×10^{-2}	5.4×10^{-2}	-2.9×10^{0}	8.3×10^{-1}
25–40	21	2.1×10^{-3}	9.8×10^{-2}	1.2×10^{-2}	2.2×10^{-2}	2.4×10^{-2}	-4.4×10^{0}	1.1×10^{0}
40–60	20	9.4×10^{-4}	2.9×10^{-2}	5.6×10^{-3}	8.0×10^{-3}	7.6×10^{-3}	-5.3×10^{0}	1.0×10^{0}
00–05	131	1.2×10^{-2}	1.4×10^{0}	1.1×10^{-1}	1.7×10^{-1}	1.9×10^{-1}	-2.2×10^{0}	8.6×10^{-1}
00–10	22	2.6×10^{-2}	5.7×10^{-1}	1.5×10^{-1}	1.9×10^{-1}	1.4×10^{-1}	-1.9×10^{0}	7.7×10^{-1}
00–15	21	2.7×10^{-2}	4.5×10^{-1}	1.7×10^{-1}	1.8×10^{-1}	1.1×10^{-1}	-1.9×10^{0}	7.0×10^{-1}
00–25	21	4.3×10^{-2}	3.0×10^{-1}	1.2×10^{-1}	1.4×10^{-1}	6.9×10^{-2}	-2.1×10^{0}	5.2×10^{-1}
00–40	21	3.6×10^{-2}	2.0×10^{-1}	9.3×10^{-2}	9.5×10^{-2}	4.5×10^{-2}	-2.5×10^{0}	5.0×10^{-1}
00–60	20	3.0×10^{-2}	1.3×10^{-1}	6.3×10^{-2}	6.5×10^{-2}	3.0×10^{-2}	-2.8×10^{0}	4.6×10^{-1}

NOTE: Specific activity is decay corrected to 1995.
N[a] stands for number of individual samples.

Table A-2. Cesium-137 radionuclide concentration summary for all soil profiles taken in the interior of the island during the 1978 NMIRS together with our recent trips from 1986 through 1993 on Rongelap Island.

Soil depth (cm)	N[a]	Bq g^{-1} dry wt. Minimum	Maximum	Median	Mean	SD	Mean of logs	SD of logs
00–05	401	4.4×10^{-4}	3.9×10^{0}	4.8×10^{-1}	5.8×10^{-1}	4.5×10^{-1}	-9.6×10^{-1}	1.3×10^{0}
05–10	323	2.5×10^{-3}	3.0×10^{0}	2.2×10^{-1}	3.0×10^{-1}	2.9×10^{-1}	-1.6×10^{0}	9.3×10^{-1}
10–15	326	7.1×10^{-3}	1.2×10^{0}	1.0×10^{-1}	1.6×10^{-1}	1.7×10^{-1}	-2.4×10^{0}	1.1×10^{0}
15–25	324	1.4×10^{-3}	4.5×10^{-1}	3.8×10^{-2}	6.9×10^{-2}	8.3×10^{-2}	-3.2×10^{0}	1.1×10^{0}
25–40	319	1.9×10^{-4}	1.9×10^{-1}	1.4×10^{-2}	2.5×10^{-2}	2.8×10^{-2}	-4.2×10^{0}	1.0×10^{0}
40–60	282	7.7×10^{-6}	1.6×10^{-1}	7.0×10^{-3}	1.6×10^{-2}	2.5×10^{-2}	-5.0×10^{0}	1.3×10^{0}
00–05	401	4.4×10^{-4}	3.9×10^{0}	4.8×10^{-1}	5.8×10^{-1}	4.5×10^{-1}	-9.6×10^{-1}	1.3×10^{0}
00–10	321	3.1×10^{-3}	2.6×10^{0}	3.8×10^{-1}	4.6×10^{-1}	3.4×10^{-1}	-1.1×10^{0}	8.1×10^{-1}
00–15	320	4.4×10^{-3}	1.8×10^{0}	2.9×10^{-1}	3.6×10^{-1}	2.6×10^{-1}	-1.3×10^{0}	7.9×10^{-1}
00–25	317	6.0×10^{-3}	1.1×10^{0}	2.0×10^{-1}	2.4×10^{-1}	1.7×10^{-1}	-1.7×10^{0}	7.6×10^{-1}
00–40	309	4.7×10^{-3}	5.8×10^{-1}	1.3×10^{-1}	1.6×10^{-1}	1.0×10^{-1}	-2.1×10^{0}	7.2×10^{-1}
00–60	271	4.9×10^{-3}	3.9×10^{-1}	9.1×10^{-2}	1.1×10^{-1}	6.7×10^{-2}	-2.5×10^{0}	6.8×10^{-1}

NOTE: Specific activity is decay corrected to 1995.
N[a] stands for number of individual samples.

Table A-3. Strontium-90 radionuclide concentration summary for all soil profiles taken in the village area during the 1978 NMIRS on Rongelap Island.

Soil depth (cm)	N[a]	Bq g^{-1} dry wt.					Mean of logs	SD of logs
		Minimum	Maximum	Median	Mean	SD		
00–05	4	3.9×10^{-2}	2.9×10^{-1}	1.6×10^{-1}	1.6×10^{-1}	1.1×10^{-1}	-2.0×10^{0}	8.8×10^{-1}
05–10	4	4.3×10^{-2}	4.7×10^{-1}	3.1×10^{-1}	2.8×10^{-1}	1.9×10^{-1}	-1.6×10^{0}	1.1×10^{0}
10–15	4	3.8×10^{-2}	4.7×10^{-1}	1.6×10^{-1}	2.0×10^{-1}	1.9×10^{-1}	-2.0×10^{0}	1.1×10^{0}
15–25	4	3.0×10^{-2}	3.1×10^{-1}	1.5×10^{-1}	1.6×10^{-1}	1.3×10^{-1}	-2.2×10^{0}	1.0×10^{0}
25–40	4	2.4×10^{-3}	1.2×10^{-1}	4.8×10^{-2}	5.4×10^{-2}	5.1×10^{-2}	-3.6×10^{0}	1.7×10^{0}
40–60	0	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
00–05	4	3.9×10^{-2}	2.9×10^{-1}	1.6×10^{-1}	1.6×10^{-1}	1.1×10^{-1}	-2.0×10^{0}	8.8×10^{-1}
00–10	4	4.1×10^{-2}	3.5×10^{-1}	2.5×10^{-1}	2.2×10^{-1}	1.4×10^{-1}	-1.8×10^{0}	9.8×10^{-1}
00–15	4	4.0×10^{-2}	3.9×10^{-1}	2.2×10^{-1}	2.2×10^{-1}	1.4×10^{-1}	-1.8×10^{0}	9.9×10^{-1}
00–25	4	3.6×10^{-2}	3.6×10^{-1}	1.9×10^{-1}	1.9×10^{-1}	1.3×10^{-1}	-1.9×10^{0}	9.9×10^{-1}
00–40	4	2.3×10^{-2}	2.7×10^{-1}	1.4×10^{-1}	1.4×10^{-1}	10.0×10^{-2}	-2.3×10^{0}	1.1×10^{0}
00–60	0	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}

NOTE: Specific activity is decay corrected to 1995.
N[a] stands for number of individual samples.

TableA-4. Strontium-90 radionuclide concentration summary for all soil profiles taken in the interior of the island during the 1978 NMIRS on Rongelap Island.

Soil depth (cm)	N[a]	Bq g^{-1} dry wt.					Mean of logs	SD of logs
		Minimum	Maximum	Median	Mean	SD		
00–05	16	4.4×10^{-3}	4.6×10^{-1}	1.9×10^{-1}	1.7×10^{-1}	1.2×10^{-1}	-2.1×10^{0}	1.2×10^{0}
05–10	16	5.6×10^{-3}	5.9×10^{-1}	1.0×10^{-1}	1.8×10^{-1}	1.8×10^{-1}	-2.3×10^{0}	1.2×10^{0}
10–15	16	8.6×10^{-4}	5.1×10^{-1}	8.5×10^{-2}	1.3×10^{-1}	1.4×10^{-1}	-2.7×10^{0}	1.5×10^{0}
15–25	16	1.4×10^{-2}	2.6×10^{-1}	6.9×10^{-2}	9.9×10^{-2}	7.7×10^{-2}	-2.7×10^{0}	9.2×10^{-1}
25–40	17	3.8×10^{-4}	2.7×10^{-1}	5.2×10^{-2}	6.6×10^{-2}	6.4×10^{-2}	-3.3×10^{0}	1.5×10^{0}
40–60	0	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
00–05	16	4.4×10^{-3}	4.6×10^{-1}	1.9×10^{-1}	1.7×10^{-1}	1.2×10^{-1}	-2.1×10^{0}	1.2×10^{0}
00–10	15	5.0×10^{-3}	5.3×10^{-1}	1.5×10^{-1}	1.8×10^{-1}	1.4×10^{-1}	-2.2×10^{0}	1.2×10^{0}
00–15	14	1.0×10^{-2}	4.8×10^{-1}	1.2×10^{-1}	1.6×10^{-1}	1.4×10^{-1}	-2.2×10^{0}	1.0×10^{0}
00–25	13	2.7×10^{-2}	3.5×10^{-1}	1.2×10^{-1}	1.4×10^{-1}	1.1×10^{-1}	-2.3×10^{0}	8.3×10^{-1}
00–40	13	2.2×10^{-2}	2.4×10^{-1}	9.6×10^{-2}	1.1×10^{-1}	7.7×10^{-2}	-2.5×10^{0}	8.0×10^{-1}
00–60	0	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}

NOTE: Specific activity is decay corrected to 1995.
N[a] stands for number of individual samples.

Table A-5. Plutonium-239+240 radionuclide concentration summary for all soil profiles taken in the village area during the 1978 NMIRS together with our recent trips from 1986 through 1992 on Rongelap Island.

Soil depth (cm)	N[a]	Bq g^{-1} dry wt. Minimum	Maximum	Median	Mean	SD	Mean of logs	SD of logs
00–05	110	3.1×10^{-3}	1.6×10^{-1}	1.9×10^{-2}	3.1×10^{-2}	3.1×10^{-2}	-3.9×10^{0}	8.6×10^{-1}
05–10	4	1.2×10^{-2}	1.6×10^{-1}	8.1×10^{-2}	8.4×10^{-2}	7.1×10^{-2}	-2.9×10^{0}	1.2×10^{0}
10–15	4	5.6×10^{-3}	5.3×10^{-2}	2.2×10^{-2}	2.5×10^{-2}	2.2×10^{-2}	-4.0×10^{0}	1.0×10^{0}
15–25	4	9.2×10^{-4}	9.0×10^{-3}	7.1×10^{-3}	6.0×10^{-3}	3.7×10^{-3}	-5.4×10^{0}	1.1×10^{0}
25–40	4	2.2×10^{-5}	3.3×10^{-3}	6.0×10^{-4}	1.1×10^{-3}	1.5×10^{-3}	-8.0×10^{0}	2.2×10^{0}
40–60	0	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
00–05	110	3.1×10^{-3}	1.6×10^{-1}	1.9×10^{-2}	3.1×10^{-2}	3.1×10^{-2}	-3.9×10^{0}	8.6×10^{-1}
00–10	4	1.3×10^{-2}	1.3×10^{-1}	9.2×10^{-2}	8.2×10^{-2}	5.3×10^{-2}	-2.8×10^{0}	1.1×10^{0}
00–15	4	1.1×10^{-2}	1.0×10^{-1}	6.9×10^{-2}	6.3×10^{-2}	4.2×10^{-2}	-3.1×10^{0}	1.0×10^{0}
00–25	4	6.8×10^{-3}	6.7×10^{-2}	4.4×10^{-2}	4.0×10^{-2}	2.7×10^{-2}	-3.5×10^{0}	1.0×10^{0}
00–40	4	4.2×10^{-3}	4.3×10^{-2}	2.8×10^{-2}	2.6×10^{-2}	1.7×10^{-2}	-4.0×10^{0}	1.1×10^{0}
00–60	0	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}

NOTE: Specific activity is decay corrected to 1995.
N[a] stands for number of individual samples.

Table A-6. Plutonium-239+240 radionuclide concentration summary for all soil profiles taken in the interior of the island during the 1978 NMIRS together with our recent trips from 1986 through 1992 on Rongelap Island.

Soil depth (cm)	N[a]	Bq g^{-1} dry wt. Minimum	Maximum	Median	Mean	SD	Mean of logs	SD of logs
00–05	196	1.9×10^{-2}	5.8×10^{-1}	1.3×10^{-1}	1.6×10^{-1}	1.1×10^{-1}	-2.1×10^{0}	7.1×10^{-1}
05–10	12	7.7×10^{-3}	3.7×10^{-1}	3.7×10^{-2}	7.7×10^{-2}	1.0×10^{-1}	-3.2×10^{0}	1.1×10^{0}
10–15	14	1.7×10^{-3}	1.3×10^{-1}	1.8×10^{-2}	3.6×10^{-2}	4.0×10^{-2}	-4.0×10^{0}	1.3×10^{0}
15–25	14	6.8×10^{-4}	3.9×10^{-2}	7.7×10^{-3}	1.1×10^{-2}	1.1×10^{-2}	-5.0×10^{0}	1.1×10^{0}
25–40	15	2.8×10^{-4}	1.8×10^{-2}	4.9×10^{-3}	5.7×10^{-3}	4.9×10^{-3}	-5.6×10^{0}	1.1×10^{0}
40–60	0	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
00–05	196	1.9×10^{-2}	5.8×10^{-1}	1.3×10^{-1}	1.6×10^{-1}	1.1×10^{-1}	-2.1×10^{0}	7.1×10^{-1}
00–10	11	1.3×10^{-2}	2.3×10^{-1}	5.7×10^{-2}	1.0×10^{-1}	8.6×10^{-2}	-2.7×10^{0}	1.1×10^{0}
00–15	10	9.8×10^{-3}	1.9×10^{-1}	5.0×10^{-2}	7.8×10^{-2}	6.7×10^{-2}	-3.0×10^{0}	1.0×10^{0}
00–25	9	6.9×10^{-3}	1.3×10^{-1}	4.3×10^{-2}	5.4×10^{-2}	4.4×10^{-2}	-3.3×10^{0}	1.0×10^{0}
00–40	9	4.7×10^{-3}	8.4×10^{-2}	3.0×10^{-2}	3.7×10^{-2}	2.7×10^{-2}	-3.6×10^{0}	9.3×10^{-1}
00–60	0	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}

NOTE: Specific activity is decay corrected to 1995.
N[a] stands for number of individual samples.

Table A-7. Americium-241 radionuclide concentration summary for all soil profiles taken in the village area during the 1978 NMIRS together with our recent trips from 1986 through 1993 on Rongelap Island.

Soil depth (cm)	N[a]	Bq g^{-1} dry wt. Minimum	Maximum	Median	Mean	SD	Mean of logs	SD of logs
00-05	90	2.6×10^{-3}	1.3×10^{-1}	1.5×10^{-2}	2.3×10^{-2}	2.4×10^{-2}	-4.2×10^{0}	8.9×10^{-1}
05-10	18	6.4×10^{-3}	1.1×10^{-1}	2.0×10^{-2}	3.6×10^{-2}	3.5×10^{-2}	-3.8×10^{0}	1.0×10^{0}
10-15	14	2.7×10^{-3}	8.4×10^{-2}	1.7×10^{-2}	2.2×10^{-2}	2.1×10^{-2}	-4.2×10^{0}	8.7×10^{-1}
15-25	15	4.7×10^{-4}	7.8×10^{-2}	7.6×10^{-3}	1.6×10^{-2}	2.3×10^{-2}	-4.9×10^{0}	1.3×10^{0}
25-40	6	2.8×10^{-5}	2.9×10^{-2}	1.0×10^{-3}	5.5×10^{-3}	1.2×10^{-2}	-7.3×10^{0}	2.5×10^{0}
40-60	5	4.6×10^{-5}	1.4×10^{-3}	1.1×10^{-4}	3.4×10^{-4}	5.8×10^{-4}	-8.9×10^{0}	1.4×10^{0}
00-05	90	2.6×10^{-3}	1.3×10^{-1}	1.5×10^{-2}	2.3×10^{-2}	2.4×10^{-2}	-4.2×10^{0}	8.9×10^{-1}
00-10	12	6.2×10^{-3}	1.2×10^{-1}	3.9×10^{-2}	4.3×10^{-2}	3.3×10^{-2}	-3.5×10^{0}	1.0×10^{0}
00-15	8	6.1×10^{-3}	8.0×10^{-2}	3.1×10^{-2}	3.4×10^{-2}	2.7×10^{-2}	-3.8×10^{0}	1.0×10^{0}
00-25	6	3.9×10^{-3}	5.6×10^{-2}	1.0×10^{-2}	1.9×10^{-2}	2.0×10^{-2}	-4.4×10^{0}	9.7×10^{-1}
00-40	3	2.4×10^{-3}	1.7×10^{-2}	7.6×10^{-3}	9.1×10^{-3}	7.6×10^{-3}	-5.0×10^{0}	9.9×10^{-1}
00-60	3	1.6×10^{-3}	1.2×10^{-2}	5.1×10^{-3}	6.1×10^{-3}	5.1×10^{-3}	-5.4×10^{0}	9.9×10^{-1}

NOTE: Specific activity is decay corrected to 1995.
N[a] stands for number of individual samples.

Table A-8. Americium-241 radionuclide concentration summary for all soil profiles taken in the interior of the island during the 1978 NMIRS together with our recent trips from 1986 through 1993 on Rongelap Island.

Soil depth (cm)	N[a]	Bq g^{-1} dry wt. Minimum	Maximum	Median	Mean	SD	Mean of logs	SD of logs
00–05	366	1.5×10^{-3}	7.1×10^{-1}	9.6×10^{-2}	1.2×10^{-1}	9.9×10^{-2}	-2.4×10^{0}	8.4×10^{-1}
05–10	237	1.5×10^{-3}	8.4×10^{-1}	3.4×10^{-2}	5.4×10^{-2}	7.1×10^{-2}	-3.4×10^{0}	1.1×10^{0}
10–15	155	2.8×10^{-5}	1.5×10^{-1}	1.8×10^{-2}	2.8×10^{-2}	2.7×10^{-2}	-4.1×10^{0}	1.2×10^{0}
15–25	78	2.8×10^{-4}	2.1×10^{-1}	7.0×10^{-3}	1.5×10^{-2}	2.6×10^{-2}	-4.8×10^{0}	1.1×10^{0}
25–40	35	1.3×10^{-4}	1.5×10^{-1}	3.1×10^{-3}	8.9×10^{-3}	2.4×10^{-2}	-5.7×10^{0}	1.3×10^{0}
40–60	16	1.2×10^{-4}	1.8×10^{-2}	3.3×10^{-3}	4.6×10^{-3}	5.3×10^{-3}	-6.2×10^{0}	1.6×10^{0}
00–05	366	1.5×10^{-3}	7.1×10^{-1}	9.6×10^{-2}	1.2×10^{-1}	9.9×10^{-2}	-2.4×10^{0}	8.4×10^{-1}
00–10	225	1.6×10^{-3}	5.5×10^{-1}	7.5×10^{-2}	9.2×10^{-2}	7.1×10^{-2}	-2.7×10^{0}	7.8×10^{-1}
00–15	128	4.9×10^{-3}	3.9×10^{-1}	6.2×10^{-2}	7.3×10^{-2}	5.2×10^{-2}	-2.9×10^{0}	7.1×10^{-1}
00–25	52	3.5×10^{-3}	2.4×10^{-1}	4.1×10^{-2}	5.4×10^{-2}	4.1×10^{-2}	-3.2×10^{0}	7.6×10^{-1}
00–40	17	2.4×10^{-3}	1.1×10^{-1}	3.6×10^{-2}	3.9×10^{-2}	2.8×10^{-2}	-3.6×10^{0}	9.4×10^{-1}
00–60	5	1.7×10^{-3}	7.7×10^{-2}	1.2×10^{-2}	2.5×10^{-2}	3.1×10^{-2}	-4.4×10^{0}	1.5×10^{0}

NOTE: Specific activity is decay corrected to 1995.
N[a] stands for number of individual samples.

Appendix B

Concentration of radionuclides in vegetation from samples collected during the 1978 NMIRS and from 1986 through 1993.

Table B-1. The concentration of radionuclides in vegetation collected during the 1978 NMIRS together with our most recent trips from 1986 through 1993 on Rongelap Island.

Food source	N[a]	Minimum	Maximum	Median	Mean	SD	Mean of logs	SD of logs
		Bq g^{-1} wet wt.						
				^{137}Cs				
Dr. coconut meat	433	1.0×10^{-2}	5.4×10^{-1}	5.2×10^{-2}	7.1×10^{-2}	6.1×10^{-2}	-2.9×10^{0}	7.0×10^{-1}
Dr. coconut juice	427	3.3×10^{-3}	2.6×10^{-1}	2.3×10^{-2}	3.2×10^{-2}	3.1×10^{-2}	-3.8×10^{0}	8.0×10^{-1}
Copra meat	108	2.8×10^{-2}	6.6×10^{-1}	8.6×10^{-2}	1.2×10^{-1}	1.0×10^{-1}	-2.4×10^{0}	6.8×10^{-1}
Pandanus	116	1.8×10^{-2}	1.2×10^{0}	1.8×10^{-1}	2.5×10^{-1}	2.3×10^{-1}	-1.8×10^{0}	8.6×10^{-1}
Breadfruit	40	3.6×10^{-2}	2.9×10^{-1}	1.2×10^{-1}	1.3×10^{-1}	6.8×10^{-2}	-2.2×10^{0}	5.5×10^{-1}
Limes	9	4.2×10^{-2}	7.4×10^{-2}	5.6×10^{-2}	5.7×10^{-2}	9.0×10^{-3}	-2.9×10^{0}	1.6×10^{-1}
Arrowroot	5	3.6×10^{-2}	5.4×10^{-1}	1.6×10^{-1}	2.0×10^{-1}	1.9×10^{-1}	-1.9×10^{0}	9.6×10^{-1}
Squash	2	1.4×10^{-1}	2.8×10^{-1}	2.1×10^{-1}	2.1×10^{-1}	1.0×10^{-1}	-1.6×10^{0}	5.2×10^{-1}
Banana	1	1.2×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	0.0×10^{0}	-4.4×10^{0}	0.0×10^{0}
				^{90}Sr				
Dr. coconut meat	14	8.4×10^{-5}	1.1×10^{-3}	2.5×10^{-4}	3.3×10^{-4}	2.5×10^{-4}	-8.2×10^{0}	6.7×10^{-1}
Dr. coconut juice	3	2.3×10^{-5}	5.2×10^{-5}	3.4×10^{-5}	3.7×10^{-5}	1.5×10^{-5}	-1.0×10^{1}	4.1×10^{-1}
Copra meat	12	3.1×10^{-4}	9.1×10^{-4}	4.8×10^{-4}	5.2×10^{-4}	1.9×10^{-4}	-7.6×10^{0}	3.6×10^{-1}
Pandanus	13	8.5×10^{-4}	7.0×10^{-2}	6.7×10^{-3}	1.5×10^{-2}	2.1×10^{-2}	-5.1×10^{0}	1.4×10^{0}
Breadfruit	2	1.6×10^{-3}	2.4×10^{-3}	2.0×10^{-3}	2.0×10^{-3}	5.5×10^{-4}	-6.2×10^{0}	2.8×10^{-1}
Arrowroot	1	2.6×10^{-3}	2.6×10^{-3}	2.6×10^{-3}	2.6×10^{-3}	0.0×10^{0}	-6.0×10^{0}	0.0×10^{0}
				$^{239+240}Pu$				
Dr. coconut meat	9	1.3×10^{-7}	3.3×10^{-6}	8.7×10^{-7}	1.2×10^{-6}	1.1×10^{-6}	-1.4×10^{1}	1.1×10^{0}
Dr. coconut juice	2	9.5×10^{-7}	1.0×10^{-6}	9.8×10^{-7}	9.8×10^{-7}	5.3×10^{-8}	-1.4×10^{1}	5.4×10^{-2}
Copra meat	9	5.6×10^{-7}	4.6×10^{-6}	1.1×10^{-6}	1.7×10^{-6}	1.4×10^{-6}	-1.4×10^{1}	7.7×10^{-1}
Pandanus	8	1.7×10^{-7}	4.4×10^{-6}	1.1×10^{-6}	1.6×10^{-6}	1.5×10^{-6}	-1.4×10^{1}	1.2×10^{0}
Breadfruit	1	6.0×10^{-7}	6.0×10^{-7}	6.0×10^{-7}	6.0×10^{-7}	0.0×10^{0}	-1.4×10^{1}	0.0×10^{0}
Arrowroot	1	2.6×10^{-5}	2.6×10^{-5}	2.6×10^{-5}	2.6×10^{-5}	0.0×10^{0}	-1.1×10^{1}	0.0×10^{0}
				^{241}Am				
Dr. coconut meat	9	3.4×10^{-8}	3.5×10^{-6}	5.0×10^{-7}	1.4×10^{-6}	1.4×10^{-6}	-1.4×10^{1}	1.5×10^{0}
Dr. coconut juice	3	4.4×10^{-7}	1.6×10^{-6}	7.8×10^{-7}	9.3×10^{-7}	5.9×10^{-7}	-1.4×10^{1}	6.4×10^{-1}
Copra meat	11	4.3×10^{-7}	5.6×10^{-6}	1.8×10^{-6}	2.1×10^{-6}	1.6×10^{-6}	-1.3×10^{1}	7.8×10^{-1}
Pandanus	6	3.2×10^{-7}	1.2×10^{-6}	8.6×10^{-7}	8.1×10^{-7}	3.0×10^{-7}	-1.4×10^{1}	4.7×10^{-1}
Breadfruit	1	7.4×10^{-7}	7.4×10^{-7}	7.4×10^{-7}	7.4×10^{-7}	0.0×10^{0}	-1.4×10^{1}	0.0×10^{0}
Arrowroot	1	1.3×10^{-5}	1.3×10^{-5}	1.3×10^{-5}	1.3×10^{-5}	0.0×10^{0}	-1.1×10^{1}	0.0×10^{0}

Note: Specific activity is decay corrected to 1995.
N[a] = the number of composite samples.

Appendix C

External dose at Rongelap Island in mrem.

Table C-1. External dose at Rongelap Island[a].

Years	Co annual dose rate mrem y^{-1}	Co annual integral dose mrem	Cs annual dose rate[b] mrem y^{-1}	Cs annual integral dose mrem[b]	Total annual dose mrem	Total integral dose mrem[b]
Initial	0.08	0	11.2	0	11.3	0
1	0.07	0.08	10.9	11.1	11.0	11.2
2	0.06	0.15	10.7	21.9	10.8	22.1
3	0.06	0.20	10.5	32.5	10.5	32.7
4	0.05	0.26	10.2	42.8	10.3	43.1
5	0.04	0.30	10.0	52.9	10.0	53.3
6	0.04	0.34	9.8	62.8	9.8	63.2
7	0.03	0.38	9.5	72.5	9.6	72.9
8	0.03	0.41	9.3	81.9	9.3	82.3
9	0.03	0.44	9.1	91.1	9.1	91.6
10	0.02	0.46	8.9	100	8.9	101
11	0.02	0.48	8.7	109	8.7	109
12	0.02	0.50	8.5	118	8.5	118
13	0.01	0.51	8.3	126	8.3	126
14	0.01	0.53	8.1	134	8.1	135
15	0.01	0.54	7.9	142	7.9	143
16	0.01	0.55	7.7	150	7.7	151
17	0.01	0.56	7.6	158	7.6	158
18	0.01	0.57	7.4	165	7.4	166
19	0.01	0.58	7.2	172	7.2	173
20	0.01	0.58	7.1	180	7.1	180
21	0.01	0.59	6.9	187	6.9	187
22	0	0.59	6.7	193	6.7	194
23	0	0.60	6.6	200	6.6	201
24	0	0.60	6.4	207	6.4	207
25	0	0.60	6.3	213	6.3	214
26	0	0.61	6.1	219	6.1	220
27	0	0.61	6.0	225	6.0	226
28	0	0.61	5.9	231	5.9	232
29	0	0.61	5.7	237	5.7	238
30	0	0.62	5.6	243	5.6	243
31	0	0.62	5.5	248	5.5	249
32	0	0.62	5.3	254	5.3	254
33	0	0.62	5.2	259	5.2	260
34	0	0.62	5.1	264	5.1	265
35	0	0.62	5.0	269	5.0	270
36	0	0.62	4.9	274	4.9	275
37	0	0.62	4.8	279	4.8	280
38	0	0.62	4.7	284	4.7	284
39	0	0.62	4.5	288	4.5	289
40	0	0.62	4.4	293	4.4	293

Table C-1. (Continued)

Years	Co annual dose rate mrem y^{-1}	Co annual integral dose mrem	Cs annual dose rate[b] mrem y^{-1}	Cs annual integral dose mrem[b]	Total annual dose mrem	Total integral dose mrem[b]
41	0	0.62	4.3	297	4.3	298
42	0	0.63	4.2	301	4.2	302
43	0	0.63	4.1	306	4.1	306
44	0	0.63	4.1	310	4.1	310
45	0	0.63	4.0	314	4.0	314
46	0	0.63	3.9	317	3.9	318
47	0	0.63	3.8	322	3.8	322
48	0	0.63	3.7	325	3.7	326
49	0	0.63	3.6	329	3.6	330
50	0	0.63	3.5	333	3.5	333
51	0	0.63	3.4	336	3.4	337
52	0	0.63	3.4	339	3.4	340
53	0	0.63	3.3	343	3.3	343
54	0	0.63	3.2	346	3.2	347
55	0	0.63	3.1	349	3.1	350
56	0	0.63	3.1	352	3.1	353
57	0	0.63	3.0	355	3.0	356
58	0	0.63	2.9	358	2.9	359
59	0	0.63	2.9	361	2.9	362
60	0	0.63	2.8	364	2.8	365
61	0	0.63	2.7	367	2.7	367
62	0	0.63	2.7	370	2.7	370
63	0	0.63	2.6	372	2.6	373
64	0	0.63	2.6	375	2.6	375
65	0	0.63	2.5	377	2.5	378
66	0	0.63	2.4	380	2.4	380
67	0	0.63	2.4	382	2.4	383
68	0	0.63	2.3	385	2.3	385
69	0	0.63	2.3	387	2.3	387
70	0	0.63	2.2	389	2.2	390

[a] Divide mrem values by 100 to obtain mSv.

[b] Three significant figures are listed only to show the actual annual difference. The results are rounded to two significant figures for dose calculation.

Appendix D

Mathematical Appendix.

Appendix D

To evaluate Eq. (4), $\overline{D_x(t)}$ and $D_{in}(t)$ were approximated as

$$\overline{D_x(t)} = \frac{2.848\times10^{-5}\ \text{cSv y}^{-1}}{\lambda}\left(1-e^{-\lambda t}\right) \quad \text{and} \tag{A1}$$

$$D_{in}(t) = (2.848\times10^{-5}\ \text{cSv y}^{-1})t + (4.333\times10^{-6}\ \text{cSv y}^{-2})t^2 \tag{A2}$$

corresponding to population-average adult external-gamma dose (Figure D1) and deterministic Am+Pu-inhalation dose (Figure D2), respectively, predicted by the more complex ICRP models. To proceed with the evaluation, define annual intake R_j of ^{137}Cs in Bq kg^{-1} y^{-1} from local foods of type j and corresponding total annual ^{137}Cs intake as $R_j = \sum_i^{n_j} \frac{365}{n_j} R_{ij}$ and $R = \sum_j R_j$, respectively. From Eqs. (1-3) and the notation, assumptions and definitions given above, integrated whole-body dose, $Q_{ij}(t)$ after t years due to ingestion of ^{137}Cs in a food item of type j at time $t_i \le t$ is given by

$$Q_{ij}(t) = \int_0^t c\,q_{ij}(u)\,du$$

$$= cFBR_{ij}\left\{\frac{e^{-\lambda T}(1-e^{-(\beta K+\lambda)(t-T)})}{\beta K+\lambda}\right\} \tag{A3}$$

$$\equiv cFBR_{ij}S \tag{A4}$$

where $T = t_i$, S in Eq. (A4) is defined as the quantity in braces in Eq. (A3) and where c = 2.431 x 10^{-4} cSv kg Bq^{-1} y^{-1} was estimated from values of cumulative whole-body-equivalent dose for adults of age 20 to 50 y that are approximately equal to those obtained using the more complex, organ-specific

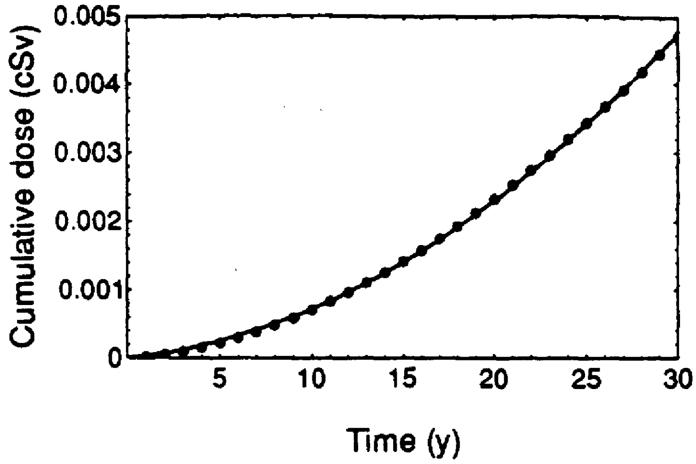

Figure D-1. LLNL/ICRP model of cumulative, expected, population-average Am+Pu inhalation dose (solid points) corresponding to hypothetical residence on Rongelap Island starting in 1995, compared with exponential approximation (A1).

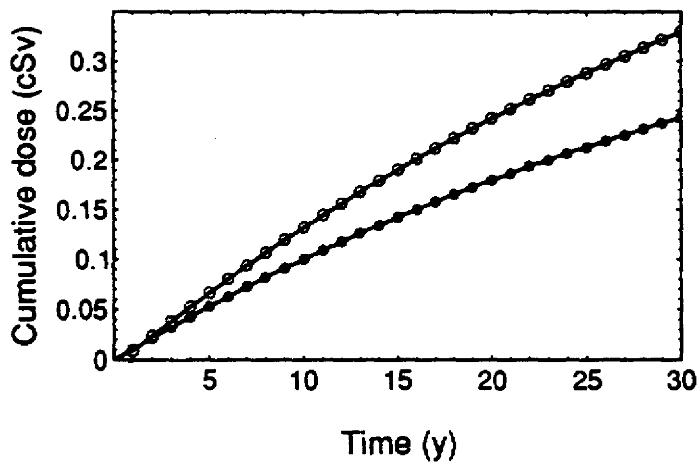

Figure D-2. LLNL/ICRP model of cumulative, expected, population-average external gamma dose (solid points) and ^{137}Cs-ingestion dose corresponding to hypothetical residence on Rongelap Island starting in 1995, compared with quadratic approximation (A2) and the population-average value of stochastic model (A6) (open circles), respectively.

ICRP model for ^{137}Cs referred to in the text (Figure D1). For large n_j and for t_i distributed randomly throughout each year, it follows that total integrated whole-body dose $Q(t)$ in Bq kg^{-1} after t years may be approximated by the quantity

$$FB\left\{c\sum^{t} RS\right\} \equiv FBX, \qquad \text{(A5)}$$

where X is here defined as the braced quantity and where the variate T, subsumed in S, is here–in contrast to Eq. (2) above–uniformly distributed between 0 and t.

Based on Eq. (4) and the preceding analysis, interindividual variability in expected dose $\langle D(t)\rangle$ by time t was characterized by evaluating

$$\langle D(t)\rangle = [(0.36+Y)\overline{D_x(t)}\,] + D_{in}(t) + \langle F\rangle \left\{ct\langle R\rangle\langle S\rangle\right\}\ , \qquad \text{(A6)}$$

in which Y was defined in the text and $\langle S\rangle$, the expectation of S with respect to both T and β, is given by

$$\langle S\rangle = 1 + \frac{\Delta\beta + e^{-\lambda t}[\mathrm{Ei}(b_1) - \mathrm{Ei}(b_0)] - \mathrm{Ei}(c_1) + \mathrm{Ei}(c_0) + \mathrm{Ln}(c_1/c_0)}{\Delta\beta K\lambda t},$$

$$b_i = -\beta_i Kt\,,\quad i = 0,1,$$

$$c_i = b_i - \lambda t\,,\quad i = 0,1, \qquad \text{and}$$

$$\Delta\beta = (\beta_1 - \beta_0) = (1.107 - 0.9) = 0.207$$

in which Ei is the exponential integral. As such, variability in $\langle D(t)\rangle$ arises from uniform variability in F and lognormal variability in both $\langle R\rangle$ and H (see text). Uncertainty in population-average dose $\overline{D(t)}$ was characterized by evaluating

$$\overline{D(t)} = \overline{D_x(t)} + D_{in}(t) + \overline{F}\,\overline{BX}\ , \qquad \text{(A7)}$$

where the uncertainty arises in part from the uniform and triangular uncertainties assumed for $\overline{F}$ and B, respectively (see text), in addition to uncertainty is associated with the variate $\overline{X}$ associated with X defined in Eq. (A5). Let the subscript p on a variate denote a variate value pertaining to a particular individual in the exposed population. Thus, $X_p = X \mid \{R = R_p, H = H_p\}$ and $(X_p \mid \beta)$ is the sum of a presumed large number of identical independently distributed random variates. From the Lindeberg and Central Limit theorems, it follows that $(X_p \mid \beta)$ is approximately normally distributed with mean and variance given by

$$\langle X_p|\beta\rangle = ct\langle R_p\rangle\langle S_p|\beta\rangle \quad \text{and}$$
$$\sigma^2_{X_p|\beta} = c^2t\langle R_p\rangle^2\left[(1+\gamma_R^2)\langle S_p^2|\beta\rangle - \langle S_p|\beta\rangle^2\right],$$

respectively, in which

$$\gamma_R = \overline{\langle R\rangle}^{-1}\left(\Sigma_j\langle R_j\rangle^2\gamma^2_{R_{ij}}n_j^{-1}\right)^{1/2} = 0.035$$

is the CV for uncertainty in any individual's lifetime, time-weighted average intake based on the assumptions stated in the text and the values listed in Table 20. If population size N is sufficiently large to ensure that the differences between sample first and second moments with respect to variability and their corresponding population moments are negligible, it follows from the definition of variability expectation that uncertainty in $\overline{X|\beta}$ is approximately normally distributed with mean and variance given by

$$\overline{\langle X|\beta\rangle} = \frac{1}{N}\sum_{p=1}^{N}\langle X_p|\beta\rangle \approx ct\overline{\langle R\rangle\langle S|\beta\rangle} \quad \text{and} \qquad \text{(A8)}$$

$$\sigma^2_{\overline{X}|\beta} = \frac{1}{N^2}\sum_{p=1}^{N}\sigma^2_{X_p|\beta}$$

$$\approx c^2 t\overline{\langle R\rangle}^2\left(1+g_R^2\right)\left[\left(1+\gamma_R^2\right)\overline{\langle S^2|\beta\rangle} - \overline{\langle S|\beta\rangle}^2\right], \qquad \text{(A9)}$$

respectively, where

$$\langle S|\beta\rangle = [(\beta K+\lambda)t]^{-1}\left[\left(1-e^{-\lambda t}\right)\lambda^{-1} - \left(e^{-(\beta K+\lambda)t} - e^{-\lambda t}\right)(\beta K)^{-1}\right], \quad \text{and}$$

$$\langle S^2|\beta\rangle = (\beta K+\lambda)^{-2}t^{-1}\left\{(2\lambda)^{-1} + e^{-\lambda t}\left[\left(1-2e^{-\beta K t}\right)(2\beta K t)^{-1} + 2\left(e^{-(\beta K-\lambda)t}-1\right)(\beta K-\lambda)^{-1} - (2\lambda)^{-1}\right]\right\}.$$

The averages $\overline{\langle S|\beta\rangle}$ and $\overline{\langle S^2|\beta\rangle}$ with respect to H were each evaluated numerically for different β values equally spaced over the range of β, whereupon it was found that $\sigma_{\overline{X}|\beta}t^{-1/2}$ is for each given t, $0 < t \le 30$ y, a virtually linear function of $\overline{\langle X|\beta\rangle}t^{-1}$ over a β - and t-dependent range of the latter, and furthermore that corresponding $\overline{\langle X|\beta\rangle}t^{-1}$ values are virtually uniformly distributed over these linear ranges (Figure D3). The linear coefficients $\{a,b\,|\,t\}$ and corresponding $\overline{\langle X|\beta\rangle}t^{-1}$-range boundaries $\{x_{lo}, x_{hi}\,|\,t\}$ were therefore determined for representative values of t and these were used to evaluate uncertainty in $\overline{X}$ modeled as a compound normal distribution with mean = Ut and SD = $t^{1/2}(a + bU)$, for U uniformly distributed between x_{lo} and x_{hi}.

All variate simulations were conducted using virtually uncorrelated vectors of 2,000 or 10,000 values for each variate involved, generated using systematic Latin-Hypercube sampling procedures. Calculations were done on a NeXT workstation using the programs *Mathematica* (Wolfram, 1991) and *RiskQ* (Bogen, 1992). Analyses of quantile convergence indicated that 0.01- to 0.99-fractiles obtained are accurate to within ~1 to 5%.

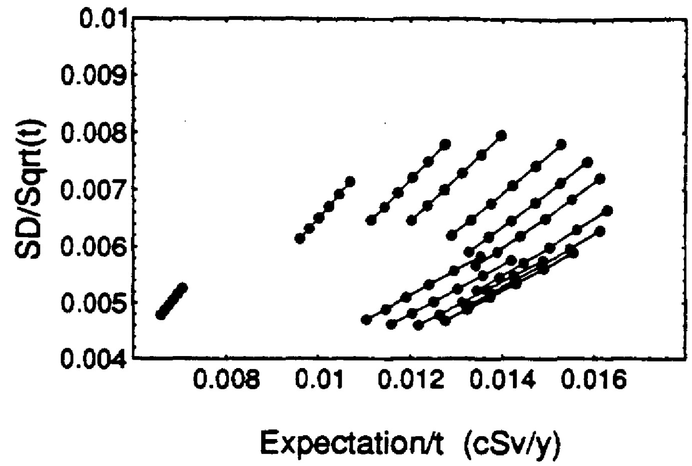

Figure D-3. The standard deviation (SD), denoted $\sigma_{\overline{X|\beta}}$ in Eq. (A9), as a function of the corresponding Expectation, denoted $\overline{\langle X|\beta \rangle}$ in Eq. (A8), where these quantities are normalized by $t^{1/2}$ and by t, respectively, evaluated for 13 values of time t ranging from 0.5 to 30 y (corresponding to 13 sets of connected points shown) and five equally spaced values of β in the range 0.9 to 1.107 (corresponding to each set of five points, which points are here shown connected by simple linear interpolation). The relations are approximately linear for given t, which is useful in numerical calculations (as described in the text), but they are rather nonlinearly related to β.

REFERENCES

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