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William L. Robison
Kenneth T. Bogen
Cynthia L. Conrado

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A Dose Assessment for a U.S. Nuclear Test Site — Bikini Atoll

William L. Robison*, Kenneth T. Bogen, and Cynthia L. Conrado

*Health & Ecological Assessment Division, L-453
Lawrence Livermore National Laboratory, Livermore CA 94550-9900

Tel: (510) 422-3885
Fax: (510) 424-6785

ABSTRACT

On March 1, 1954, a nuclear weapon test, code-named BRAVO, conducted at Bikini Atoll in the northern Marshall Islands contaminated the major residence island. There has been a continuing effort since 1977 to refine dose assessments for resettlement options at Bikini Atoll. Here we provide a radiological dose assessment for the main residence island, Bikini, using extensive radionuclide concentration data derived from analysis of food crops, ground water, cistern water, fish and other marine species, animals, air, and soil collected at Bikini Island as part of our continuing research and monitoring program that began in 1975. The unique composition of coral soil greatly alters the relative contribution of cesium-137 (^{137}Cs) and strontium-90 (^{90}Sr) to the total estimated dose relative to expectations based on North American and European soils. Cesium-137 produces 96% of the estimated dose for returning residents, mostly through uptake from the soil to terrestrial food crops but also from external gamma exposure. The doses are calculated assuming a resettlement date of 1996. The estimated maximum annual effective dose is 4.4 mSv y^{-1} when imported foods, which are now an established part of the diet, are available. The 30-, 50-, and 70-y integral effective doses are 10 cSv, 14 cSv, and 16 cSv, respectively. An analysis of interindividual variability in 0- to 30-y expected integral dose indicates that 95% of Bikini residents would have expected doses within a factor of 3.4 above and 4.8 below the population-average value. A corresponding uncertainty analysis showed that after about 5 y of residence, the 95% confidence limits on population-average dose would be ±35% of its expected value. We have evaluated various countermeasures to reduce ^{137}Cs in food crops. Treatment with potassium reduces the uptake of ^{137}Cs into food crops, and therefore the ingestion dose, to less than 10% of pretreatment levels and has essentially no negative environmental consequencs.

1. INTRODUCTION

Bikini Atoll was one of the two sites in the northern Marshall Islands that was used by the United States as testing grounds for the nuclear weapons program. Twenty-three nuclear tests were conducted from 1946 to 1958. The BRAVO test, on March 1, 1954, had an explosive yield that greatly exceeded expectations, with the result that heavy fallout was experienced at Bikini Island and atolls east of Bikini Atoll. The Bikini people, since their initial relocation to Rongerik Island in 1946, have had a continuing desire to return to their homeland. In 1969 a general cleanup of debris and buildings as well as the planting of coconut, breadfruit, *Pandanus*, papaya, and banana trees began at Bikini Atoll. After a preliminary survey in 1970 Bikini families moved back to Bikini Island.

A radiological survey was conducted in 1975, but few samples of locally grown food crops were available to confidently establish the radionuclide concentrations on Bikini Island to reliably estimate the dose; predictions based on the preliminary data indicated that when food crops matured the body burden of ^{137}Cs and resulting doses would exceed federal guidelines. In 1978, when the coconuts started producing fruits, whole body counting revealed that ^{137}Cs body burdens in the people on Bikini were well above the U.S. recommended level. Consequently, in August 1978 Trust Territory officials arrived at Bikini Island and relocated the people to Kili Island.

A preliminary dose assessment of Bikini Island in 1982, and an earlier dose assessment of Enewetak Atoll, indicated that the most significant potential exposure pathway to the contaminated atolls was the terrestrial food chain [1, 2]. Nearly 95% of the estimated effective dose at Bikini Island results from ^{137}Cs; 90% of the total dose from ^{137}Cs arises from ingestion of ^{137}Cs in terrestrial foods, with the remainder coming from external gamma exposure. We have developed an extensive data base for ^{137}Cs, ^{90}Sr,plutonium-239+240 ($^{239+240}Pu$,) and americium-241 (^{241}Am) concentration in the atoll ecosystem through the sampling of soil, vegetation, animal, ground water, cistern water and marine species in an effort to refine dose assessments for resettlement options at Bikini Atoll. In this report we present the most recent dose estimates, uncertainty in the estimates, and countermeasures designed to reduce the dose to people resettling Bikini Island.

2. EXPOSURE PATHWAYS

The radiological dose to inhabitants at the 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: natural background radiation; nuclear test-related radiation, (2) Internal Exposure: natural background radiation; nuclear test-related radiation — radionuclides in terrestrial foods, marine foods, drinking water and radionuclides inhaled.

The external natural background radiation in the northern Marshall Island Atolls is 3.5 $\mu R\ h^{-1}$ or 0.22 $mSv\ y^{-1}$ [3] due to cosmic radiation; the external background dose due to terrestrial radiation is very low in the Marshall Islands. The internal equivalent dose is about 2.2 $mSv\ y^{-1}$ for natural occurring radionuclides such as Potassium-40 (^{40}K), Polonium-210 (^{210}Po), andLead-210 (^{210}Pb) that result from consumption of local and imported foods. The natural background dose is not included in the doses presented in the paper unless specifically stated.

3. DATA BASES

3.1 *External Exposusre Measurements*

The external exposure rates at Bikini Atoll were measured by EG&G as part of the aerial survey conducted in the 1978 Northern Marshall Islands Radiological Survey (NMIRS) [4]. The average exposure rate on Bikini Island as measured by EG&G in 1978 was abour 31 $\mu R\ h^{-1}$. In 1986 and 1988 additional external gamma measurements were made of ^{137}Cs and cobalt-60 (^{60}Co) inside and outside houses and other buildings, and around the village area; crushed coral placed around the buildings provides sheilding in addition to the buildings. Measurements at Bikini Island indicate that the average exposure inside the houses is about 2.1 $\mu R\ h^{-1}$ while in the immediate area around the houses it is 11 $\mu R\ h^{-1}$.

3.2 *External Beta-Particle Exposure*

The unshielded beta contribution to the external dose was estimated at Enewetak Atoll in 1980 [5]. 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 of 1-m height [6]. Thus, the unshielded beta dose at 1-cm on Bikini Island could be equal to or slightly greater than the external gamma dose. 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. The walls and floors of the houses and the crushed coral customarily put around houses and the village area absorb most of the beta radiation. In addition, any clothing, shoes, zories, *Pandanus* mats, or other coverings also greatly reduce exposure to beta radiation.

3.3 *Airborne Radionuclide Concentrations*

Airborne concentrations of $^{239+240}Pu$ and ^{241}Am are estimated from data development in resuspension experiments conducted at Enewetak Atoll in 1977, Bikini Atoll in 1978, and Rongelap Atoll in 1991. We briefly describe the resuspension methodology here; more detail can be found in Shinn et al.[7]. 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 as a worst-case condition, (3) a study of resuspension of radioactive particles by vehicular and foot traffic, and (4) a study of personal inhalation exposure using small air samplers carried by volunteers during daily routines. The "normal" or "background" mass loading (the mass of solid material per unit volume of air) measured by gravimetric methods for the atolls is approximately 55 $\mu g\ m^{-3}$. The data from the Bikini experiments indicate that 34 $\mu g\ m^{-3}$ of this total is due to sea salt that 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 μg m^{-3}. The highest terrestrial mass loading observed was 136 μg m^{-3} immediately after bulldozing.

Concentrations of $^{239+240}$Pu were determined for collected aerosols (1) for normal ground cover and conditions in coconut groves, (2) for high-activity conditions, i.e., areas being cleared by bulldozers and being tilled, and (3) for stabilized bare soil, i.e., cleared areas after a few days' weathering. The plutonium concentration in the collected aerosols changes with respect to 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 divided by the $^{239+240}$Pu surface-soil (0- to 5-cm) concentration. 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. Similarly, the enhancement factor of 3 for high-resuspension conditions results from the increased resuspension of particle sizes with a higher plutonium concentration than observed in the total 0- to 5-cm soil sample.

We have developed additional personal-enhancement factors (PEF) from personal air-sampler data. These data represent the enhancement that occurs around individuals due to their daily activities. 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 is 2.9 (3.1 × 0.92).

To calculate inhalation exposure, we assume that a person spends 1 h d^{-1} in high-resuspension conditions, 23 h d^{-1} under normal resuspension conditions and has a breathing rate of 23 m^3 per day (1.2 m^3 under high-resuspension conditions and 21.8 m^3 under normal-resuspension conditions). The radionuclide concentrations in surface soil (0- to 5-cm) for Bikini Island complete the information necessary for calculation of plutonium and americium intake through inhalation.

3.4 *Radionuclides in Marine Foods, Soil, and Terrestrial Food*

The average concentrations of ^{137}Cs, ^{90}Sr, $^{239+240}$Pu and ^{241}Am in marine foods and terrestrial foods are listed in Table 1. Most of the data for the marine foods is a result of work conducted by Noshkin et al. [8]. The data for the terrestrial foods are part of our continuing program where samples have been collected and analyzed from 1975 through 1989 on Bikini Island [9]. The number of samples analyzed for drinking coconut meat, drinking coconut juice, copra meat, copra juice, *Pandanus*, breadfruit, papaya, squash, banana and animals are 797, 732, 188, 177, 66, 41, 93, 53, 39 and 36, respectively. The median concentration of ^{137}Cs, ^{90}Sr, $^{239+240}$Pu and ^{241}Am in soil profiles are listed in Table 2. The soil data is also part of our continuing program.

3.5 *Radionuclides in Drinking Water*

The major source of water used in cooking and for drinking is rainwater collected from roofs of houses and other buildings that is stored in cisterns. If extreme drought conditions occur, then the freshest groundwater available is used; the groundwater is contaminated with radionuclides from the soil column. The concentrations of radionuclides in both cistern water and groundwater are listed in Table 1. For the dose estimates, we use an intake of 1 L d^{-1} of drinking water. We assume for the dose assessment that cistern waster is available for 60% of the year and that groundwater is used for 40% of the year. Soda and fruit 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}.

3.6 *Diet*

The 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 others, 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. The diet model we use for estimating the intake of local plus imported foods is presented in Table 1. The basis of this diet model was the survey of the Ujelang

TABLE 1. DIET MODEL FOR ADULTS GREATER THAN 18 YEARS: BIKINI ISLAND, LOCAL FOOD COMPONENT WHEN IMPORTED FOODS ARE AVAILABLE.

				Specific Activity in 1996, in (Bq g^{-1} wet wt.)			
Local Food	Grams d^{-1}	kcal g^{-1}	kcal d^{-1}	^{137}Cs	^{90}Sr	$^{239+240}$Pu	^{241}Am
Reef Fish	24.2	1.40	33.84	3.1×10^{-3}	4.9×10^{-5}	1.3×10^{-5}	6.5×10^{-6}
Tuna	13.9	1.40	19.39	4.8×10^{-3}	5.7×10^{-6}	1.9×10^{-6}	1.3×10^{-6}
Mahi Mahi	3.56	1.10	3.92	4.8×10^{-3}	5.7×10^{-6}	1.9×10^{-6}	1.3×10^{-6}
Marine Crabs	1.68	0.90	1.51	1.5×10^{-3}	9.6×10^{-5}	3.6×10^{-5}	2.6×10^{-5}
Lobster	3.88	0.90	3.49	1.5×10^{-3}	9.6×10^{-5}	3.6×10^{-5}	2.6×10^{-5}
Clams	4.56	0.80	3.65	4.9×10^{-4}	9.3×10^{-5}	8.3×10^{-4}	4.6×10^{-4}
Trochus	0.10	0.80	0.08	4.9×10^{-4}	9.3×10^{-5}	8.3×10^{-4}	4.6×10^{-4}
Tradacna Muscle	1.67	1.28	2.14	4.9×10^{-4}	9.3×10^{-5}	8.3×10^{-4}	4.6×10^{-4}
Jedrul	3.08	0.80	2.46	4.9×10^{-4}	9.3×10^{-5}	8.3×10^{-4}	4.6×10^{-4}
Coconut Crabs	3.13	0.70	2.19	2.7×10^{0}	3.8×10^{-1}	2.6×10^{-4}	1.9×10^{-4}
Land Crabs	0.00	0.70	0.00	2.7×10^{0}	3.8×10^{-1}	2.6×10^{-4}	1.9×10^{-4}
Octopus	4.51	1.00	4.51	2.0×10^{-3}	4.9×10^{-5}	1.3×10^{-5}	6.5×10^{-6}
Turtle	4.34	0.89	3.86	3.0×10^{-4}	4.9×10^{-5}	1.3×10^{-5}	6.5×10^{-6}
Chicken Muscle	8.36	1.70	14.21	7.0×10^{-1}	1.6×10^{-3}	7.7×10^{-6}	6.0×10^{-6}
Chicken Liver	4.50	1.64	7.38	7.0×10^{-1}	1.6×10^{-3}	7.7×10^{-6}	6.0×10^{-6}
Chicken Gizzard	1.66	1.48	2.46	7.0×10^{-1}	1.6×10^{-3}	7.7×10^{-6}	6.0×10^{-6}
Pork Muscle	5.67	4.50	25.52	7.5×10^{0}	1.6×10^{-3}	7.7×10^{-6}	6.0×10^{-6}
Pork Kidney	NR	1.40	0.00	7.0×10^{0}	6.6×10^{-3}	3.5×10^{-5}	1.2×10^{-5}
Pork Liver	2.60	2.41	6.27	3.9×10^{0}	3.1×10^{-3}	1.2×10^{-4}	5.2×10^{-5}
Pork Heart	0.31	1.95	0.60	4.5×10^{0}	1.6×10^{-3}	5.9×10^{-6}	1.8×10^{-5}
Bird Muscle	2.71	1.70	4.61	2.7×10^{-3}	2.5×10^{-4}	1.3×10^{-5}	6.5×10^{-6}
Bird Eggs	1.54	1.50	2.31	7.2×10^{-4}	3.8×10^{-4}	1.3×10^{-5}	6.5×10^{-6}
Chicken Eggs	7.25	1.63	11.82	7.0×10^{-1}	1.6×10^{-3}	7.7×10^{-6}	6.0×10^{-6}
Turtle Eggs	9.36	1.50	14.04	3.0×10^{-4}	4.9×10^{-5}	1.3×10^{-5}	6.5×10^{-6}
Pandanus Fruit	8.66	0.60	5.20	4.5×10^{0}	1.0×10^{-1}	3.2×10^{-6}	3.8×10^{-6}
Pandanus Nuts	0.50	2.66	1.33	4.5×10^{0}	1.0×10^{-1}	3.2×10^{-6}	3.8×10^{-6}
Breadfruit	27.2	1.30	35.31	4.1×10^{-1}	7.4×10^{-2}	1.8×10^{-6}	1.2×10^{-6}
Coconut Juice	99.1	0.11	10.90	1.2×10^{0}	4.9×10^{-4}	1.0×10^{-6}	8.5×10^{-6}
Coconut Milk	51.9	3.46	179.44	5.7×10^{0}	3.4×10^{-3}	1.9×10^{-6}	1.1×10^{-6}
Tuba/Jerkero	0.00	0.50	0.00	5.7×10^{0}	3.4×10^{-3}	1.9×10^{-6}	1.1×10^{-6}
Drinking Coco Meat	31.7	1.02	32.33	3.1×10^{0}	6.3×10^{-3}	2.7×10^{-6}	3.6×10^{-6}
Copra Meat	12.2	4.14	50.30	5.7×10^{0}	3.4×10^{-3}	1.9×10^{-6}	1.1×10^{-6}
Sprout. Coco	7.79	0.80	6.23	5.7×10^{0}	3.4×10^{-3}	1.9×10^{-6}	1.1×10^{-6}
Marsh. Cake	11.7	3.36	39.18	5.7×10^{0}	3.4×10^{-3}	1.9×10^{-6}	1.1×10^{-6}
Papaya	6.59	0.39	2.57	2.4×10^{0}	5.2×10^{-2}	2.5×10^{-6}	3.6×10^{-7}
Spuash	NR	0.47	0.00	1.3×10^{0}	7.3×10^{-2}	2.2×10^{-5}	3.0×10^{-6}
Pumpkin	1.24	0.30	0.37	1.3×10^{0}	7.3×10^{-2}	2.2×10^{-5}	3.0×10^{-6}
Banana	0.02	0.88	0.02	1.9×10^{-1}	5.2×10^{-2}	2.5×10^{-6}	3.6×10^{-7}
Arrowroot	3.39	3.46	13.60	5.8×10^{-2}	7.3×10^{-2}	2.2×10^{-5}	3.0×10^{-6}
Citrus	0.10	0.49	0.05	1.3×10^{-1}	5.2×10^{-2}	2.5×10^{-6}	3.6×10^{-7}
Rainwater	313	0.00	0.00	4.6×10^{-5}	1.6×10^{-5}	3.3×10^{-7}	3.7×10^{-8}
Wellwater	207	0.00	0.00	4.8×10^{-3}	1.3×10^{-3}	6.1×10^{-7}	4.4×10^{-7}
Malolo	199	0.00	0.00	4.6×10^{-5}	1.6×10^{-5}	3.3×10^{-7}	3.7×10^{-8}
Coffee/Tea	228	0.00	0.00	4.6×10^{-5}	1.6×10^{-5}	3.3×10^{-7}	3.7×10^{-8}
Soil[a]	0.10	0.00	0.00	2.8×10^{0}	2.2×10^{0}	4.0×10^{-1}	2.8×10^{-1}
Total Local	1322		547				

[a] Bq g^{-1} dry wt.

TABLE 2. THE MEDIAN CONCENTRATION IN Bq g^{-1} DRY WEIGHT OF ^{137}Cs, ^{90}Sr, $^{239+240}Pu$ AND ^{241}Am IN SOIL AT BIKINI ISLAND.

Soil depth, cm	No. of Samples	^{137}Cs[a]	No. of Samples	^{90}Sr[a]	No. of Samples	$^{239+240}Pu$[a]	No. of Samples	^{241}Am[a]
0–5	242	2.3(2.2)	98	1.5(2.3)	96	0.26(0.44)	220	0.21(0.28)
5–10	241	1.2(1.8)	98	1.7(2.3)	97	0.26(0.46)	213	0.17(0.27)
10–15	238	0.62(1.2)	98	1.6(2.3)	97	0.19(0.42)	190	0.093(0.24)
15–25	233	0.23(1.2)	97	0.91(1.7)	91	0.074(0.25)	139	0.037(0.19)
25–40	231	0.095(0.85)	89	0.58(1.8)	87	0.014(0.32)	111	0.019(0.15)
40–60	178	0.023(0.43)	31	0.34(1.8)	30	0.0069(0.20)	43	0.013(0.19)
0–40	227	0.74(0.86)	89	1.3(1.4)	85	0.18(0.22)	104	0.12(0.13)

[a] Decay corrected to 1996. Number in parentheses is the standard deviation.

community in 1978 by the Micronesian Legal Services Corporation (MLSC) staff and the Marshallese school teacher on Ujelang [10].

4. DOSE METHODOLOGY

4.1 *External Exposure*

4.1.1 Gamma Radiation

The external exposure calculations for gamma radiation are based on measurements made on Bikini Island in 1978 and 1988 that are decay corrected to 1996. The following arbitrary distribution of time was used to develop the average external exposure:

- Nine h d^{-1} are spent in the house where the exposure rate is 2.1 μR h^{-1}.
- Six h d^{-1} around the house and village area where the exposure rate is assumed to be 11 μR h^{-1} (weighted average of outside house and general village sites).
- Seven h d^{-1} in the interior region of the island where the average exposure is 31 μR h^{-1} [4].
- Two h d^{-1} on the beach or lagoon where the exposure is 0.1 μR h^{-1}, based on EG&G data [4].

Although the selection of this particular time distribution is arbitrary, general discussions with Marshallese people and observations while we have been in the islands make the selection reasonable. The resultant contributions of ^{137}Cs to the average equivalent dose from a year's occupancy of various island areas described in the above scenario are: inside houses, 0.015 mSv; elsewhere in the housing and village area, 0.056 mSv; island interior, 0.35 mSv; beaches and lagoon, 55 μSv. The total average external dose attributable to such occupancy in 1996 on Bikini Island is about 0.42 mSv y^{-1}. Natural external background is about 0.22 mSv y^{-1}.

4.1.2 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; consequently, the beta contribution to the total effective dose is extremely small.

4.2 *Internal Exposure*

4.2.1 Cesium-137

The conversion from the intake of ^{137}Cs to the equivalent dose for the adult is based upon the ICRP methods described in ICRP Publications 56, 61 [11, 12], which are based on Leggett's model [13]. The biological half-life of ^{137}Cs is determined as a function of mass (i.e., age) by the methods described in Leggett [13]. In a separate report we estimated the comparative doses between adults and children [14]. 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 at any other age. In this report we calculate only the doses to adults.

4.2.2 Strontium-90

The model developed by Leggett et al.[15] is based on the structure and function of bone compartments as generally outlined in the ICRP model [11]. 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. 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 [15, 16]. Doses listed in this paper are calculated from the Leggett model.

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

We calculated the equivalent dose from ingestion of transuranic radionuclides ($^{239+240}Pu$ and ^{241}Am) by ICRP methods [17, 18]. The amount of ingested plutonium or americium crossing the gut wall to the blood is assumed to be 1×10^{-3} for Pu and Am in vegetation, and 10^{-4} [19] and 10^{-3} for the fraction of Pu and Am, respectively, ingested via soil. Of the fraction of Pu or Am reaching the blood, 45% is assumed to go to bone and 45% to the liver [17, 18]. The biological half-life is 50 y in bone and 20 y in liver for both elements [17]. The quality factor is 20 for the alpha particles from ^{239}Pu, ^{240}Pu, and ^{241}Am. The equivalent 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 [17,11]. The $^{239+240}Pu$ and ^{241}Am are considered class W particles, and the quality factor is 20. Other parameters are as 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.

4.3 *Body Weights and Biological Half-Life of Cesium-137*

Data from Brookhaven National Laboratory (BNL) have been summarized to determine the body weights of the Marshallese people [20, 21, 22, 23, 24]. The average adult male body weight is 72 kg for Bikini, 71 kg for Enewetak, and 69 kg for Utirik. We have used 70 kg as the average male body weight in our dose calculations. The average biological half-life for the long-term compartment for ^{137}Cs in adults is listed as 110 d in ICRP [11] and NCRP [25]. This is consistent with data obtained by BNL on the half-time of the long-term compartment in Marshallese [26, 27]. The distribution of biological half-life in 23 Marshallese adult males is lognormal with a median of 115 d, a mean of 119 d, and a range of 76–178 d. 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.

5. COUNTERMEASURES — MITIGATION OF FOOD-CHAIN DOSE

All remedial actions were evaluated against the criteria of reducing the estimated average maximum annual effective dose to less than the world-wide average background effective dose of 2.4 mSv and the integral 30-y effective dose to less than the federal guideline of 0.05 Sv. A countermeasure is not recommended to the communities for consideration if it cannot lead to doses below these criteria. Moreover, we strived for a countermeasure that would reduce the average maximum annual effective dose to about 1 mSv. Countermeasures evaluated to reduce the dose from ^{137}Cs through the terrestrial food chain include salt water irrigation (leaching), zeolites and mineral clay soil amendments, repeated cropping, soil removal (excavation), and potassium (K) treatment. All but the last two options have been discarded as either less effective or difficult to implement or both.

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 0.24 to 1.3 Bq g^{-1} wet weight, while the ^{137}Cs concentrations in foods grown using potassium-rich fertilizer are less than 0.074 Bq g^{-1} [28]. 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} wet weight to about0.55 to 0.74 Bq g^{-1} wet weight; in those trees where the initial concentration was between 1.9 to 3.7 Bq g^{-1} wet weight, the potassium treatment has reduced the ^{137}Cs concentration to less than 0.37 Bq g^{-1} [28].

Of course, excavation of the top 30 to 40 cm of soil over the whole island also will reduce effectively the potential dose, both external and internal. This option, however, would entail significant 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 centuries to develop and that contains most all of the nutrients needed for plant growth and provides water-retention capacity of the coral soil. Moreover, this would obviously require removing all the mature coconut, breadfruit, *Pandanus*, lime, and other trees that supply food, windbreak, and shade at the island and take years to mature. 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.

6. UNCERTAINTY AND INTERINDIVIDUAL VARIABILITY IN ESTIMATED BIKINI DOSES

Doses estimated as described in Section 4 are based on 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; consequently, predicted dose will necessarily reflect both of these characteristics as well. To characterize such uncertainty and interindividual variability it is necessary to systematically distinguish these attributes as each or both may pertain to each input variate [29, 30, 31, 32]. Below, doses to potential Bikini residents are recalculated using a general method allowing characterization of integrated uncertainty and variability in predicted dose as a function of distributed input variates, that are all assumed to be uncorrelated. The uncertainty and variability in this dose was modeled solely as a function of uncertainty and variability in predicted dose due to ingested ^{137}Cs, since this is clearly the dominant exposure route (see Results). In this approximation, the complex, multicompartment physiological model used above to calculate internal adult dose as a function of ingested ^{137}Cs [11, 33, 13] was replaced by a much simpler, single-compartment model in order to facilitate the Monte Carlo evaluations:

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

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

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

where: $q_{ij}(u)$ 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, $K = \mathrm{Ln}(2)H^{-1}$ 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.

Daily intakes R_{ij} in Bq kg^{-1} d^{-1} of ^{137}Cs in local food items of type j were assumed to be obtained from independent random samples of such items collected n_j days per year from among the possible selections of the type available on Bikini. The corresponding cumulative dose $D(t)$ from all major exposure routes was estimated as

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

where $D_x(t)$ and $D_{in}(t)$ were taken to be deterministic approximations of adult external-gamma and Am+Pu inhalation doses, respectively, and where c is a constant.

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, where angle brackets ($\langle\ \rangle$) denote mathematical expectation only with respect to uncertainty and an overbar denotes expectation only with respect to interindividual variability. These assumptions approximately characterize the empirical data on the value of F obtained for 17 individuals reported by Schwartz and Dunning [34].

Interindividual variability in the biological half-time of the dominant slow compartment, H, was modeled as lognormally distributed based on the data pertaining to 23 Marshallese males indicating a median of 115 d and a geometric standard deviation (SD_g) of 1.23 [10]. 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 [35] reference mean value (used earlier) and on data reviewed by Schwartz and Dunning [34] 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 Bikini residents as of 1966 (assuming imports are available) was taken to be 365 × 12.1 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 12.1 Bq Kg^{-1} d^{-1}. 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 Bikini sources, using LLNL-model-diet assumptions discussed previously along with the information summarized in Table 3 about predicted amounts and measured inter-sample variability of ^{137}Cs in different food items local to Bikini. For the purpose of this analysis, the activities associated with the items listed in this table—which account for ~99% of total ^{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 coefficient of variation, $\gamma_{ij} = \sigma_{R_{ij}} / \langle R_{ij} \rangle$ with respect to presumed dietary sampling error was assumed to be the measured value appearing in column 6 of Table 3, and was assumed to pertain to every individual in the modeled exposed population. The local food items appearing in Table 3 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}).

Finally, a characterization of potential model-uncertainty (i.e., misspecification error) was obtained using information on how well the LLNL model diet predicted BNL measurements of whole-body dose among different samples of Marshallese people tested during the period 1977-1983 (Figure 1, discussed in Section 8). Based on these data, potential model-uncertainty for the LLNL model diet assuming imported foods are available was assumed to be symetrically and triangularly distributed within ± 25% of doses predicted by the LLNL-model-diet.

TABLE 3. DIET MODEL: BIKINI ISLAND (ADULTS > 18 YRS).

Local Food	IA Intake: Local Foods ($g\ d^{-1}$)	^{137}Cs Activity Mean ($Bq\ g^{-1}$)	^{137}Cs Activity SD/Mean (%)	^{137}Cs Intake Imports Available Mean ($Bq\ d^{-1}$)	^{137}Cs Intake Imports Available SD/Mean (%)
Coconut					
Milk	51.9	5.7	65		
Meat	31.7	3.1	73		
Copra Meat	12.2	5.7	65		
Juice	99.1	1.2	78		
Total	194.9	3.0	73	590	73
Pork					
Heart	0.31	4.5	110		
Muscle	5.67	7.5	64		
Liver	2.6	3.9	91		
Total	8.58	6.3	74	54	74
Chicken					
Muscle	8.36	0.70	64		
Liver	4.5	0.70	91		
Gizzard	1.66	0.70	91		
Total	14.52	0.70	75	10	75
Breadfruit	27.2	0.41	56	11	56
Pandanus	9.16	4.5	86	41	86
Sprouting Coconut	7.79	5.7	65	45	65
Papaya	6.59	2.4	134	16	134
Arrowroot	3.93	0.058	41	0.22	41
Pumpkin	1.24	1.3	118	1.6	118
Marsh. Cake	11.7	5.7	65	67	65
Coconut Crabs	3.13	2.7	41	8.4	41
Subtotal	289	2.9		844	
% of Total	22			99	

To characterize uncertainty and interindividual variability in $D(t)$, we performed Monte Carlo evaluations of interindividual variability associated with our model of expected dose $\langle D(t)\rangle$ and of uncertainty associated with our model of corresponding population-average dose $D(t)$ using a general analytical framework for undertaking integrated analysis of uncertainty and interindividual variability [29, 31, 36, 32].

7. RESULTS

The estimated maximum annual and integral effective dose for people resettling Bikini 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. 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 Bikini 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 the results of future observations, and 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 40% from locally grown foods.

The average maximum annual effective dose estimated for residents on Bikini Island is 4.4 mSv^{-1}. The 30-, 50- and 70-y integral effective dose for residents of Bikini Island, for IA, are listed in Table 4. 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 10 cSv, 14 cSv, and 16 cSv, respectively; the same doses for the local foods only diet (IUA) are 20 cSv, 27 cSv, and 32 cSv.

The relative contribution of each of the exposure pathways is presented in Table 5. The dose from the terrestrial food-chain pathway accounts for about 90% 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 people living on Bikini Island. The external gamma exposure is next in significance and contributes about 9% of the 30-y integral effective dose.

Based on the analysis of uncertainty and interindividual variability in predicted dose, it was calculated that the expected value of 30-y integral population-average dose, $\langle D(30) \rangle$ is 9.8 cSv, and

TABLE 4. THE 30-, 50- AND 70-Y INTEGRAL EFFECTIVE DOSE FOR BIKINI ISLAND RESIDENTS WHEN IMPORTED FOODS ARE AVAILABLE (IA).

	Integral effective dose, cSv		
	30 y	50 y	70 y
External	.91	1.3	1.5
Internal			
Ingestion			
^{137}Cs	8.9	12	14
^{90}Sr	0.1	0.15	0.18
$^{239+240}Pu$	0.011	0.028	0.051
^{241}Am	0.0067	0.016	0.028
Inhalation			
$^{239+240}Pu$	0.013	0.032	0.058
^{241}Am	0.0079	0.019	0.032
Total[a]	10	14	16

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

TABLE 5. THE 30-, 50-, AND 70-Y INTEGRAL EFFECTIVE DOSE FOR THE VARIOUS EXPOSURE PATHWAYS.

	Effective integral equivalent dose, cSv		
Exposure pathway	30 y	50 y	70 y
Terrestrial food	9	12	15
External gamma	0.91	1.3	1.5
Marine food	0.0049	0.0098	0.017
Cistern and ground water	0.016	0.023	0.027
Inhalation	0.021	0.051	0.09
Total[a]	10	14	16

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

that the chance that $\langle D(30) \rangle > 47$ cSv is ~1%, e.g., indicating that this is the 30-y dose most likely to be incurred by the highest exposed among 100 hypothetical Bikini residents. The relationship between cumulative exposure time t and interindividual variability in $\langle D(t) \rangle$ (Figure 2a) indicates that the 95% confidence limits on $\langle D(t) \rangle$ variability are ~4.8-fold and ~3.4-fold below and above, respectively, the population-average expected-value function $\langle D(t) \rangle$. The relationship between cumulative exposure time t and the 95% confidence limits of $D(t)$ uncertainty is shown in Figure 2b, which illustrates how uncertainty in $\overline{D}(t)$ is predicted to decrease substantially over time and effectively become independent of time after ~5 y of Bikini residence, by which time residual uncertainty is derived solely from $\overline{F}$, B, and β, and is characterized by confidence limits equal to $\langle D(t) \rangle \pm 35\%$. In particular, the chance that $\overline{D}(30) > 12.5$ cSv is ~5%.

8. VALIDATION OF ENVIRONMENTALLY DERIVED DOSE ASSESSMENT

We assessed the "environmental data/model" approach by comparing our estimates of the body burden (i.e., dose) in people residing on Rongelap Atoll using our environmental data, the models and methods outlined in this paper, and three diet models with the actual whole-body measurements conducted by BNL [37]. Figure 1 shows that the LLNL diet model predicts very closely the results of the whole-body measurements over an eight-year period. Two other proposed diet models lead to estimated body burdens far in excess of those observed by whole-body measurements. Results from Utirik Atoll are similar in that the LLNL diet model predicts actual observation while the other two proposed diets once again significantly exceed the observations.

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 [38]. These two very independent methods are in excellent agreement on the magnitude of the dose from the transuranic radionuclides as shown in Table 6. The estimated average committed effective dose for 50-y residence from Pu based on environmental data and models is 0.4 mSv (0.14 mSv 50-y integral effective dose). The value of 0.40 mSv committed effective dose from urine analyses is based on the detection limit of the analytical method used for detection of Pu in urine. The median value for Pu in the urine of all the people analyzed is below this detection limit value. The people have been living on Rongelap Island for about 28 y subsequent to the fallout from BRAVO where the Pu concentration in the surface soil is about 0.11 Bq g^{-1}. Consequently, both methods indicate that the effective committed dose from Pu at Rongelap Island is below 0.40 mSv for residence between 30 and 50 y.

9. DISCUSSION

9.1 *Comparison of Estimated Doses to Adopted Guidelines and to Background Doses*

To place the magnitude of the estimated doses in perspective, we have compared them to current background dose and 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

TABLE 6. THE AVERAGE COMMITTED EFFECTIVE DOSE FROM Pu AND Am AT RONGELAP ISLAND IN mSv.

	Method	
	Environmental (LLNL)	Urine Analysis (BNL)
Source	Committed effective dose	Committed effective dose
Pu	0.41[a] (0.14)[b]	0.40[c]
Am	0.37 (0.10)	No estimate

[a] Two significant figures to show slight difference between Pu and Am.

[b] Value in parentheses is the 50-y integral effective dose.

[c] Based on the detection limit; actual dose is below this number.

applicable to 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 many provide useful insight for those who must decide on future actions. The National Council on Radiation Protection and Measurements [39] and the International Commission on Radiological Protection [11] have recently recommended an average annual effective dose of 1 mSv y^{-1} to the general public for continuous exposure resulting from operating nuclear industries. The maximum annual effective dose for Bikini Island in 1996, using average values for parameters in the dose model, is 4.4 mSv y^{-1} when imported foods are available. The 30-y integral effective dose for Bikini Island is 0.1 Sv which is about twice the federal guideline for the 30-y integral effective dose of 0.05 Sv for the general population. Additional perspective can be obtained by comparing these estimated doses for Bikini Island with natural background sources in the United States. The average annual effective dose from natural background sources in the United States is about 3 mSv y^{-1}; the breakdown by source is given in NCRP [40]. The world-wide average background effective dose is 2.4 mSv y^{-1} with some areas over 10 mSv y^{-1} [41]. The average maximum annual rate at Bikini Island without countermeasures is about 4 mSv y^{-1}.

The application of K to the surface soil and the subsequent dissolution and transport into the root zone during periods of rainfall is very effective in reducing the concentration of ^{137}Cs in edible foods. 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. This salutary plan, coupled with the soil removal and addition of crushed coral in the housing and village areas, could reduce the average maximum annual dose from about 4.4 mSv to about 0.8 mSv and the estimated 30 y integral effective dose from 10 cSv to about 1.8 cSv. 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.

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Figure 1.

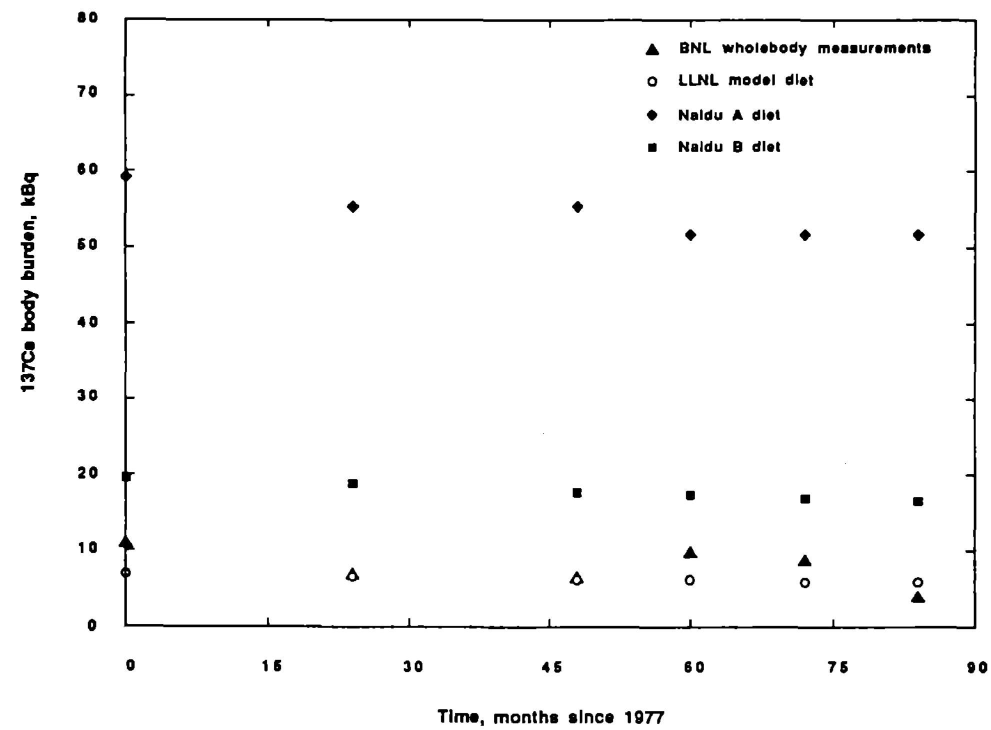

Figure 2a.

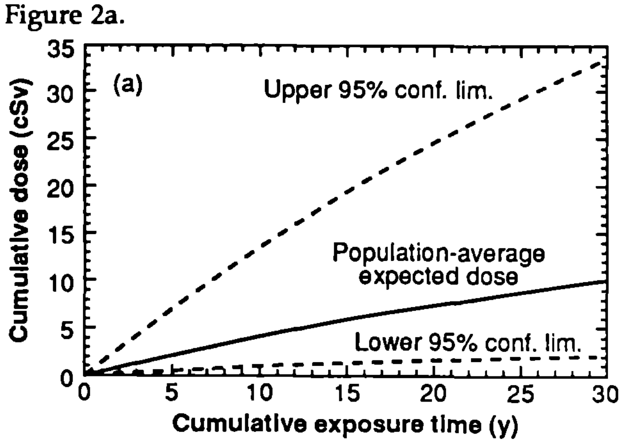

Figure 2b.

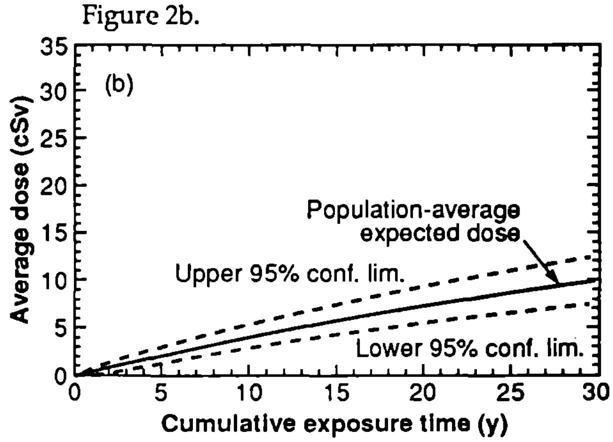

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Figure 1. A comparison of body burden estimates from environmental data and models with direct whole-body measurements for residents of Rongelap Island.

Figure 2a. Confidence limits reflecting interindividual variability in the expected value (with respect to uncertainty), $\langle D(t) \rangle$, of cumulative dose by time t to hypothetical adult Bikini residents beginning in 1966.

Figure 2b. Confidence limits reflecting uncertainty in the corresponding population-average dose $\overline{D(t)}$.