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# Estimates of the Radiological Dose from Ingestion of $^{137}Cs$ and $^{90}Sr$ to Infants, Children, and Adults in the Marshall Islands

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# Radionuclide Intake

## Diet

We will first discuss the adult diet model currently used in our dose assessments because the fetus and infant dose will be dependent on the intake of radionuclides by the mother.

### Adult (≥ 18 y)

The estimated average intake of local foods, i.e., those grown on the atoll, and imported foods, i.e., those brought in from outside the contaminated atoll, is a very important parameter in the dose assessment; radiological dose is directly proportional to the total intake of $^{137}Cs$ and $^{90}Sr$, which is proportional to the quantity of locally grown foods that are consumed at a contaminated atoll. Therefore, a reasonable estimate of the average daily consumption rate of each food item is essential. There is in general, however, a paucity of data available to develop a diet model at the atolls.

The diet model we use for estimating the intake of local and imported foods is presented in Robison et al. (1980 and 1987). The model results for the case where imported foods are available are summarized in Table 1. The basis of this diet model was the survey of the Ujelang community in 1978 by the Micronesian Legal Services Corporation (MLSC) staff and the Marshallese school teacher on Ujelang; details of the MLSC diet summary are presented in our 1980 dose-assessment paper (Robison et al., 1980). This survey is the best estimate of the current dietary practices of the Enewetak people. Data are presented for women, men, teenagers, and children. Adult intake exceeded those 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, however, indicative of the acknowledged uncertainty in the dietary estimates. Nevertheless, we believe that the MLSC survey provides a reasonable basis for estimating dietary intake. Pending the availability of empirical data, we have chosen to use the higher (female) diet for 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 is higher in the Brookhaven National Laboratory (BNL) diet than in our diet model (Naidu et al., 1980); 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 intakes estimated by the BNL is also discussed in the 1980 report (Robison et al., 1980). When the estimated body burdens from both our dose model using the MLSC diet and the BNL diet are compared to actual whole-body measurements of the Rongelap and Utirik people made by another BNL team, the MLSC diet predicted observed body burdens better than the BNL diet (Robison, 1983; Robison et al., 1987). 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 Table 2.

Further support of our diet model is found in the estimates of coconut consumption. The coconut, at many stages of growth, is the food product that is of major significance and dominates the potential exposure of people. The current estimate of consumption of coconut meat and fluid in our diet model, which is 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 on living habits at outer atolls (DeBrum, 1985). Based on data published by Mary Muari in 1954, the average intake of

Table 1. **Dietary intake of local and imported foods used in the dose assessments.**

| Food | Children 1.5–3 years grams/d | 4–11 years grams/d | Teenage 12–17 years grams/d | Adult > 18 y grams/d |
|---|---|---|---|---|
| | Dietary intake of local foods when imports are available | | | |
| Reef fish | 7.66 | 13.8 | 15.6 | 24.2 |
| Tuna | 9.04 | 12.1 | 15.0 | 13.9 |
| Mahi mahi | 3.84 | 3.76 | 5.44 | 3.56 |
| Marine crabs | NR | 0.09 | 0.40 | 1.68 |
| Lobster | 1.33 | 4.48 | 2.66 | 3.88 |
| Clams | 1.60 | 4.65 | 8.12 | 4.56 |
| Trochus | NR | NR | 0.35 | 0.10 |
| Tridacna muscle | 0.49 | 1.53 | 1.09 | 1.67 |
| Jedrul | 1.25 | 3.47 | 1.47 | 3.08 |
| Coconut crabs | 1.98 | 2.23 | 3.51 | 3.13 |
| Land crabs | NR | NR | 0.16 | NR |
| Octopus | 1.66 | 2.14 | 6.17 | 4.51 |
| Turtle | 0.67 | 1.54 | 2.77 | 4.34 |
| Chicken muscle | 1.65 | 5.49 | 5.79 | 8.36 |
| Chicken liver | 1.78 | 2.70 | 2.57 | 4.50 |
| Chicken gizzard | NR | NR | 0.12 | 1.66 |
| Pork muscle | 2.58 | 3.90 | 3.52 | 5.67 |
| Pork kidney | NR | NR | NR | NR |
| Pork liver | 1.08 | 1.15 | 2.71 | 2.60 |
| Pork heart | NR | NR | NR | 10.6 |
| Bird muscle | 1.15 | 2.82 | 6.51 | 2.71 |
| Bird eggs | 0.19 | 0.24 | 6.42 | 1.54 |
| Chicken eggs | 2.02 | 5.12 | 3.03 | 7.25 |
| Turtle eggs | 1.01 | 1.26 | 1.87 | 9.36 |
| *Pandanus* fruit | 9.84 | 4.40 | 6.12 | 8.66 |
| *Pandanus* nuts | 0.35 | 0.83 | 0.56 | 0.50 |
| Breadfruit | 9.90 | 9.41 | 17.8 | 27.2 |
| Coconut juice | 46.6 | 44.9 | 64.3 | 99.1 |
| Coconut milk | 31.1 | 37.1 | 57.2 | 51.9 |
| Tuba/Jekero | 0.80 | NR | NR | NR |
| Drinking coco meat | 16.9 | 12.5 | 26.3 | 31.7 |
| Copra meat | 3.40 | 6.12 | 15.3 | 12.2 |
| Sprouting coconut | 14.3 | 7.23 | 5.01 | 7.79 |
| Marsh. cake | 4.65 | 11.0 | 7.65 | 11.7 |
| Papaya | NR | 5.62 | NR | 6.59 |
| Squash | NR | NR | NR | NR |
| Pumpkin | 0.04 | 0.04 | 4.01 | 1.24 |
| Banana | 0.02 | NR | NR | 0.02 |
| Arrowroot | 0.24 | 0.10 | NR | 3.93 |

**Table 1. (Continued)**

| Food | Children 1.5–3 years grams/d | Children 4–11 years grams/d | Teenage 12–17 years grams/d | Adult > 18 y grams/d |
|---|---|---|---|---|
| Citrus | NR | NR | NR | 0.10 |
| Rainwater | 166 | 204 | 206 | 313 |
| Wellwater | 115 | 139 | 139 | 207 |
| Malolo | 122 | 191 | 106 | 199 |
| Coffee/tea | 161 | 137 | 190 | 228 |
| Total Local Foods | 743 | 883 | 940 | 1332 |
| Fluids | 611 | 716 | 705 | 1046 |
| Solids | 132 | 167 | 235 | 286 |
| | Dietary intake of imported food | | | |
| Baked bread | 10.5 | 21.1 | 23.5 | 30.3 |
| Fried bread | 26.2 | 43.5 | 52.8 | 72.0 |
| Pancakes | 25.2 | 38.4 | 43.7 | 59.5 |
| Cake | 1.54 | 1.23 | 1.68 | 2.64 |
| Rice | 97.0 | 154 | 211 | 234 |
| Instant mashed potatoes | 49.0 | 80.3 | 135 | 127 |
| Sugar | 44.9 | 55.7 | 67.6 | 65.2 |
| Canned chicken | 9.13 | 7.42 | 5.35 | 12.97 |
| Corned beef | 21.7 | 56.3 | 72.0 | 78.7 |
| Spam | 19.1 | 32.2 | 46.1 | 55.0 |
| Canned mackerel | 14.7 | 32.1 | 34.5 | 44.0 |
| Canned sardines | 11.8 | 29.7 | 41.8 | 42.5 |
| Canned tuna | 17.0 | 38.5 | 48.6 | 59.0 |
| Canned salmon | 0.11 | NR | NR | NR |
| Other canned fish | NR | NR | NR | NR |
| Other meat, fish, or poultry | NR | 48.7 | NR | NR |
| Carbonated drinks | 171 | 227 | 286 | 338 |
| Orange juice | 68.1 | 100 | 118 | 188 |
| Tomato juice | 15.6 | 45.7 | 69.5 | 99.5 |
| Pineapple juice | NR | 148 | 155 | 178 |
| Other canned juice | 3.20 | 0.95 | NR | 25.4 |
| Evaporated milk | 103 | 137 | 154 | 201 |
| Powdered milk | 19.7 | 61.1 | 93.4 | 72.9 |
| Whole milk | NR | NR | 0.00 | 0.00 |
| Canned butter | NR | NR | NR | 0.00 |
| Onion | NR | 0.06 | 0.00 | 0.00 |
| Canned vegetables | 24.4 | NR | NR | NR |
| Baby food | 68.2 | NR | NR | NR |

Table 1. (Continued)

| Food | Children 1.5–3 years grams/d | Children 4–11 years grams/d | Teenage 12–17 years grams/d | Adult > 18 y grams/d |
|---|---|---|---|---|
| Cocoa | NR | NR | NR | 178 |
| Ramen noodles | NR | NR | 6.07 | 6.07 |
| Candy | 0.53 | 0.53 | NR | NR |
| Total Imported Food | 822 | 1359 | 1666 | 2168 |
| Fluids | 381 | 720 | 876 | 1281 |
| Solids | 441 | 639 | 790 | 887 |
| Total Local and Imported Foods | 1565 | 2242 | 2606 | 3500 |
| Fluids | 992 | 1436 | 1581 | 2327 |
| Solids | 573 | 806 | 1025 | 1173 |

Note: NR stands for no response.
[a] Data from Robison et al. (1982a), Appendix A.

coconut products was drinking coconut fluid, 95 mL/d; copra meat, 48 g/d; and drinking coconut meat, 10 g/d; 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. In addition, the Bikini Atoll Rehabilitation Committee (BARC) recently asked the Bikini people for a survey on coconut consumption at Kili Island and Majuro (BARC, 1986). The result of this limited survey was that coconut consumption was about one-third that indicated in the MLSC diet listed in Table 1. 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. Finally, recent data from Eneu Island shows 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/d were all drinking nuts, the average intake would be about 160 g/d. This is in agreement with the results from the MLSC survey at Ujelang. Experience at Enewetak Atoll also supports our model. During the past 2 or 3 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; some were discarded or fed to pigs, 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 somewhat higher than that from most 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. Table 3 lists a summary of the grams per day (g/d) intake in our diet model compared with average U.S. and Japanese diets.

Table 2. Comparison of predicted and measured body burdens of $^{137}Cs$ for three atolls in the Marshall Islands.

| | Predicted $^{137}Cs$ adult body burdens in μCi | | | Measured $^{137}Cs$ body burdens in μCi in 1978[b] |
|---|---|---|---|---|
| | LLNL diet model | | | |
| Atoll | Imports available | Imports unavailable | BNL diet[a] | |
| Bikini | 5.5 | 11 | ~20 | 2.4 (M); 1.7 (F) |
| Rongelap | 0.19 | 0.42 | 0.58 | 0.17 (A) |
| Utirik | 0.043 | 0.098 | 0.18 | 0.053 (A) |

[a] Naidu et al., 1981.

[b] (M) stands for male, (F) stands for female, and (A) stands for adult; BNL data, (Lessard et al., 1980a, 1980b; Miltenberger et al., 1980).

Also listed are the kilocalories per day (kcal/d) intake for the diet model when imported foods are both available and unavailable.

The intake of 1450 g/d including milk products in our diet model when imported foods are available is higher by about 200 to 400 g/d than the results from the U.S. and Japan surveys. The 3003 kcal/d in the diet model exceeds the U.S. average by a little more than 1000 kcal/d. The average recommended allowances for caloric intake range from 2000 to 3200 kcal/d, and individual recommended allowances from 1600 to 4000 kcal/d (Committee for Revision of the Canadian Dietary Standard, 1964; Food and Agricultural Organization, 1957; ICRP, 1975; National Academy of Science, 1980). It appears that the U.S. population average intake seldom reaches these high recommended levels.

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 intake or for total daily calories consumed. It appears likely that the overall error is in the conservative direction of overestimating total intake.

The estimates for "Imported Foods Unavailable" scenario (Tables 2 and 3) are based upon the assumption that no imported foods are available; that is, people would consume only local foods for their entire lifetime. Our observation is that in today's world this is quite unrealistic. The demand is present, suppliers and commercial transport are available, and the people have cash in hand. Even though resupply schedules may be somewhat erratic, inventories of imported foods are expected to be such that the total absence of imported foods from the diet is most unlikely.

A final consideration for the diet model is the predicted amount of calcium. Dietary calcium has to be considered because most models for $^{90}Sr$ dosimetry depend on strontium/calcium ratios (Papworth and Vennart, 1973, 1984; Bennett, 1973, 1977, 1978; Cristy et al., 1984; Leggett et al., 1982). Generally, the models are designed based on the assumption that the daily intake of calcium is about 0.9 g, as it is in the United States and Europe. The estimated calcium intake for the diet model is 0.85 g/d, which we believe validates the applicability of the model for $^{90}Sr$ dosimetry.

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

1. Coconut meat and fluid consumption is the major source of $^{137}Cs$ intake in the diet model; the diet model does predict the $^{137}Cs$ burden observed in actual whole-body counting of the adult population for two atolls.
2. The dietary habits are, to a degree, atoll specific and should be generalized from one atoll to another only when

**Table 3. Comparison of the average adult diet model for the Northern Marshall Islands with the average adult diet for the United States and for Japan.**

| | Average adult diet model for the Northern Marshall Islands | | Average adult diet for the United States | | | Average adult diet for Japan | |
|---|---|---|---|---|---|---|---|
| | Imports available | Imports unavailable | Yang and Nelson, 1986 | Abraham et al., 1979 | Rupp, 1980 | Hisamatsu et al., 1987 | Japan's Ministry of Health[a] |
| Food intake, g/d | 1450 | 900 | 1066 | — | 1232 | 1253 | 1352 |
| Fluid intake, g/d | 2326[b] | 758 | 1526 | — | 1351 | — | — |
| Caloric intake, kcal/d | 3231 | 1256 | 1853 | 1925 | — | — | — |

[a] Reported by Hisamatsu et al. (1987).

[b] Milk is listed under both food and fluid intake.

supporting atoll-specific data are unavailable.

3. There is still some uncertainty about what the 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.
6. Even though there is some uncertainty in the precise adult diet at an atoll, the relative difference in average intake between adults and infants and children are consistent between the two surveys (Robison et al., 1980; Naidu et al., 1980).

**Teenage (12 to 17 y)**

The average total daily intake of food for this age is very similar to that of adults. Although the average intake is somewhat less than for adults, some individuals at the older end of the age group may well exceed the average adult intake (Robison et al., 1980).

**Children (4 to 11 y)**

At this age, the children are essentially on a diet similar to that of the adults. The intake of drinking coconut fluid and coconut milk may approach that for adults, but diet surveys indicate it to be less (Robison et al., 1980; Naidu et al., 1980). Consumption of other food products, both local and imported, is less than that of adults (Robison et al., 1980; Naidu et al., 1980).

**Children (1.5 to 3 y)**

At about 1.5 y, children are weaned from breast- or bottle-feeding with mixtures of soft rice and tea, or flour boiled in water and mixed with tea, and/or foods cooked for longer periods of time to make them softer in texture (Marsh, 1973; Pollock, 1974). Flaherty (1988) mentions that rice or flour-tea mixtures are preferred even if local dishes such as *Pandanus* pudding and breadfruit soup are available. This weaning leads to a diet by about age 2 that is similar in composition to the adult diet, but with total intake being significantly less than that for teenagers or adults (Robison et al., 1980, 1982a;

Naidu et al., 1980). The relative difference in intake between the 1.5-y to 3-y age group and adults is nearly the same for both major diet surveys (Robison et al., 1980; Naidu et al., 1980).

**Infant/Child (9 months to 1.4 y)**

Both breast-fed and bottle-fed infants, starting around 9 months, occasionally are given small amounts of soft crab, fish, breadfruit, papaya, and pumpkin (Marsh, 1973; Pollock, 1974; Hinshaw, 1988). These additional local foods would probably be no more than 20% of the adult intake.

**Infants (4 to 8 months)**

The diet of infants 4 to 8 months old in the Marshall Islands varies depending on a mother's preference and the mixture of locally grown and imported foods applicable to a specific atoll. In general, however, infants are usually breast-fed for the first 12 to 18 months, and sometimes for as long as 2 years (Marsh, 1973; Pollock, 1974; Flaherty, 1988; Hinshaw, 1988). Bottle-fed babies occasionally are given coconut fluid or milk if formula becomes scarce and breast-fed babies may also be given small quantities of coconut milk.

In summary, the infant (4 to 8 months) diet in the Marshall Islands consists primarily of milk either by breast-feeding or bottle-feeding with occasional, small supplements of coconut milk or coconut fluid.

**Infant (0 to 3 months)**

The diet of infants in the Marshall Islands varies depending on a mother's preference. Infants are either breast-fed, which is the most usual case, or they are bottle-fed with formula and evaporated milk (Marsh, 1973; Pollock, 1974; Flaherty, 1988; Hinshaw, 1988). Our general observation is that the use of formula and evaporated milk for feeding infants has increased over the past few years. In either case, the total diet consists of one or the other over the first 3 to 4 months.

## Radionuclide Concentrations in Local Foods at Rongelap Island

The concentrations of radionuclides in foods at Rongelap Island at Rongelap Atoll are listed in Table A-1.

The listed concentrations are from the Northern Marshall Islands Radiological Survey completed in 1978 and additional sampling done by LLNL in 1985 and 1986.

## Intake of $^{90}Sr$ and $^{137}Cs$ from Ingestion of Local Foods

**Strontium-90**

**Newborn/Fetus.** Work conducted during the height of the atmospheric nuclear testing program, when $^{90}Sr$ in milk was of concern, indicates that the $OR^{\frac{newborn/fetus}{adult}} = 0.5$, where the OR is a term coined by Comar et al. (1956), and is defined as the ratio of the pCi $^{90}Sr$ per g of calcium in a target organ divided by the pCi $^{90}Sr$ per g of calcium in a reference source. In other words, the discrimination against strontium compared to calcium across the placental barrier is about a factor of 2 (Bryant and Loutit, 1964; Comar et al., 1965; Kawamura et al., 1986; Tanaka et al., 1981). Furthermore, the $OR_{\frac{adult}{adult\ diet}} = 0.25$ (Bryant and Loutit, 1964; Comar et al., 1965). Consequently, the $OR_{\frac{newborn}{adult\ diet}}$, which includes the discrimination across the placental barrier, is $0.25 \times 0.5 = 0.13$ (Bryant and Loutit, 1964; Lenihan, 1967; Comar et al., 1965).

The $OR^{\frac{newborn}{adult}}$ of 0.5 means that half as much $^{90}Sr$ per g of calcium is present in the newborn/fetus as the adult, and the dose received by the newborn/fetus will be a combination of this lesser $^{90}Sr$ concentration and the difference in dosimetry for a fetus versus an adult.

**Infant (0 to 3 months).** As was discussed in the diet section, the major source of food for infants through about 3 months is either breast milk or formula. Formulas are imported and contain very low concentrations of $^{90}Sr$ representative of worldwide background concentrations.

The concentration of $^{90}Sr$ in breast milk may be determined from the OR. The $OR^{\text{mothers' milk}}_{\text{adult diet}}$ has been reported to be 0.10 (Lough et al., 1960; Comar, 1967), indicating a discrimination across the mammary barrier similar to that across the placental barrier. The OR is based upon the $^{90}Sr$ per g of calcium and consequently is not directly of use in dose calculations. The total g of calcium in the reference and target must be known so that the total amount of $^{90}Sr$ transferred from a specific source to a specific target can be determined.

A more convenient form for the data for dose calculations to infants using current models is the $^{90}Sr$ concentration per kg of mothers' milk based on the mothers' dietary intake. The average percentage of $^{90}Sr$ ingested that is secreted per kg of milk was determined to be 0.31% for 4 women (Lough et al., 1960). Using this average value for the percentage of $^{90}Sr$ ingested that is secreted in milk and the average $^{90}Sr$ daily intake of 14 pCi/d at Rongelap Atoll for women, the concentration of $^{90}Sr$ per kg (~1 L) of milk would be 0.043 pCi/kg.

Thus, assuming that an infant's diet is about 1.3 L/d of milk, the daily intake of $^{90}Sr$ from birth through 3 months would be 0.056 pCi/d.

The $OR^{\text{infant}}_{\text{diet}}$ in the first few months after birth is about 0.9 (Comar et al., 1965; Bryant and Loutit, 1964; Lough et al., 1963; Comar, 1967); that is, the infant nearly equilibrates with his diet. The $OR^{\text{body}}_{\text{diet}}$ changes to about 0.5 by 1 y (Bryant and Loutit, 1964; Comar, 1967; Kawamura et al., 1986) and levels out at about the adult value of 0.25 by age 3 to 5 y (Lough et al., 1960, 1963; Comar et al., 1965; Comar, 1967; Burton and Mercer, 1962). This type of information has been incorporated in the retention model discussed later in the paper.

**Infant (4 to 8 months).** We assume that infants from 4 to 8 months occasionally receive diluted coconut milk to supplement or replace the milk from breast- or bottle-feeding. For a daily total intake of 1.3 L/d, we assume that, on the average, 95% of the daily intake is breast milk and 5% is a mixture of equal parts coconut milk and water. Consequently, the daily intake of $^{90}Sr$ from 4 to 8 months would be

$$
\begin{aligned}
&0.043\ \text{pCi/L}\ (0.95)\ 1.3\ \text{L/d} \\
&+ 0.016\ \text{pCi/mL} \frac{(0.05)}{2}\ 1300\ \text{mL/d} \\
&= 0.053\ \text{pCi/d} + 0.52\ \text{pCi/d} \\
&= 0.57\ \text{pCi/d}\ ,
\end{aligned}
$$

where the concentration of $^{90}Sr$ in coconut milk at Rongelap Island is 0.016 pCi/mL and in breast milk is 0.043 pCi/L.

**Infant/Child (9 months to 1.4 y).** At about age 9 months to 1.5 y, small quantities of local foods are given to the infants to supplement breast-feeding. The estimated $^{90}Sr$ intake from consumption of local foods is assumed to be 20% of the adult intake and is 2.8 pCi/d. Thus, the daily intake of $^{90}Sr$ is assumed to go from the 4- to 8-month-old value of 0.57 pCi/d to about 3.4 pCi/d.

**Child (1.5 y to 3 y).** The average daily intake of $^{90}Sr$ for the 1-y to 3-y age group from our diet model is 9.2 pCi/d (Appendix A, Table A-2).

**Child (4 y to 11 y).** The average daily intake of $^{90}Sr$ for children 4-y to 11-y old from our diet model when imported foods are available is 8.2 pCi/d (Appendix A, Table A-3).

**Teenage (12 y to 17 y).** The average daily intake of $^{90}Sr$ for teenagers from our diet model when imported foods are available is 11 pCi/d (Appendix A, Table A-4).

**Adult (≥ 18 y).** The average daily intake of $^{90}Sr$ for adults from our diet model when imported foods are available is 14 pCi/d (Appendix A, Table A-1).

The daily intakes of $^{90}Sr$ for the various age groups, based on the data and assumptions described above, are summarized in Table 4.

**Table 4. Estimates of the daily intake of $^{90}Sr$ from local foods by age at Rongelap Atoll.**

| Age | $^{90}Sr$ intake, pCi/d |
|---|---|
| 0 to 3 months | 0.056 |
| 4 to 8 months | 0.57 |
| 9 months to 1.4 y | 3.4 |
| 1.5 y to 3 y | 9.2 |
| 4 y to 11 y | 8.2 |
| 12 y to 17 y | 11 |
| ≥ 18 y | 14 |

### Cesium-137

**Newborn/Fetus.** The concentration of $^{137}Cs$ in the fetus in the early months of pregnancy appears to be less than that of the mother (Iinuma et al., 1969) and about equal to that of the mother in the latter months of pregnancy and at birth (Iinuma et al., 1969; Wilson and Spiers, 1967). Thus, the average concentration of $^{137}Cs$ during the entire gestation period would appear to be somewhat less than that of the mother.

**Infant (0 to 3 months).** The entire diet for this age range is essentially breast milk or formula. Measurements of $^{137}Cs$ in breast milk and in the diet of a 24-y-old woman show that about 30% of the ingested $^{137}Cs$ is secreted per L of milk (Aarkrog, 1963). Consequently, with the infant diet being breast milk, the intake of $^{137}Cs$ by an infant would not exceed the adult intake. In fact, measurements of $^{137}Cs$ in the infants and their mothers show that the concentration of $^{137}Cs$ in infants on breast milk never exceeded the $^{137}Cs$ concentration in their mothers (Rundo, 1970); the infant's $^{137}Cs$ concentration, on the average, was 75% of the mother. Using the value of 30% for the $^{137}Cs$ ingested that is secreted per L of milk and the average adult intake of 1085 pCi/d, the $^{137}Cs$ concentration in breast milk would be 326 pCi/L. If the average milk intake by the infant is 1.3 L/d, the average daily intake of $^{137}Cs$ for an infant is 424 pCi/d.

**Infant (4 to 8 months).** For infants between 4 and 8 months, we assume that diluted coconut milk is given occasionally to supplement or replace breast milk. On the average, breast milk accounts for 95% of the 1.3 L/d intake and a mixture of equal parts water and coconut milk make up the other 5%. The daily intake of $^{137}Cs$ is thus:

$$
\begin{aligned}
&326\ \text{pCi/L}\ (0.95)\ 1.3\ \text{L/d} \\
&+ 1300\ \text{mL/d}\frac{(0.05)}{2}\ 4.7\ \text{pCi/mL} \\
&= 403\ \text{pCi/d} + 153\ \text{pCi/d} \\
&= 556\ \text{pCi/d}\ ,
\end{aligned}
$$

where the $^{137}Cs$ concentration in coconut milk is 4.7 pCi/mL and in breast milk is 325 pCi/L.

**Infant/Child (9 months to 1.4 y).** Breast milk or formula is still the main food source for infants/children in this age group, but small amounts of local foods are given to the infants to supplement the milk. We assume the $^{137}Cs$ intake to be no more than 20% of the adult intake. Consequently, the $^{137}Cs$ intake from breast and coconut milk is 556 pCi/d, as for infants 4 to 8 months (see above), plus 217 pCi/d (0.20 x 1085 pCi/d) from local foods, for a total daily intake of 773 pCi.

**Child (1.5 y to 3 y).** The average daily intake of $^{137}Cs$ for children aged 1.5 y to 3 y from our diet model when imported foods are available is 517 pCi/d (Appendix A, Table A-2).

**Child (4 y to 11 y).** The average daily intake of $^{137}Cs$ from our diet model for children aged 4 y to 11 y, when imported foods are available, is 594 pCi/d (Appendix A, Table A-3).

**Teenage (12 y to 17 y).** The average daily intake of $^{137}Cs$ for teenagers from our diet model when imported foods are available is 761 pCi/d (Appendix A, Table A-4).

**Adult (≥ 18 y).** The average daily intake of $^{137}Cs$ for adults is obtained from our diet model. When imported foods are available, the intake is 1085 pCi/d (specific data are presented in Appendix A, Table A-1).

A summary of the $^{137}Cs$ intake by age group is given in Table 5.

**Table 5. Estimates of the daily intake of $^{137}Cs$ from local foods by age group at Rongelap Atoll.**

| Age | $^{137}Cs$ intake, pCi/d |
|---|---|
| 0 to 3 months | 424 |
| 4 to 8 months | 556 |
| 9 months to 1.4 y | 773 |
| 1.5 y to 3 y | 517 |
| 4 y to 11 y | 594 |
| 12 y to 17 y | 761 |
| ≥ 18 y | 1085 |

# Retention of $^{137}Cs$ and $^{90}Sr$

## Cesium-137

### Fetus

The fetus is assumed to be in dynamic equilibrium with the mother. Experimental results indicate that in the first few months of pregnancy the ratio of the $^{137}Cs$ concentration in mothers to that in the fetus is 3:1, changing to about 1:1 in last months (Iinuma et al., 1969; Nagai, 1970). Consequently, the dose received by the fetus should be no more and perhaps less than that received by the adult mother (Iinuma et al., 1969; Nagai, 1970).

In addition, the biological half-life of $^{137}Cs$ is shorter in pregnant women than in nonpregnant women, leading to lesser body burdens in pregnant women (Bengtsson et al., 1964; Zundel et al., 1969; Godfrey and Vennart, 1968). Consequently, the dose to pregnant women would be less than to nonpregnant women. Based on data presented by Iinuma et al. (1969), the dose to the fetus would be about half that calculated for an adult.

### Infants, Children, Adolescents, and Adults

It is assumed that when $^{137}Cs$ is ingested, 100% of the $^{137}Cs$ crosses the gut and enters the blood, i.e., $F_1$ = 1.0 (NCRP, 1977; ICRP, 1979). The loss of $^{137}Cs$ from the body is then generally represented by a two-compartment, exponential model, where for adults the short-term compartment has a biological half-life ($T^{1/2}$) for $^{137}Cs$ of 2 d for both males and females, and the long-term compartment a $T^{1/2}$ of 110 d and 85 d for males and females, respectively (ICRP, 1979; NCRP, 1977; Richmond et al., 1962). In some cases, the loss of $^{137}Cs$ is better represented by a three-compartment model (Leggett et al., 1984), but generally the short-term compartment in the two-compartment model represents an average of compartments with half-lives the order of a few hours, a few days, and 1 or 2 weeks. The fractional deposition of $^{137}Cs$ in the model for the short- and long-term compartments for adults is 0.10 and 0.90, respectively (ICRP, 1979; NCRP, 1977). These fractional depositions and half-lives represent a model for an average adult around which particular individuals will vary.

The long-term compartment is the most significant compartment for dose assessment, and there is abundant evidence in the literature that shows the long-term $T^{1/2}$ changes dramatically with age from birth to adulthood (Lloyd et al.,, 1966, 1970; Wilson and Spiers, 1967; Boni, 1969; Iinuma et al., 1969; Weng and Beckner, 1973; Lloyd, 1973; Cryer, 1972; Karcher et al., 1969; Richmond et al., 1962). The $T^{1/2}$ for $^{137}Cs$ ranges from 10 to 12 d in infants (Wilson and Spiers, 1967; Lloyd, 1966), to 20 to 50 d for children (Karcher et al., 1969; Boni, 1969; Naversten, 1964; Bengtsson et al., 1964; Lloyd et al., 1966, 1970), and to 110 d and 85 d for adult men and women (Richmond et al., 1962; Van Dilla, 1965; Boni, 1969; Lloyd, 1966; Lloyd et al., 1970; ICRP, 1979; NCRP, 1977). Leggett (Leggett, 1987) indicates that the long-term $T^{1/2}$ is about 22 d for newborns, decreases to about 13 d by 1 y, and then begins to increase again to about 30 d by 5 y.

In addition to the change in $T^{1/2}$ with age, the fractional deposition of $^{137}Cs$ in the short- and long-term compartments also changes (Leggett et al., 1984). The fractional deposition for newborns is 0.5 in the short-term compartment and 0.5 in the long-term compartment; this gradually changes to 0.10 and 0.90 for the short- and long-term compartments, respectively, for adults. Table 6, abstracted from Leggett (1987), shows the change with age for the total body potassium, fractional deposits, and $T^{1/2}$.

Models have been proposed indicating that the long-term $T^{1/2}$ for $^{137}Cs$ is correlated with age (Boni, 1969; McCraw, 1965; Weng and Beckner, 1973; Fisher and Snyder, 1967), body weight (Eberhardt, 1967; Cryer, 1972), and sex (Clemente et al., 1971; Boni, 1969). However, Lloyd (1973) has indicated that the correlation with body weight and age is only significant when infants, juveniles, and teenagers are included and that there is no correlation with either for adult males or adult females (Karcher, 1973; Cryer, 1972). The only significant difference in $T^{1/2}$ among adults is that between males and females where there is a distinct difference in the average body weight (Lloyd, 1973; NCRP, 1977; ICRP, 1979). The average biological half-life for $^{137}Cs$ in Japanese males, whose average body weight is significantly less than for U.S. and European males, was determined to be about 85 d (Uchiyama et al., 1969; Fujita, 1966). Lloyd indicates that it is more likely that the $T^{1/2}$ for $^{137}Cs$ is correlated with some other factor common to age, body weight, and sex.

Leggett (1986, 1987) has recently shown that the strongest correlation for the biological half-life of $^{137}Cs$ appears to be with the total amount of potassium (K) in the body. The model proposed by Leggett is the standard two-compartment model of the form:

$$A(t) = a\, e^{-0.693\, t/T_1} + (1-a)e^{-0.693\, t/T_2},$$

where

A(t) = the $^{137}Cs$ activity in the body at time t after ingestion,

**Table 6. Estimated compartmental fractions and half-times in the age-dependent retention function for cesium.**

| Age | Total-body K | Short- plus intermediate-term fraction | Short- plus intermediate-term $T^{1/2}$ (days) | Long-term fraction | Long-term $T^{1/2}$ (days) |
|---|---|---|---|---|---|
| Newborn | 5.2 | 0.60 | 22 | 0.40 | 22 |
| 100 days | 11.4 | 0.60 | 16 | 0.40 | 16 |
| 1 year | 20.8 | 0.60 | 13 | 0.40 | 13 |
| 5 years | 42.7 | 0.45 | 9.1 | 0.55 | 30 |
| 10 years | 71.0 | 0.30 | 5.8 | 0.70 | 50 |
| 15 years | 131.4 | 0.13 | 2.2 | 0.87 | 93 |
| Adult | 150 | 0.10 | 1.6 | 0.90 | 107 |

a = the fractional deposition of the ingested $^{137}Cs$ in the short-term compartment,

(1-a) = the fractional deposition in the long-term compartment,

$T_1$ = the biological half-life of $^{137}Cs$ in days in the short-term compartment,

$T_2$ = the biological half-life of $^{137}Cs$ in days in the long-term compartment.

The biological half-life and fractional deposition for both compartments are determined by the total potassium, $K_t$, in the body. Values for the grams of potassium in the total body, taken from Leggett 1987, were used with a polynomial interpolation to generate $K_t$ for other ages. The body weight as a function of age, $M_t$, in kg, is taken from ICRP (1975) and represented with equations developed by Adams (1981). The body weight as a function of age is shown in Figs. 1 and 2.

The mass of most body organs is assumed to be proportional to total body mass; the proportionality is established by the ratio of a specific organ mass to the body mass of a standard adult. Thus, the organ mass as a function of age is also based on the ICRP age-dependent body weights.

The biological half-lives and fractional depositions for males are then determined from the following equations (Leggett, 1986, 1987):

$$T_1 = T_2 = -0.9\,K_t + 26.5 \qquad (5\,g \leq K_t \leq 15\,g)\,,$$

$$T_1 = T_2 = 13 \qquad (15\,g < K_t \leq 20\,g)\,,$$

$$\left.\begin{aligned} T_2 &= -1.22 + 0.72K_t \\ T_1 &= 18\,e^{(-0.016K_t)} \end{aligned}\right\} \qquad (K_t > 20\,g)$$

$$a = 0.6 \qquad (5\,g \leq K_t < 20\,g)\,,$$

$$a = 0.81\,e^{(-0.014\,K_t)} \qquad (K_t > 20\,g)\,.$$

The model for females is the same as for males up to a K mass of $K_t = 43$ g. The model for females is then represented by the following equations:

$$T_2 = -17.1 + 1.09\,K_t \qquad (K_t > 43\,g)\,,$$

$$T_1 = 14\,e^{(-0.01\,K_t)} \qquad (K_t > 43\,g)\,,$$

$$a = 0.89\,e^{(-0.016\,K_t)} \qquad (K_t > 43\,g)\,.$$

The biological half-life of $^{137}Cs$ for Marshallese children of various ages has been measured by BNL (Lessard et al., 1979) and can be compared with those predicted using the model described above. The average $T^{1/2}$ for $^{137}Cs$ for 14 children ages 5 to 10 was 43 d; the average from the model is 40 d. For the 11- to 15-y age group, the BNL wholebody counting of 9 children gave a $T^{1/2}$ of 70 d; the model value for this age group is 72 d. Thus, the model predictions are quite good for the Marshallese children.

## Strontium-90

### Infants, Children, and Adults

The cycling and retention of ingested $^{90}Sr$ is much more complex than that for ingested $^{137}Cs$. The development and changing physiology of bone structure from birth to adulthood greatly affects retention and discrimination factors for $^{90}Sr$ and also deposition patterns in the various compartments of developing bone. For example, the distinct cortical (compact bone) and trabecular (cancellous) bone compartments in adults are not nearly as well differentiated in infants. Turnover times of calcium and strontium due to bone modeling are much more rapid in infants and children than adults, and the Sr/Ca discrimination factors and the gut transfer of $^{90}Sr$ change markedly with age. Rather than attempt a detailed discussion of bone

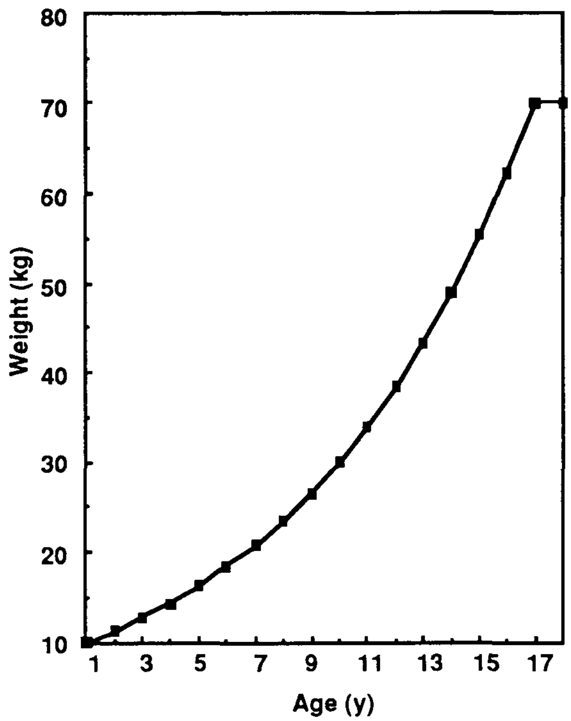


Figure 1. Body weight as a function of age, 1 to 18 y.

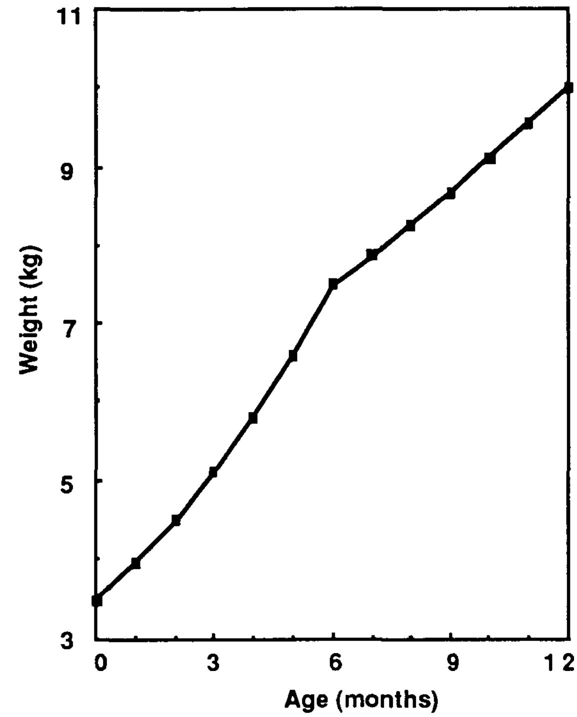


Figure 2. Body weight as a function of age, 0 to 12 mo.

development and Ca/Sr metabolism as a function of age, the reader is directed to papers by the authors of the various age-dependent $^{90}Sr$ dose models and their associated references (ICRP, 1972; Cristy et al., 1984; Leggett et al., 1982, 1984; Papworth and Vennart, 1973, 1984; Spiers, 1968; Bennett, 1973, 1977, 1978).

# Dosimetry

## Cesium-137

The conversion from the intake of $^{137}Cs$ to the dose-equivalent rate and integral dose equivalent is based upon the ICRP methods described in ICRP Publication 30 (ICRP, 1979). For charged-particle emission, the basic ICRP methodology is adjusted for age dependence by using body weights (and organ weights) for various ages determined by methods described in the "Retention" section of this paper. It is assumed for charged-particle emissions that all of the energy is deposited in the organ that contains the activity, i.e., the source (S) organ, and that no energy is transferred to any other organ, i.e., target (T) organ. In other words, for charged particles, the source organ is also the target organ. As a result, the specific effective energy, SEE, (T← S), in meV/g per transformation, changes proportionally with mass for the standard adult; the relationship as a function of age is

$$(SEE)_t = \frac{70}{M_t}(SEE)_{adult},$$

where $(SEE)_{adult}$ is the ICRP value for standard man, 70 kg is the mass of standard man, and $M_t$ is the body or organ mass at age t. This is the basis of the generic method described by Adams (1981) and by Leggett et al. (1984).

The calculation for photon emissions is more complex because the entire energy of the photon is not absorbed in the source organ. As the body and organ size become smaller, a larger portion of the energy escapes the source organ and the relative position of the organs is significant. Consequently, if the charged-particle-emission concept is used for making age-dependent adjustments for the total energy released per transformation for a radionuclide like $^{137}Cs$ that has both charged-particle and photon emissions, the actual dose for infants and children will be overestimated. However, this procedure can be used for $^{137}Cs$ for a quick, conservative approach to the relative dose from $^{137}Cs$ as a function of the age at intake.

Leggett et al. (1984) and Cristy and Ekerman (1987a to 1987g) have calculated age-dependent energy deposition factors (S factors) that account for changes in deposition of photon energy as a function of size (i.e., age). The results are based on Monte Carlo calculations in various sizes of computer-generated phantoms; the S factors are presented for newborn, 1-y-old, 5-y-old, 10-y-old, 15-y-old males, and adult females and adult males. Values for other ages are obtained by linear interpolation.

We have combined the age-dependent modifications to 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 to 1987g) for the photon emission (E = 0.66 meV) associated with $^{137}Cs$ decay to generate the final age-dependent 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 "Retention" section.

The age-dependent energy deposition factors and biological half-life are combined to adjust the ICRP dosimetry methods for $^{137}Cs$ to an age-dependent model.

## 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 (Kulp and Schulert, 1962; Rivera, 1967; Bennett, 1973, 1977, 1978; Klusek, 1979; Papworth and Vennart, 1973; Leggett et al., 1982). We have previously used both the model developed at EML (Rivera, 1967; Bennett, 1973, 1977, 1978; Klusek, 1979) and that of Papworth and Vennart (1973). The two models give very similar results, with the biggest difference in results occurring for persons between ages 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), in the EML model, but Papworth and Vennart's model does include the two compartments of compact and cancellous bone.

A 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 (1972, 1979). 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. Doses listed in this paper are from the Leggett model.

# Results of Dose Calculations for Rongelap Atoll

## Cesium-137 Dose Equivalent

The dose-equivalent rate calculated for Rongelap Island using the age-dependent model for estimating the $^{137}Cs$ body burden is shown in Fig. 3. The age-dependent intake of $^{137}Cs$ is as described in the "Intake of $^{90}Sr$ and $^{137}Cs$" section of the paper for birth (424 pCi/d), 4 months (556 pCi/d), 9 months (773 pCi/d), 1.5 y (517 pCi/d), 4 y (594 pCi/d), 12 y (761 pCi/d), and 18 y (1085 pCi/d), with the continuous intake in subsequent years decreasing by radiological decay (i.e., $T^{1/2}$ = 30 y for $^{137}Cs$). The maximum annual dose-equivalent rates for intake at the beginning of each age range are listed in Table 7. They are birth, 38 mrem; 4 months, 50 mrem; 9 months, 15 mrem; 1.5 y, 16 mrem; 4 y, 16 mrem; 12 y, 20 mrem; adult, 22 mrem. Thus, the estimated maximum annual dose equivalent for adults is less than for intake beginning at birth or at 4 months but is about the same as that for intake beginning at all other ages. The annual dose rate in the second year when intake begins at birth or at 4 months drops from the first year doses of 38 mrem and 50 mrem to about 16 mrem. This result is similar to that described by Iinuma et al. (1969) for the Japanese data where the doses to infants and children based on whole-body counting were less than adult doses.

The integral 30-, 50-, and 70-y dose equivalents are also listed in Table 7 for each age. The integral 30-y dose equivalent for intake starting at each age range is as follows: birth, 377 mrem; 4 months, 389 mrem; 9 months, 358 mrem; 1.5 y, 361 mrem; 4 y, 382 mrem; 12 y, 459 mrem, and 18 y, 504 mrem. The corresponding integral 50-y dose equivalents are birth, 567 mrem; 4 months, 579 mrem; 9 months, 547 mrem; 1.5 y, 551 mrem; 4 y, 572 mrem; 12 y, 649 mrem, and 18 y, 693 mrem. Thus, the integral 30- and 50-y dose equivalent calculated for

**Table 7. The integral 30-, 50-, and 70-y effective dose equivalent and maximum annual effective dose-equivalent rate for continuous intake of $^{137}Cs$ beginning at various ages.**

| | Integral dose equivalent (mrem) | | | Maximum dose-equivalent rate |
|---|---|---|---|---|
| Age intake begins | 30 y | 50 y | 70 y | (mrem/y) |
| Birth | 377 | 567 | 686 | 38 |
| 4 months | 389 | 579 | 698 | 50 |
| 9 months | 358 | 547 | 667 | 15 |
| 1.5 y | 361 | 551 | 671 | 16 |
| 4 y | 382 | 572 | 692 | 16 |
| 12 y | 459 | 649 | 769 | 20 |
| 18 y | 504 | 693 | 813 | 22 |

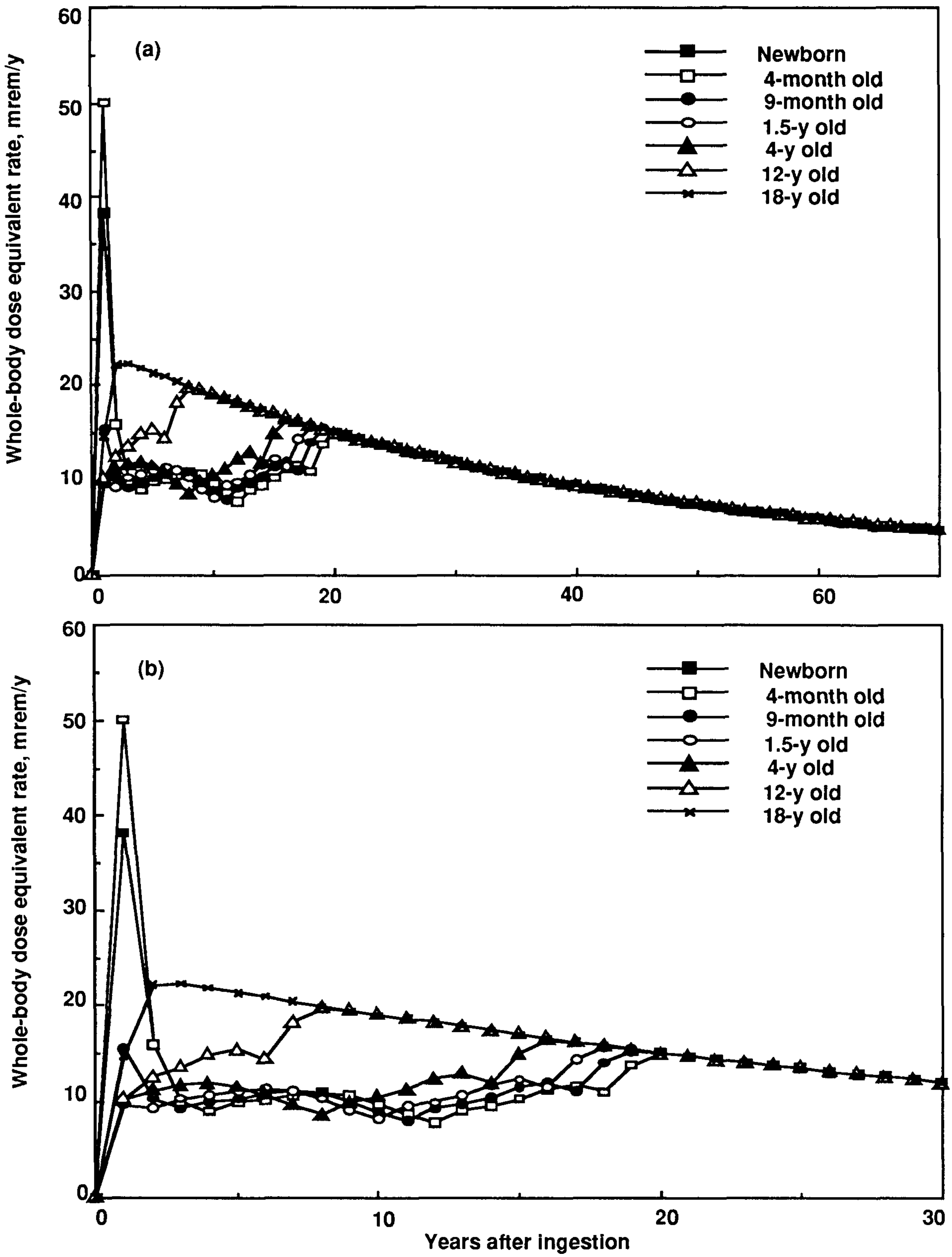


Figure 3. The annual dose equivalent from ingestion of $^{137}Cs$ beginning at different ages; (a) shows lifetime dose equivalent rates and (b) shows an expanded view of (a) for the first 30 y of exposure.

intake beginning as adults always exceeds that calculated for intake beginning at any other age.

To determine the consequence of equal intake of $^{137}Cs$ for each age, the dose equivalent for an initial intake of 1000 pCi/d was calculated for each age group. The results are listed in Table 8. Even for the extreme case of equal, continuous intake for each age group (which does not occur under real dietary conditions) with the annual intake declining at a rate determined by the radiological half-life of $^{137}Cs$, the integral 30-, 50- or 70-y dose equivalents are very similar regardless of when the age intake begins. The results for the integral 50-y dose equivalent for intake beginning at each age range are birth, 688 mrem; 4 months, 690 mrem; 9 months, 619 mrem; 1.5 y, 619 mrem; 4 y, 622 mrem; 12 y, 633 mrem; and 18 y, 640 mrem.

Recent changes in the modeling and dosimetry for $^{137}Cs$ used by the United Kingdom show that the effective committed dose equivalent per single unit intake of $^{137}Cs$ is the same regardless of the age of intake (Kendall et al., 1986).

**Table 8. The integral 30-, 50-, and 70-y effective dose equivalent for equal (1000 pCi/d) initial and continuous intake of $^{137}Cs$ starting at various ages.**

| | Integral dose equivalent, (mrem) | | |
|---|---|---|---|
| Age intake begins | 30 y | 50 y | 70 y |
| Birth | 513 | 688 | 794 |
| 4 months | 515 | 690 | 801 |
| 9 months | 444 | 619 | 729 |
| 1.5 y | 444 | 619 | 729 |
| 4 y | 447 | 622 | 732 |
| 12 y | 458 | 633 | 743 |
| 18 y | 465 | 640 | 750 |

## Strontium-90 Dose Equivalent

Strontium-90 is primarily deposited in the bone after ingestion, and the two major organs receiving exposure are the bone marrow and the bone surface cells. The annual dose equivalent from the ingestion of $^{90}Sr$ beginning at different ages is shown in Fig. 4. The maximum annual dose equivalent to the bone marrow is about 2 mrem/y, and this occurs when $^{90}Sr$ intake begins at ages 12 and 18.

The integral 30-, 50-, and 70-y dose equivalent to bone marrow and bone surface are listed in Table 9. The integral dose equivalent is very similar for all ages. For example, the 50-y integral dose equivalent ranges from 60 to 70 mrem for bone marrow and from 150 to 200 mrem for bone surface depending on when the age intake begins. The highest dose comes when intake begins at age 12.

The integral 30-, 50-, and 70-y effective dose equivalent due to the intake of $^{90}Sr$ is also listed in Table 9 and ranges from 8.6 to 10 mrem for 30 y, 12.9 to 14.4 mrem for 50 y, and 15.7 to 17.3 mrem for 70 y.

## Total Effective Dose Equivalent ($^{137}Cs$ + $^{90}Sr$)

The total integral 30-, 50-, and 70-y effective doses from the ingestion of $^{137}Cs$ and $^{90}Sr$ at Rongelap Island are listed in Table 10. The integral 30-y effective dose ranges from about 370 mrem to about 510 mrem, the integral 50-y effective dose ranges from about 560 mrem to about 700 mrem, and the integral 70-y effective dose ranges from about 680 mrem to about 830 mrem. Of the total estimated dose equivalent due to the ingestion of $^{90}Sr$ and $^{137}Cs$, the $^{90}Sr$ contributes only 2 or 3%, while $^{137}Cs$ contributes 97 to 98%.

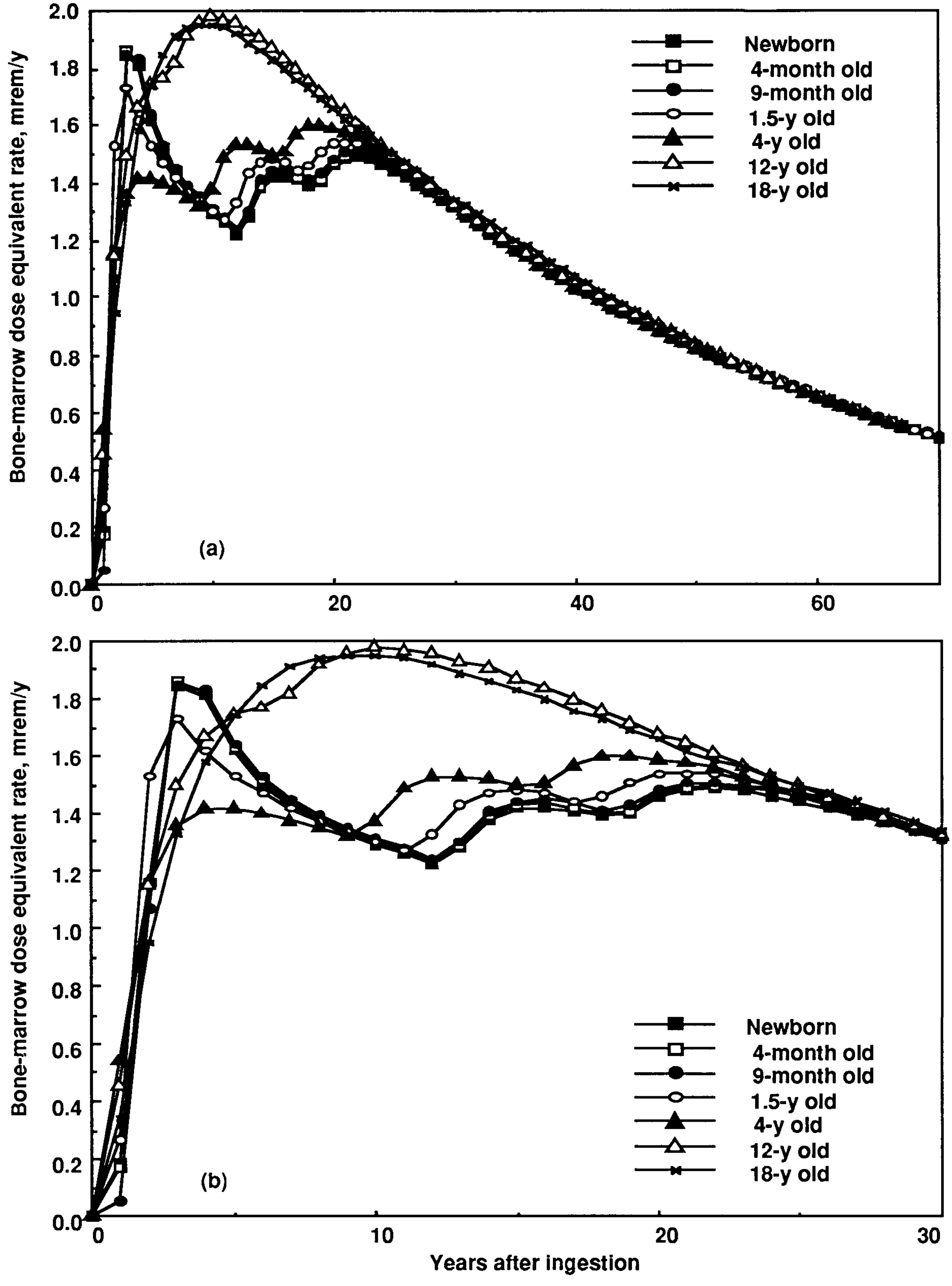


Figure 4. The annual bone-marrow dose when intake of $^{90}Sr$ begins at different ages; (a) shows lifetime dose equivalent rates and (b) shows an expanded view of (a) for the first 30 y of exposure.

**Table 9. The integral 30-, 50-, and 70-y dose equivalents for bone marrow and bone surfaces for intake of $^{90}Sr$ beginning at various ages.**

| | Integral dose equivalent, mrem | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Bone marrow | | | Bone surface | | | Effective | | |
| Age intake begins | 30 y | 50 y | 70 y | 30 y | 50 y | 70 y | 30 y | 50 y | 70 y |
| Birth | 41.4 | 62.0 | 75.0 | 122 | 182 | 223 | 8.6 | 12.9 | 15.7 |
| 4 months | 41.7 | 62.5 | 75.6 | 123 | 184 | 224 | 8.7 | 13.0 | 15.8 |
| 9 months | 43.1 | 63.7 | 76.6 | 127 | 187 | 227 | 9.0 | 13.3 | 16.0 |
| 1.5 y | 43.8 | 64.3 | 77.1 | 129 | 189 | 229 | 9.1 | 13.4 | 16.1 |
| 4 y | 43.2 | 64.0 | 77.0 | 126 | 187 | 228 | 9.0 | 13.3 | 16.1 |
| 12 y | 49.3 | 70.4 | 83.5 | 137 | 199 | 241 | 10.0 | 14.4 | 17.3 |
| 18 y | 48.5 | 69.8 | 82.9 | 116 | 175 | 217 | 9.3 | 13.6 | 16.5 |

**Table 10. The integral 30-, 50-, and 70-y effective dose equivalent for continuous intake of $^{137}Cs$ and $^{90}Sr$ beginning at various ages.**

| | Integral effective dose equivalent, mrem[a] | | | Fraction due to $^{90}Sr$ | | |
|---|---|---|---|---|---|---|
| Age intake begins | 30 y | 50 y | 70 y | 30 y | 50 y | 70 y |
| Birth | 386 | 580 | 702 | 0.02 | 0.02 | 0.02 |
| 4 months | 398 | 592 | 714 | 0.02 | 0.02 | 0.02 |
| 9 months | 367 | 560 | 683 | 0.03 | 0.02 | 0.02 |
| 1.5 y | 370 | 564 | 687 | 0.03 | 0.02 | 0.02 |
| 4 y | 391 | 585 | 708 | 0.02 | 0.02 | 0.02 |
| 12 y | 469 | 663 | 786 | 0.02 | 0.02 | 0.02 |
| 18 y | 513 | 705 | 829 | 0.02 | 0.02 | 0.02 |

[a] The effective dose equivalent is a unit defined by the ICRP (1984) which allows for the different mortality risks associated with irradiation of different organs, together with a proportion of the hereditary effects.

## Discussion

The result of our analysis is that the integral 30-, 50-, and 70-y effective dose equivalent estimated for intake beginning as adults at a contaminated atoll is greater than that for intake beginning at any other age. Consequently, the estimated integral dose equivalent for adults is a conservative estimate for infants and children. There are two basic reasons for this result. The first, and major, reason is the consistently higher intake of local foods, and thus $^{137}Cs$ , for adults found in the diet surveys from the Marshall Islands. Also, the higher intake of food in general by adults is supported by diet surveys of other societies; the intake for adults is greater than for infants and children.

The second reason is that even for continuous $^{137}Cs$ intake that declines at a rate equal to the radiological half-life of $^{137}Cs$ and where the initial intake is the same regardless of age, the integral 30-, 50-, and 70-y dose equivalents are slightly greater when intake begins as an adult than for intake beginning at any other age. This results from the combination of changing body weights, fractional deposits, and biological half-life for $^{137}Cs$ with age and the reduced concentration of $^{137}Cs$ in food with time. For example, when intake begins as an infant, the $^{137}Cs$ concentration in food has declined by about 35% by the time the infant reaches 18 y of age, when the dietary intake is greater and the biological half-life of $^{137}Cs$ longer. Consequently, if the intake of $^{137}Cs$ for an infant or child were equal to that for the adult (which it is not based on available dietary information from the Marshall Islands), the estimated integral 30-, 50-, and 70-y dose equivalent would still be similar to that estimated for adults.

In the case of $^{90}Sr$, the dose commitment per unit intake is greater by about a factor of 5 for intake beginning at ages 0 to 5 y than for intake beginning as an adult. However, when age-dependent differences in intake of $^{90}Sr$ via the diet are accounted for, the estimated integral 30-, 50-, and 70-y dose equivalents are less when intake begins as an infant or child than when intake begins as an adult.

Even if the $^{90}Sr$ intake for infants and children were significantly higher than what we have estimated, the total integral 30-, 50-, and 70-y effective dose equivalent from both $^{137}Cs$ and $^{90}Sr$ would be greater for adults than for infants and children because $^{137}Cs$ accounts for about 97% of the total estimated effective dose equivalent at the atolls via the ingestion pathway and $^{90}Sr$ for less than 3%.

Doses from $^{137}Cs$ and $^{90}Sr$ are insignificant through the inhalation pathway as compared to that via ingestion (Robison et al., 1987; ICRP, 1979; Cristy et al., 1984; Kendall, 1986). Consequently, the relative magnitude of the integral dose equivalent among infants, children, and adults can be determined by evaluating the ingestion pathway; that analysis indicates that the estimated effective integral dose equivalents for adults due to ingestion of $^{137}Cs$ and $^{90}Sr$ is a conservative estimate for intake beginning in infancy and childhood.

## References


Aarkrog, A. (1963), "Caesium-37 from Fall-out in Human Milk," *Nature 197*, 667-668.

Abraham, S., M.D. Carroll, C.L. Johnson, and C.M. Villa Dresser (1979), *Caloric and Selected Nutrient Values for Persons 1-74 years of Age: First Health and Nutrition Examination Survey, United States 1971-1974*, U.S. Department of Health, Education and Welfare, DHEW Publication No. (DHS) 79-1657, Series 11, No. 209.

Adams, N. (1981), "Dependence on Age at Intake of Committed Dose Equivalents from Radionuclides," *Phys. Med. Biol. 26*, 1019-1034.

Bengtsson, L.G., Y. Naversten, and K.G. Svensson (1964), "Maternal and Infantile Metabolism of Caesium," *Assessment of Radioactivity in Man, Vol. II*, International Atomic Energy Agency, Vienna, Austria, pp. 21-32.

Bennett, B.C. (1973), *Strontium-90 in Human Bone, 1972 Results from New York City and San Francisco,* United States Atomic Energy Commission Health and Safety Laboratory, New York, NY, HASL-274.

Bennett, B.C. (1977), *Strontium-90 in Human Bone, 1976 Results from New York City and San Francisco,* United States Atomic Energy Commission Health and Safety Laboratory, New York, NY, HASL-328.

Bennett, B.C. (1978), *Strontium-90 in Human Bone, 1977 Results from New York City and San Francisco,* United States Atomic Energy Commission Health and Safety Laboratory, New York, NY, HASL-344.

Bikini Atoll Rehabilitation Committee (BARC) (1986), *Bikini Atoll Rehabilitation Committee Report No. 4,* BARC, Berkeley, CA.

Boni, A.L. (1969), "Variations in the Retention and Excretion of $^{137}Cs$ with Age and Sex," *Nature 222,* 1188-1189.

Bryant, F.J., and J.F. Loutit (1964), "The Entry of Strontium-90 into Human Bone," *Proc. Roy. Soc. 159B,* 449-465.

Buchanan, J.R.C. (1947), *A Guide to Pacific Island Dietaries,* South Pacific Board of Health, Sava, Fiji.

Burton, B. (1965), *The Heinz Handbook of Nutrition,* 2nd ed. (McGraw-Hill, New York, NY).

Burton, J.D., and E.R. Mercer (1962), "Discrimination Between Strontium and Calcium in Their Passage from Diet to the Bone of Adult Man," *Nature 193*, 846-847.

Clemente, G.F., A. Mariani, and G.P. Santaroni (1971), "Sex Differences in Cs Metabolism in Man," *Health Phys. 21,* 709-711.

Comar, C.L. (1967), "Some Principles of Strontium Metabolism: Implications, Applications, Limitations," *Strontium Metabolism,* J.M.A. Lenihan, J.F. Loutit, and J.H. Martin, Eds. (Academic Press, New York, NY), pp. 17-31.

Comar, C.L., K. Kostial, N. Gruden, and G.E. Harrison (1965), "Metabolism of Strontium in the Newborn," *Health Phys. 11,* 609-615.

Comar, C.L., R.H. Wasserman, and M.M. Nold (1956), "Strontium-Calcium Discrimination Factors in the Rat," *Proc. Soc. Exp. Biol. and Med. 92,* 859-863.

Committee for Revision of the Canadian Dietary Standard (1976), *Dietary Standard for Canada,* published by the Authority of the Minister of National Health and Welfare, Ottawa, Canada.

Cristy, M., and K.F. Eckerman (1987a), *Specific Absorbed Fractions of Energy at Various Ages from Internal Photon Sources. I. Methods*, Oak Ridge National Laboratory, Oak Ridge, TN, ORNL/TM-8381/V1.

Cristy, M., and K.F. Eckerman (1987b), *Specific Absorbed Fractions of Energy at Various Ages from Internal Photon Sources. II. One-Year-Old*, Oak Ridge National Laboratory, Oak Ridge, TN, ORNL/TM-8381/V2.

Cristy, M., and K.F. Eckerman (1987c), *Specific Absorbed Fractions of Energy at Various Ages from Internal Photon Sources. III. Five-Year-Old*, Oak Ridge National Laboratory, Oak Ridge, TN, ORNL/TM-8381/V3.

Cristy, M., and K.F. Eckerman (1987d), *Specific Absorbed Fractions of Energy at Various Ages from Internal Photon Sources. IV. Ten-Year-Old*, Oak Ridge National Laboratory, Oak Ridge, TN, ORNL/TM-8381/V4.

Cristy, M., and K.F. Eckerman (1987e), *Specific Absorbed Fractions of Energy at Various Ages from Internal Photon Sources. V. Fifteen-Year-Old Male and Adult Female*, Oak Ridge National Laboratory, Oak Ridge, TN, ORNL/TM-8381/V5.

Cristy, M., and K.F. Eckerman (1987f), *Specific Absorbed Fractions of Energy at Various Ages from Internal Photon Sources. VI. Newborn*, Oak Ridge National Laboratory, Oak Ridge, TN, ORNL/TM-8381/V6.

Cristy, M., and K.F. Eckerman (1987g), *Specific Absorbed Fractions of Energy at Various Ages from Internal Photon Sources. VII. Adult Male*, Oak Ridge National Laboratory, Oak Ridge, TN, ORNL/TM-8381/V7.

Cristy, M., R.W. Leggett, D.E. Dunning, Jr., and K.F. Eckerman (1984), *Age-Dependent Dose-Conversion Factors for Selected Bone-Seeking Radionuclides*, Oak Ridge National Laboratory, Oak Ridge, TN, ORNL/TM-8929.

Cryer, M.A., and K.F. Baverstock (1972), "Biological Half-Life of $^{137}$Cs in Man," *Health Phys. 23*, 394-395.

DeBrum, R. (1985), Marshall Islands Liaison Representative to U.S. Department of Energy, and O. DeBrum, Chief Secretary of the Marshall Islands, personal communication, March 1985.

Domnick, C., and M. Seelye (1967), "Subsistence Patterns Among Selected Marshallese Villagers," *Laura Report*, L. Mason, Ed., University of Hawaii, Honolulu, HI, pp. 1-41.

Eberhardt, L.L. (1967), "Relationship of Cesium-137 Half-Life in Humans to Body Weight," *Health Phys. 13*, 88-90.

Fisher, H.L., and W.S. Snyder (1967), "An Age-Dependent Model for the Bodily Retention of Cesium," *Health Physics Division Annual Report*, Oak Ridge National Laboratory, Oak Ridge, TN, ORNL-4168, 261-267.

Flaherty, M. (1988), Peace Corps volunteer at Ailinglapalap Atoll, Marshall Islands, personal communication to Dr. Henry Kohn, referee of the Rongelap Reassessment Project.

Food and Agricultural Organization of the United Nations (1957), *Calorie Requirements*, FAO Nutritional Studies No. 15, Rome, Italy.

Fujita, M., A. Yabe, J. Akaishi, and S. Ohtani (1966), "Relationship Between Ingestion, Excretion and Accumulation of Fallout Cesium-137 in Man on a Long-Term Scale," *Health Phys. 12*, 1649-1653.

Godfrey, B.E., and J. Vennart (1968), "Measurements of Caesium-137 in Human Beings in 1958-67," *Nature 218*, 741-746.

Hinshaw, J. (1988), Peace Corps volunteer at Ailinglapalap Atoll, personal communication to Dr. Henry Kohn, referee of the Rongelap Reassessment Project.

Hisamatsu, S., Y. Takizawa, and T. Abe (1987), "Fallout $^{3}H$ Ingestion in Akita, Japan," *Health Phys. 53*, 287-293.

Iinuma, T.A., S. Yashiro, T. Ishihara, M. Uchiyama, T. Nagai, and N. Yamagata (1969), "Estimation of Internal Dose in Human Fetus and Newborn Infants Due to Fallout Cesium-137," *Proceedings of the Ninth Annual Hanford Biology Symposium, Radiation Biology of the Fetal and Juvenile Mammal*, M.R. Sikov and D.D. Mahlum, Eds. U.S. Atomic Energy Commission, pp. 105-116.

International Commission on Radiological Protection (ICRP) (1972), *Alkaline Earth Metabolism in Adult Man*, Publication 20 (Pergamon Press, Oxford, England).

International Commission on Radiological Protection (ICRP) (1975), *Report of the Task Group on Reference Man*, Publication 23 (Pergamon Press, New York, NY).

International Commission on Radiological Protection (ICRP) (1979), *Limits for Intakes of Radionuclide by Workers*, Publication 30, Part 1 and Supp. (Pergamon Press, New York, NY).

International Commission on Radiological Protection (ICRP) (1984), *A Compilation of the Major Concepts and Quantities in Use by ICRP*, Publication 42 (Pergamon Press, New York, NY).

Karcher, G.J., J.K. Wheeler, G.L. Helgeson, and B. Kohn (1969), "Cesium-137 Body Burdens and Biological Half-Life in Children at Tampa, Florida and Lake Bluff, Illinois," *Health Phys. 16*, 301-313.

Kawamura, H., G. Tanaka, and K. Shiraishi (1986), "Distribution of Sr in the Fetal Skeleton," *Health Phys. 50*, 159-162.

Kendall, G.M., B.W. Kennedy, N. Adams, and T.P. Fell (1986), "Effective Dose per Unit Intake of Radionuclides by Adults and Young People," *Radiat. Prot. Dosim. 16*, 307-312.

Klusek, C.S. (1979), *Strontium-90 in Human Bone—1987 Results for New York City and San Francisco*, U.S. Department of Energy, Environmental Measurements Laboratory, New York, NY, EML 363.

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

Leggett, R.W. (1987), *Age-Specific Models for Evaluating Dose and Risks from Internal Exposures to Radionuclides*, Oak Ridge National Laboratory, Oak Ridge, TN, ORNL/TM-10080.

Leggett, R.W. (1986), "Predicting the Retention of Cs in Individuals," *Health Phys. 50*, 747-759.

Leggett, R.W., K.F. Eckerman, D.E. Dunning, Jr., M. Cristy, D.J. Crawford-Brown, and L.R. Williams (1984), *On Estimating Dose Rates to Organs as a Function of Age Following Internal Exposure to Radionuclides*, Oak Ridge National Laboratory, Oak Ridge, TN, ORNL/TM-8265.

Leggett, R.W., K.F. Eckerman, and L.R. Williams (1982), "Strontium-90 in Bone: A Case Study in Age-Dependent Dosimetric Modeling," *Health Phys. 43*, 307-322.

Lenihan, J.M.A. (1967), "Studies in Strontium Metabolism," *Strontium Metabolism*, J.M.A. Lenihan, J.F. Loutit, and J.H. Martin, Eds. (Academic Press, New York, NY), pp. 57-61.

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

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

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

Lloyd, R.D. (1973), "Cesium-137 Half-times in Humans," *Health Phys. 25*, 605-612.

Lloyd, R.D., C.W. Mays, B.W. Church, R.C. Pendleton, and S.F Mays (1970), "Does the Elimination Rate of Cesium in Humans Change with the Seasons," *Health Phys. 18*, 623-629.

Lloyd, R.D., W.S. Zundel, C.W. Mays, W.W. Wagner, R.C. Pendleton, and R.L. Aarnodt (1966), "Cesium-137 Half-times in Normal, in Dystrophic, and in Pregnant Humans," in *Research in Radiobiology*, University of Utah, Salt Lake City, Utah, COO-119-234, pp. 297-317.

Lough, S.A., G.H. Hamada, and C.L. Comar (1960), "Secretion of Dietary Strontium-90 and Calcium in Human Milk," *Proc. Soc. Exp. Biol. Med. 104*, 194-198.

Lough, S.A., J. Rivera, and C.L. Comar (1963), "Retention of Strontium, Calcium, and Phosphorous in Human Infants," *Proc. Soc. Exp. Biol. Med. 112*, 631-636.

Marsh, K.V. (1973), *Expected Living Patterns After Resettlement*, Enewetak Radiological Survey Report, USAEC, Las Vegas, NV, NVO-140, Vol. I, pp. 29-37, and an internal report entitled "The Living and Eating Habits of the Ujelang People."

McCraw, T.F. (1965), "The Half-Time of Cesium-137 in Man," *Radiol. Health Data 6*, 711-718.

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

Murai, M. (1954), *Nutrition Study in Micronesia*, Atoll Research Bulletin, 27.

Murai, M., F. Pen, and C. Miller (1958), *Some Tropical South Pacific Island Food: Description, History, Use, Composition and Nutritive Value*, University of Hawaii Press, Honolulu, Hawaii.

Nagai, T., T.A. Iinuma, M. Uchiyama, T. Ishimara, S. Yashiro, and J. Sternberg (1970), "Radio Contamination of the Environment and Its Effects on the Mother and Fetus-III, Part II-Retention of Cesium 137 by Pregnant Women, Placentae and Infants," *Int. J. App. Rad. Isotopes 21*, 363-374.

Naidu, J., N.A. Greenhouse, G. Knight, and E.C. Craighead (1981), *Marshall Islands: A Study of Diet and Living Patterns*, Brookhaven National Laboratory, Upton, NY, BNL-51313.

National Academy of Science (1980), *Recommended Dietary Allowances*, 9th revised ed., NAS, Food and Nutrition Board, Washington, DC.

National Council on Radiation Protection and Measurements (NCRP) (1977), *Cesium-137 from the Environment to Man: Metabolism and Dose*, National Council on Radiation Protection and Measurements, Washington, DC, NCRP-52.

Naversten, Y., and K. Linden (1964), "Half-Life Studies of Radiocaesium in Humans," *Assessment of Radioactivity in Man, Vol. II*, International Atomic Energy Agency, Vienna, Austria, pp. 79-87.

Noshkin, V.E., R.J. Eagle, K.M. Wong, T.A. Jokela, and W.L. Robison (1981), *Radionuclide Concentrations and Dose Assessment of Cistern Water and Groundwater at the Marshall Islands*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-52853, Pt. 2.

Papworth, D.G., and J. Vennart (1973), "Retention of $^{90}$Sr in Human Bone at Different Ages and the Resulting Radiation Doses," *Phys. Med. Biol. 18*, 168.

Papworth, D.G., and J. Vennart (1984), "The Uptake and Turnover of $^{90}$Sr in the Human Skeleton," *Phys. Med. Biol. 29*, 1045-1061.

Pennington, J.A.T. (1976), *Dietary Nutrient Guide* (Avi Publishing Co., Westport, CO).

Pollock, N.J. (1974), "Breadfruit or Rice, Dietary Choice on a Micronesian Atoll," *Ecol. and Food Nutr. 3*, 107-115.

Richmond, C.R., J.E. Furchner, and W.H. Langham (1962), "Long-Term Retention of Radiocesium by Man," *Health Phys. 8*, 201-205.

Rivera, J. (1967), "Predicting Strontium-90 Concentrations in Human Bones," *Strontium Metabolism*, J.M.A. Lenihan, J.F. Loutit, and J.H. Martin, Eds., (Academic Press, New York, NY) pp. 47-55.

Robison, W.L. (1983), "Radiological Dose Assessments of Atolls in the Northern Marshall Islands," *Proceedings Nineteenth Annual Meeting of the National Council on Radiation Protection and Measurements: Environmental Radioactivity, No. 5*, National Council on Radiation Protection and Measurements, Bethesda, MD, pp. 40-82.

Robison, W.L., C.L. Conrado, and W.A. Phillips (1987), *Enjebi Island Dose Assessment*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53805.

Robison, W., M. Mount, W. Phillips, C. Conrado, M. Stuart, and C. Stoker (1982a), *The Northern Marshall Islands Radiological Survey: Terrestrial Food Chain and Total Doses*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-52853, Pt. 4.

Robison, W.L., M.E. Mount, W.A. Phillips, M.L. Stuart, S.E. Thompson, and A.C. Stoker (1982b), *An Updated Radiological Dose Assessment of Bikini and Eneu Islands at Bikini Atoll*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53225.

Robison, W.L., V.E. Noshkin, W.A. Phillips, and R.J. Eagle (1981), *The Northern Marshall Islands Radiological Surveys: Radionuclide Concentrations in Fish and Clams and Estimated Doses Via the Marine Pathway*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-52853, Part 3.

Robison, W.L., W.A. Phillips, M.E. Mount, B.R. Clegg, and C.L. Conrado (1980), *Reassessment of the Potential Radiological Doses for Residents Resettling Enewetak Atoll*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53066.

Robison, W.L., W.A. Phillips, Y.C. Ng, D.E. Jones, and O.A. Lowe (1975), *Annual Bone and Whole-Body Doses, Environmental Impact Statement, Cleanup, Rehabilitation, Resettlement of Enewetak Atoll-Marshall Islands, Vol. II, TAB B*, AEC Task Group on Recommendations for Cleanup and Rehabilitation of Enewetak Atoll June 19, 1974, Defense Nuclear Agency, Washington, DC.

Rundo, J. (1970), "Fall-out Caesium-137 in Breast- and Bottle-fed Infants," *Health Phys. 18*, 437-438.

Rupp, E.M. (1980), "Age Dependent Values of Dietary Intake for Assessing Human Exposures to Environmental Pollutants," *Health Phys. 39*, 151-163.

Spiers, F.W. (1968), *Radioisotopes in the Human Body: Physical and Biological Aspects* (Academic Press, New York, NY).

Tanaka, G., H. Kawamura, and E. Nomura (1981), "Reference Japanese Man - II Distribution of Strontium in the Skeleton and in the Mass of Mineralized Bone," *Health Phys. 40*, 601-614.

Uchiyama, M., T. Iinuma, and M. Saiki (1969), "Relationship Between Body Burden and Urinary Excretion of Cesium-137 in Man Following Fallout Cesium-137 Ingestion," *Health Phys. 16*, 277-286.

Van Dilla, M.A. (1965), "On the Retention of Cesium-137 in People," *Health Phys. 11*, 21-22.

Watt, B., and A. Merrill (1963), *Agricultural Handbook No. 8, Composition of Foods-Raw, Processed, Prepared*, U.S. Department of Agriculture, Washington, DC.

Weng, D.S., and W.M. Beckner (1973), "Cesium-137 Turnover Rates in Human Subjects of Different Ages," *Health Phys. 25*, 603-605.

Wilson, A.G. (1985), Assistant Attorney General to the Trust Territory of the Pacific Island, in charge of the Enewetak Food Program, personal communication.

Wilson, A.R., and F.W. Spiers (1967), "Fallout Caesium-137 and Potassium in Newborn Infants," *Nature 215*, 470-474.

Yang, Y., and C.B. Nelson (1986), "An Estimation of Daily Food Usage Factors for Assessing Radionuclide Intakes in the U.S. Population," *Health Phys. 50*, 245-257.

Zundel, W.S., F.H. Tyler, C.W. Mays, R.D. Lloyd, W.W. Wagner, and R.C. Pendleton (1969), "Short Half-Times of Caesium-137 in Pregnant Women," *Nature 221*, 89-90.

# Appendix A:
# Concentration of Radionuclides in Foods in pCi/g, Food Intake in g/d, and Radionuclide Intake in pCi/d by Age Group

**Table A-1. Model diet: Rongelap Island, local and imported food available for adults greater than 18 y.**

| | | | | Specific activity in 1990 (pCi/g wet wt) | | | | pCi/day | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Local food | Grams/d | Kcal/g[a,b] | Kcal/d | $^{137}Cs$ | $^{90}Sr$ | $^{239+240}Pu$ | $^{241}Am$ | $^{137}Cs$ | $^{90}Sr$ | $^{239+240}Pu$ | $^{241}Am$ |
| Reef fish[c,d] | 24.2 | 1.40 | 33.8 | 1.9E-02 | 6.5E-04 | 2.4E-04 | 4.2E-05 | 4.7E-01 | 1.6E-02 | 5.8E-03 | 1.0E-03 |
| Tuna[c,d,e] | 13.9 | 1.40 | 19.4 | 1.9E-02 | 6.5E-04 | 2.4E-04 | 4.2E-05 | 2.7E-01 | 9.0E-03 | 3.3E-03 | 5.8E-04 |
| Mahi Mahi[c,d,e] | 3.56 | 1.10 | 3.92 | 1.9E-02 | 6.5E-04 | 2.4E-04 | 4.2E-05 | 6.8E-02 | 2.3E-03 | 8.5E-04 | 1.5E-04 |
| Marine crabs[c,f] | 1.68 | 0.90 | 1.51 | 5.8E-04 | 1.6E-03 | 1.1E-03 | 1.9E-04 | 9.7E-04 | 2.7E-03 | 1.8E-03 | 3.2E-04 |
| Lobster[c,f] | 3.88 | 0.90 | 3.49 | 5.8E-04 | 1.6E-03 | 1.1E-03 | 1.9E-04 | 2.2E-03 | 6.3E-03 | 4.2E-03 | 7.4E-04 |
| Clams[c,d,g] | 4.56 | 0.80 | 3.65 | 1.2E-03 | 4.0E-03 | 1.0E-02 | 3.1E-03 | 5.6E-03 | 1.8E-02 | 4.6E-02 | 1.4E-02 |
| Trochus[c,d,g] | 0.10 | 0.80 | 0.08 | 1.2E-03 | 4.0E-03 | 1.0E-02 | 3.1E-03 | 1.2E-04 | 4.0E-04 | 1.0E-03 | 3.1E-04 |
| Tridacna muscle[c,d,g] | 1.67 | 1.28 | 2.14 | 1.2E-03 | 4.0E-03 | 1.0E-02 | 3.1E-03 | 2.1E-03 | 6.8E-03 | 1.7E-02 | 5.2E-03 |
| Jedrul[c,d,g] | 3.08 | 0.80 | 2.46 | 1.2E-03 | 4.0E-03 | 1.0E-02 | 3.1E-03 | 3.8E-03 | 1.2E-02 | 3.1E-02 | 9.7E-03 |
| Coconut crabs[c,h] | 3.13 | 0.70 | 2.19 | 2.7E+00 | 1.2E+00 | 1.9E-03 | 6.2E-04 | 8.5E+00 | 3.7E+00 | 6.1E-03 | 2.0E-03 |
| Land crabs[c,i] | NR | 0.70 | 0.00 | 2.7E+00 | 1.2E+00 | 1.9E-03 | 6.2E-04 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Octopus[c,j] | 4.51 | 1.00 | 4.51 | 1.1E-02 | 1.6E-03 | 2.6E-04 | 4.6E-05 | 4.8E-02 | 7.3E-03 | 1.2E-03 | 2.1E-04 |
| Turtle[c,k] | 4.34 | 0.89 | 3.86 | 3.1E-03 | 2.5E-04 | 8.2E-05 | 1.4E-05 | 1.3E-02 | 1.1E-03 | 3.5E-04 | 6.2E-05 |
| Chicken muscle | 8.36 | 1.70 | 14.2 | 3.9E+00[l] | 4.1E-03[c] | 6.8E-05[m] | 9.0E-04[m] | 3.3E+01 | 3.4E-02 | 5.7E-04 | 7.5E-03 |
| Chicken liver | 4.50 | 1.64 | 7.38 | 2.7E+00[l] | 8.7E-03[c] | 3.4E-04[c] | 8.4E-04[m] | 1.2E+01 | 3.9E-02 | 1.5E-03 | 3.8E-03 |
| Chicken gizzard | 1.66 | 1.48 | 2.46 | 1.6E+00[c] | 9.7E-03[c] | 1.6E-04[c] | 2.7E-04[m] | 2.7E+00 | 1.6E-02 | 2.7E-04 | 4.5E-04 |
| Pork muscle | 5.67 | 4.50 | 25.5 | 1.0E+01[l] | 2.7E-03[c] | 3.6E-05[c] | 2.5E-05[c] | 5.8E+01 | 1.6E-02 | 2.0E-04 | 1.4E-04 |
| Pork kidney | NR | 1.40 | 0.00 | 1.3E+01[l] | 4.5E-03[c] | 3.4E-04[m] | 6.4E-04[m] | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Pork liver | 2.60 | 2.41 | 6.27 | 5.7E+00[l] | 4.5E-03[n] | 9.1E-04[m] | 3.4E-04[m] | 1.5E+01 | 1.2E-02 | 2.4E-03 | 8.9E-04 |
| Pork heart[o] | 10.6 | 1.95 | 20.6 | 1.0E+01 | 2.7E-03 | 3.6E-05 | 2.5E-05 | 1.1E+02 | 2.9E-02 | 3.8E-04 | 2.6E-04 |
| Bird muscle[c,e] | 2.71 | 1.70 | 4.61 | 1.9E-02 | 6.5E-04 | 2.4E-04 | 4.2E-05 | 5.2E-02 | 1.8E-03 | 6.5E-04 | 1.1E-04 |
| Bird eggs[c,p] | 1.54 | 1.50 | 2.31 | 1.2E-02 | 2.9E-04 | 2.4E-04 | 4.2E-05 | 1.8E-02 | 4.5E-04 | 3.7E-04 | 6.5E-05 |
| Chicken eggs[q] | 7.25 | 1.63 | 11.8 | 3.9E+00 | 4.1E-03 | 6.8E-05 | 9.0E-04 | 2.9E+01 | 2.9E-02 | 4.9E-04 | 6.5E-03 |
| Turtle eggs[c,r] | 9.36 | 1.50 | 14.0 | 3.1E-03 | 2.5E-04 | 8.2E-05 | 1.4E-05 | 2.9E-02 | 2.3E-03 | 7.6E-04 | 1.3E-04 |
| *Pandanus* fruit[l] | 8.66 | 0.60 | 5.20 | 9.0E+00 | 4.6E-01 | 8.4E-05 | 2.2E-05 | 7.8E+01 | 4.0E+00 | 7.3E-04 | 1.9E-04 |
| *Pandanus* nuts[s] | 0.50 | 2.66 | 1.33 | 9.0E+00 | 4.6E-01 | 8.4E-05 | 2.2E-05 | 4.5E+00 | 2.3E-01 | 4.2E-05 | 1.1E-05 |
| Breadfruit[l] | 27.2 | 1.30 | 35.3 | 2.8E+00 | 6.1E-02 | 1.6E-05 | 2.0E-05 | 7.6E+01 | 1.7E+00 | 4.4E-04 | 5.4E-04 |
| Coconut juice[l] | 99.1 | 0.11 | 10.9 | 1.1E+00 | 1.1E-03 | 2.7E-05 | 2.5E-05 | 1.0E+02 | 1.1E-01 | 2.6E-03 | 2.5E-03 |

**Table A-1. (Continued)**

| Local food | Grams/d | Kcal/g[a,b] | Kcal/d | Specific activity in 1990 (pCi/g wet wt) | | | | pCi/day | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $^{137}Cs$ | $^{90}Sr$ | $^{239+240}Pu$ | $^{241}Am$ | $^{137}Cs$ | $^{90}Sr$ | $^{239+240}Pu$ | $^{241}Am$ |
| Coconut milk[t] | 51.9 | 3.46 | 179 | 4.7E+00 | 1.6E-02 | 5.9E-05 | 5.9E-05 | 2.5E+02 | 8.4E-01 | 3.1E-03 | 3.1E-03 |
| Tuba/Jekero[t] | NR | 0.50 | 0.00 | 4.7E+00 | 1.6E-02 | 5.9E-05 | 5.9E-05 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Drinking coco meat[l] | 31.7 | 1.02 | 32.3 | 1.9E+00 | 1.3E-02 | 1.2E-04 | 5.6E-05 | 6.2E+01 | 4.2E-01 | 3.7E-03 | 1.8E-03 |
| Copra meat[l] | 12.2 | 4.14 | 50.3 | 4.7E+00 | 1.6E-02 | 5.9E-05 | 5.9E-05 | 5.7E+01 | 2.0E-01 | 7.2E-04 | 7.2E-04 |
| Sprouting coco[t] | 7.79 | 0.80 | 6.23 | 4.7E+00 | 1.6E-02 | 5.9E-05 | 5.9E-05 | 3.7E+01 | 1.3E-01 | 4.6E-04 | 4.6E-04 |
| Marsh. cake[t] | 11.7 | 3.36 | 39.2 | 4.7E+00 | 1.6E-02 | 5.9E-05 | 5.9E-05 | 5.5E+01 | 1.9E-01 | 6.9E-04 | 6.9E-04 |
| Papaya | 6.59 | 0.39 | 2.57 | 9.8E+00[u] | 1.4E-01[v] | 1.3E-04[w] | 6.2E-05[u] | 6.4E+01 | 9.2E-01 | 8.6E-04 | 4.1E-04 |
| Squash | NR | 0.47 | 0.00 | 6.3E+00[l] | 8.6E-02[v] | 1.7E-05[v] | 8.3E-06[w] | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Pumpkin[x] | 1.24 | 0.30 | 0.37 | 6.3E+00 | 8.6E-02 | 1.7E-05 | 8.3E-06 | 7.8E+00 | 1.1E-01 | 2.1E-05 | 1.0E-05 |
| Banana | 0.02 | 0.88 | 0.02 | 1.1E+00[u] | 2.6E-02[v] | 1.3E-04[y] | 6.2E-05[y] | 2.2E-02 | 5.3E-04 | 2.6E-06 | 1.2E-06 |
| Arrowroot[l] | 3.93 | 3.46 | 13.6 | 6.5E+00 | 7.8E-02 | 6.9E-04 | 3.6E-04 | 2.5E+01 | 3.0E-01 | 2.7E-03 | 1.4E-03 |
| Citrus[l] | 0.10 | 0.49 | 0.05 | 1.8E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 1.8E-01 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Rainwater[z] | 313 | 0.00 | 0.00 | 5.2E-04 | 1.9E-04 | 2.4E-06 | 3.9E-07 | 1.6E-01 | 6.0E-02 | 7.5E-04 | 1.2E-04 |
| Wellwater[z] | 207 | 0.00 | 0.00 | 8.0E-04 | 1.8E-03 | 1.3E-05 | 7.5E-06 | 1.7E-01 | 3.8E-01 | 2.7E-03 | 1.6E-03 |
| Malolo[z] | 199 | 0.00 | 0.00 | 5.2E-04 | 1.9E-04 | 2.4E-06 | 3.9E-07 | 1.0E-01 | 3.8E-02 | 4.8E-04 | 7.8E-05 |
| Coffee/tea[z] | 228 | 0.00 | 0.00 | 5.2E-04 | 1.9E-04 | 2.4E-06 | 3.9E-07 | 1.2E-01 | 4.4E-02 | 5.5E-04 | 9.0E-05 |
| Total Local | 1332 | | 567 | | | | | 1085 | 14 | 0.15 | 0.068 |
| Fluids | 1046 | | 11 | | | | | 107 | 1 | 0.01 | 0.004 |
| Solids | 286 | | 556 | | | | | 978 | 13 | 0.14 | 0.064 |

NOTE: Grams/d were taken from Table 1; footnotes for Tables A-1 through A-4 provided on page A-10; NR stands for no response.

**Table A-2. Model Diet: Rongelap Island, local and imported food available for children, ages 1 to 3 y.**

| | | | | Specific activity in 1990 (pCi/g wet wt) | | | | pCi/day | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Local food | Grams/d | Kcal/g[a,b] | Kcal/d | $^{137}$Cs | $^{90}$Sr | $^{239+240}$Pu | $^{241}$Am | $^{137}$Cs | $^{90}$Sr | $^{239+240}$Pu | $^{241}$Am |
| Reef fish[c,d] | 7.66 | 1.40 | 10.7 | 1.9E-02 | 6.5E-04 | 2.4E-04 | 4.2E-05 | 1.5E-01 | 5.0E-03 | 1.8E-03 | 3.2E-04 |
| Tuna[c,d,e] | 9.04 | 1.40 | 12.7 | 1.9E-02 | 6.5E-04 | 2.4E-04 | 4.2E-05 | 1.7E-01 | 5.9E-03 | 2.2E-03 | 3.8E-04 |
| Mahi Mahi[c,d,e] | 3.84 | 1.10 | 4.22 | 1.9E-02 | 6.5E-04 | 2.4E-04 | 4.2E-05 | 7.4E-02 | 2.5E-03 | 9.2E-04 | 1.6E-04 |
| Marine crabs[c,f] | NR | 0.90 | 0.00 | 5.8E-04 | 1.6E-03 | 1.1E-03 | 1.9E-04 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Lobster[c,f] | 1.33 | 0.90 | 1.20 | 5.8E-04 | 1.6E-03 | 1.1E-03 | 1.9E-04 | 7.7E-04 | 2.2E-03 | 1.4E-03 | 2.5E-04 |
| Clams[c,d,g] | 1.60 | 0.80 | 1.28 | 1.2E-03 | 4.0E-03 | 1.0E-02 | 3.1E-03 | 2.0E-03 | 6.5E-03 | 1.6E-02 | 5.0E-03 |
| Trochus[c,d,g] | NR | 0.80 | 0.00 | 1.2E-03 | 4.0E-03 | 1.0E-02 | 3.1E-03 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Tridacna muscle[c,d,g] | 0.49 | 1.28 | 0.63 | 1.2E-03 | 4.0E-03 | 1.0E-02 | 3.1E-03 | 6.0E-04 | 2.0E-03 | 4.9E-03 | 1.5E-03 |
| Jedrul[c,d,g] | 1.25 | 0.80 | 1.00 | 1.2E-03 | 4.0E-03 | 1.0E-02 | 3.1E-03 | 1.5E-03 | 5.1E-03 | 1.2E-02 | 3.9E-03 |
| Coconut crabs[c,h] | 1.98 | 0.70 | 1.39 | 2.7E+00 | 1.2E+00 | 1.9E-03 | 6.2E-04 | 5.4E+00 | 2.3E+0 | 3.8E-03 | 1.2E-03 |
| Land crabs[c,i] | NR | 0.70 | 0.00 | 2.7E+00 | 1.2E+00 | 1.9E-03 | 6.2E-04 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Octopus[c,j] | 1.66 | 1.00 | 1.66 | 1.1E-02 | 1.6E-03 | 2.6E-04 | 4.6E-05 | 1.8E-02 | 2.7E-03 | 4.4E-04 | 7.7E-05 |
| Turtle[c,k] | 0.67 | 0.89 | 0.60 | 3.1E-03 | 2.5E-04 | 8.2E-05 | 1.4E-05 | 2.1E-03 | 1.7E-04 | 5.5E-05 | 9.6E-06 |
| Chicken muscle | 1.65 | 1.70 | 2.80 | 3.9E+00[l] | 4.1E-03[c] | 6.8E-05[m] | 9.0E-04[m] | 6.5E+00 | 6.7E-03 | 1.1E-04 | 1.5E-03 |
| Chicken liver | 1.78 | 1.64 | 2.92 | 2.7E+00[l] | 8.7E-03[c] | 3.4E-04[c] | 8.4E-04[m] | 4.8E+00 | 1.6E-02 | 6.1E-04 | 1.5E-03 |
| Chicken gizzard | NR | 1.48 | 0.00 | 1.6E+00[c] | 9.7E-03[c] | 1.6E-04[c] | 2.7E-04[m] | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Pork muscle | 2.58 | 4.50 | 11.6 | 1.0E+01[l] | 2.7E-03[c] | 3.6E-05[c] | 2.5E-05[c] | 2.7E+01 | 7.1E-03 | 9.3E-05 | 6.3E-05 |
| Pork kidney | NR | 1.40 | 0.00 | 1.3E+01[l] | 4.5E-03[c] | 3.4E-04[m] | 6.4E-04[m] | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Pork liver | 1.08 | 2.41 | 2.60 | 5.7E+00[l] | 4.5E-03[n] | 9.1E-04[m] | 3.4E-04[m] | 6.2E+00 | 4.9E-03 | 9.9E-04 | 3.7E-04 |
| Pork heart[o] | NR | 1.95 | 0.00 | 1.0E+01 | 2.7E-03 | 3.6E-05 | 2.5E-05 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Bird muscle[c,e] | 1.15 | 1.70 | 1.95 | 1.9E-02 | 6.5E-04 | 2.4E-04 | 4.2E-05 | 2.2E-02 | 7.5E-04 | 2.8E-04 | 4.9E-05 |
| Bird eggs[c,p] | 0.19 | 1.50 | 0.29 | 1.2E-02 | 2.9E-04 | 2.4E-04 | 4.2E-05 | 2.2E-03 | 5.5E-05 | 4.6E-05 | 8.0E-06 |
| Chicken eggs[q] | 2.02 | 1.63 | 3.29 | 3.9E+00 | 4.1E-03 | 6.8E-05 | 9.0E-04 | 8.0E+00 | 8.2E-03 | 1.4E-04 | 1.8E-03 |
| Turtle eggs[c,r] | 1.01 | 1.50 | 1.52 | 3.1E-03 | 2.5E-04 | 8.2E-05 | 1.4E-05 | 3.1E-03 | 2.5E-04 | 8.2E-05 | 1.5E-05 |
| *Pandanus* fruit[l] | 9.84 | 0.60 | 5.90 | 9.0E+00 | 4.6E-01 | 8.4E-05 | 2.2E-05 | 8.8E+01 | 4.6E+00 | 8.3E-04 | 2.1E-04 |
| *Pandanus* nuts[s] | 0.35 | 2.66 | 0.93 | 9.0E+00 | 4.6E-01 | 8.4E-05 | 2.2E-05 | 3.1E+00 | 1.6E-01 | 2.9E-05 | 7.6E-06 |
| Breadfruit[l] | 9.90 | 1.30 | 12.9 | 2.8E+00 | 6.1E-02 | 1.6E-05 | 2.0E-05 | 2.8E+01 | 6.1E-01 | 1.6E-04 | 2.0E-04 |
| Coconut juice[l] | 46.6 | 0.11 | 5.12 | 1.1E+00 | 1.1E-03 | 2.7E-05 | 2.5E-05 | 4.9E+01 | 5.2E-02 | 1.2E-03 | 1.2E-03 |

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**Table A-3. (Continued)**

| Local food | Grams/d | Kcal/g[a,b] | Kcal/d | Specific activity in 1990 (pCi/g wet wt) $^{137}Cs$ | $^{90}Sr$ | $^{239+240}Pu$ | $^{241}Am$ | pCi/day $^{137}Cs$ | $^{90}Sr$ | $^{239+240}Pu$ | $^{241}Am$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Coconut milk[t] | 37.1 | 3.46 | 128 | 4.7E+00 | 1.6E-02 | 5.9E-05 | 5.9E-05 | 1.8E+02 | 6.0E-01 | 2.2E-03 | 2.2E-03 |
| Tuba/Jekero[t] | NR | 0.50 | 0.00 | 4.7E+00 | 1.6E-02 | 5.9E-05 | 5.9E-05 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Drinking coco meat[l] | 12.5 | 1.02 | 12.8 | 1.9E+00 | 1.3E-02 | 1.2E-04 | 5.6E-05 | 2.4E+01 | 1.7E-01 | 1.5E-03 | 7.1E-04 |
| Copra meat[l] | 6.12 | 4.14 | 25.3 | 4.7E+00 | 1.6E-02 | 5.9E-05 | 5.9E-05 | 2.9E+01 | 9.9E-02 | 3.6E-04 | 3.6E-04 |
| Sprouting coco[t] | 7.23 | 0.80 | 5.78 | 4.7E+00 | 1.6E-02 | 5.9E-05 | 5.9E-05 | 3.4E+01 | 1.2E-01 | 4.3E-04 | 4.3E-04 |
| Marsh. cake[t] | 11.0 | 3.36 | 37.0 | 4.7E+00 | 1.6E-02 | 5.9E-05 | 5.9E-05 | 5.2E+01 | 1.8E-01 | 6.5E-04 | 6.5E-04 |
| Papaya | 5.62 | 0.39 | 2.19 | 9.8E+00[u] | 1.4E-01[v] | 1.3E-04[w] | 6.2E-05[u] | 5.5E+01 | 7.9E-01 | 7.3E-04 | 3.5E-04 |
| Squash | NR | 0.47 | 0.00 | 6.3E+00[l] | 8.6E-02[v] | 1.7E-05[v] | 8.3E-06[w] | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Pumpkin[x] | 0.04 | 0.30 | 0.01 | 6.3E+00 | 8.6E-02 | 1.7E-05 | 8.3E-06 | 2.5E-01 | 3.4E-03 | 6.8E-07 | 3.3E-07 |
| Banana | NR | 0.88 | 0.00 | 1.1E+00[u] | 2.6E-02[v] | 1.3E-04[y] | 6.2E-05[y] | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Arrowroot[l] | 0.10 | 3.46 | 0.35 | 6.5E+00 | 7.8E-02 | 6.9E-04 | 3.6E-04 | 6.5E-01 | 7.8E-03 | 6.9E-05 | 3.6E-05 |
| Citrus[l] | NR | 0.49 | 0.00 | 1.8E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Rainwater[z] | 204 | 0.00 | 0.00 | 5.2E-04 | 1.9E-04 | 2.4E-06 | 3.9E-07 | 1.1E-01 | 3.9E-02 | 4.9E-04 | 8.0E-05 |
| Wellwater[z] | 139 | 0.00 | 0.00 | 8.0E-04 | 1.8E-03 | 1.3E-05 | 7.5E-06 | 1.1E-01 | 2.5E-01 | 1.8E-03 | 1.0E-03 |
| Malolo[z] | 191 | 0.00 | 0.00 | 5.2E-04 | 1.9E-04 | 2.4E-06 | 3.9E-07 | 9.9E-02 | 3.7E-02 | 4.6E-04 | 7.5E-05 |
| Coffee/tea[z] | 137 | 0.00 | 0.00 | 5.2E-04 | 1.9E-04 | 2.4E-06 | 3.9E-07 | 7.1E-02 | 2.6E-02 | 3.3E-04 | 5.4E-05 |
| Total Local | 883 | | 341 | | | | | 594 | 8.2 | 0.13 | 0.054 |
| Fluids | 716 | | 5 | | | | | 47 | 0.40 | 0.0043 | 0.0023 |
| Solids | 167 | | 336 | | | | | 547 | 7.8 | 0.13 | 0.052 |

NOTE: Grams/d were taken from Table 1; footnotes for Tables A-1 through A-4 provided on page A-10; NR stands for no response.

Table A-4. **Model diet: Rongelap Island, local and imported food available for teenagers, ages 12 to 17 y.**

| | | | | Specific activity in 1990 (pCi/g wet wt) | | | | pCi/day | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Local food | Grams/d | Kcal/g[a,b] | Kcal/d | $^{137}$Cs | $^{90}$Sr | $^{239+240}$Pu | $^{241}$Am | $^{137}$Cs | $^{90}$Sr | $^{239+240}$Pu | $^{241}$Am |
| Reef fish[c,d] | 15.6 | 1.40 | 21.9 | 1.9E-02 | 6.5E-04 | 2.4E-04 | 4.2E-05 | 3.0E-01 | 1.0E-02 | 3.7E-03 | 6.6E-04 |
| Tuna[c,d,e] | 15.0 | 1.40 | 21.0 | 1.9E-02 | 6.5E-04 | 2.4E-04 | 4.2E-05 | 2.9E-01 | 9.8E-03 | 3.6E-03 | 6.3E-04 |
| Mahi Mahi[c,d,e] | 5.44 | 1.10 | 5.98 | 1.9E-02 | 6.5E-04 | 2.4E-04 | 4.2E-05 | 1.0E-01 | 3.5E-03 | 1.3E-03 | 2.3E-04 |
| Marine crabs[c,f] | 0.40 | 0.90 | 0.36 | 5.8E-04 | 1.6E-03 | 1.1E-03 | 1.9E-04 | 2.3E-04 | 6.5E-04 | 4.3E-04 | 7.6E-05 |
| Lobster[c,f] | 2.66 | 0.90 | 2.39 | 5.8E-04 | 1.6E-03 | 1.1E-03 | 1.9E-04 | 1.5E-03 | 4.3E-03 | 2.9E-03 | 5.1E-04 |
| Clams[c,d,g] | 8.12 | 0.80 | 6.50 | 1.2E-03 | 4.0E-03 | 1.0E-02 | 3.1E-03 | 1.0E-02 | 3.3E-02 | 8.1E-02 | 2.6E-02 |
| Trochus[c,d,g] | 0.35 | 0.80 | 0.28 | 1.2E-03 | 4.0E-03 | 1.0E-02 | 3.1E-03 | 4.3E-04 | 1.4E-03 | 3.5E-03 | 1.1E-03 |
| Tridacna muscle[c,d,g] | 1.09 | 1.28 | 1.40 | 1.2E-03 | 4.0E-03 | 1.0E-02 | 3.1E-03 | 1.3E-03 | 4.4E-03 | 1.1E-02 | 3.4E-03 |
| Jedrul[c,d,g] | 1.47 | 0.80 | 1.18 | 1.2E-03 | 4.0E-03 | 1.0E-02 | 3.1E-03 | 1.8E-03 | 5.9E-03 | 1.5E-02 | 4.6E-03 |
| Coconut crabs[c,h] | 3.51 | 0.70 | 2.46 | 2.7E+00 | 1.2E+00 | 1.9E-03 | 6.2E-04 | 9.5E+00 | 4.1E+00 | 6.8E-03 | 2.2E-03 |
| Land crabs[c,i] | 0.16 | 0.70 | 0.11 | 2.7E+00 | 1.2E+00 | 1.9E-03 | 6.2E-04 | 4.3E-01 | 1.9E-01 | 3.1E-04 | 1.0E-04 |
| Octopus[c,j] | 6.17 | 1.00 | 6.17 | 1.1E-02 | 1.6E-03 | 2.6E-04 | 4.6E-05 | 6.5E-02 | 1.0E-02 | 1.6E-03 | 2.9E-04 |
| Turtle[c,k] | 2.77 | 0.89 | 2.47 | 3.1E-03 | 2.5E-04 | 8.2E-05 | 1.4E-05 | 8.5E-03 | 6.8E-04 | 2.3E-04 | 4.0E-05 |
| Chicken muscle | 5.79 | 1.70 | 9.84 | 3.9E+00[l] | 4.1E-03[c] | 6.8E-05[m] | 9.0E-04[m] | 2.3E+01 | 2.4E-02 | 3.9E-04 | 5.2E-03 |
| Chicken liver | 2.57 | 1.64 | 4.21 | 2.7E+00[l] | 8.7E-03[c] | 3.4E-04[c] | 8.4E-04[m] | 6.9E+00 | 2.2E-02 | 8.7E-04 | 2.2E-03 |
| Chicken gizzard | 0.12 | 1.48 | 0.18 | 1.6E+00[c] | 9.7E-03[c] | 1.6E-04[c] | 2.7E-04[m] | 1.9E-01 | 1.2E-03 | 1.9E-05 | 3.2E-05 |
| Pork muscle | 3.52 | 4.50 | 15.8 | 1.0E+01[l] | 2.7E-03[c] | 3.6E-05[c] | 2.5E-05[c] | 3.6E+01 | 9.7E-03 | 1.3E-04 | 8.6E-05 |
| Pork kidney | NR | 1.40 | 0.00 | 1.3E+01[l] | 4.5E-03[c] | 3.4E-04[m] | 6.4E-04[m] | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Pork liver | 2.71 | 2.41 | 6.53 | 5.7E+00[l] | 4.5E-03[n] | 9.1E-04[m] | 3.4E-04[m] | 1.6E+01 | 1.2E-02 | 2.5E-03 | 9.3E-04 |
| Pork heart[o] | NR | 1.95 | 0.00 | 1.0E+01 | 2.7E-03 | 3.6E-05 | 2.5E-05 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Bird muscle[c,e] | 6.51 | 1.70 | 11.1 | 1.9E-02 | 6.5E-04 | 2.4E-04 | 4.2E-05 | 1.3E-01 | 4.2E-03 | 1.6E-03 | 2.7E-04 |
| Bird eggs[c,p] | 6.42 | 1.50 | 9.63 | 1.2E-02 | 2.9E-04 | 2.4E-04 | 4.2E-05 | 7.4E-02 | 1.9E-03 | 1.5E-03 | 2.7E-04 |
| Chicken eggs[q] | 3.03 | 1.63 | 4.94 | 3.9E+00 | 4.1E-03 | 6.8E-05 | 9.0E-04 | 1.2E+01 | 1.2E-02 | 2.0E-04 | 2.7E-03 |
| Turtle eggs[c,r] | 1.87 | 1.50 | 2.81 | 3.1E-03 | 2.5E-04 | 8.2E-05 | 1.4E-05 | 5.8E-03 | 4.6E-04 | 1.5E-04 | 2.7E-05 |
| *Pandanus* fruit[l] | 6.12 | 0.60 | 3.67 | 9.0E+00 | 4.6E-01 | 8.4E-05 | 2.2E-05 | 5.5E+01 | 2.8E+00 | 5.1E-04 | 1.3E-04 |
| *Pandanus* nuts[s] | 0.58 | 2.66 | 1.54 | 9.0E+00 | 4.6E-01 | 8.4E-05 | 2.2E-05 | 5.2E+00 | 2.7E-01 | 4.9E-05 | 1.3E-05 |
| Breadfruit[l] | 17.8 | 1.30 | 23.1 | 2.8E+00 | 6.1E-02 | 1.6E-05 | 2.0E-05 | 4.9E+01 | 1.1E+00 | 2.9E-04 | 3.5E-04 |
| Coconut juice[l] | 64.3 | 0.11 | 7.08 | 1.1E+00 | 1.1E-03 | 2.7E-05 | 2.5E-05 | 6.8E+01 | 7.1E-02 | 1.7E-03 | 1.6E-03 |

**Table A-4. (Continued)**

| Local food | Grams/d | Kcal/g[a,b] | Kcal/d | Specific activity in 1990 (pCi/g wet wt) $^{137}$Cs | $^{90}$Sr | $^{239+240}$Pu | $^{241}$Am | pCi/day $^{137}$Cs | $^{90}$Sr | $^{239+240}$Pu | $^{241}$Am |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Coconut milk[t] | 57.2 | 3.46 | 198 | 4.7E+00 | 1.6E-02 | 5.9E-05 | 5.9E-05 | 2.7E+02 | 9.3E-01 | 3.4E-03 | 3.4E-03 |
| Tuba/Jekero[t] | NR | 0.50 | 0.00 | 4.7E+00 | 1.6E-02 | 5.9E-05 | 5.9E-05 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Drinking coco meat[l] | 26.3 | 1.02 | 26.8 | 1.9E+00 | 1.3E-02 | 1.2E-04 | 5.6E-05 | 5.1E+01 | 3.5E-01 | 3.1E-03 | 1.5E-03 |
| Copra meat[l] | 15.3 | 4.14 | 63.5 | 4.7E+00 | 1.6E-02 | 5.9E-05 | 5.9E-05 | 7.3E+01 | 2.5E-01 | 9.0E-04 | 9.1E-04 |
| Sprouting coco[t] | 5.01 | 0.80 | 4.01 | 4.7E+00 | 1.6E-02 | 5.9E-05 | 5.9E-05 | 2.4E+01 | 8.1E-02 | 3.0E-04 | 3.0E-04 |
| Marsh. cake[t] | 7.65 | 3.36 | 25.7 | 4.7E+00 | 1.6E-02 | 5.9E-05 | 5.9E-05 | 3.6E+01 | 1.2E-01 | 4.5E-04 | 4.5E-04 |
| Papaya | NR | 0.39 | 0.00 | 9.8E+00[u] | 1.4E-01[v] | 1.3E-04[w] | 6.2E-05[u] | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Squash | NR | 0.47 | 0.00 | 6.3E+00[l] | 8.6E-02[v] | 1.7E-05[v] | 8.3E-06[w] | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Pumpkin[x] | 4.01 | 0.30 | 1.20 | 6.3E+00 | 8.6E-02 | 1.7E-05 | 8.3E-06 | 2.5E+01 | 3.5E-01 | 6.8E-05 | 3.3E-05 |
| Banana | NR | 0.88 | 0.00 | 1.1E+00[u] | 2.6E-02[v] | 1.3E-04[y] | 6.2E-05[y] | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Arrowroot[l] | NR | 3.46 | 0.00 | 6.5E+00 | 7.8E-02 | 6.9E-04 | 3.6E-04 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Citrus[l] | NR | 0.49 | 0.00 | 1.8E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Rainwater[z] | 206 | 0.00 | 0.00 | 5.2E-04 | 1.9E-04 | 2.4E-06 | 3.9E-07 | 1.1E-01 | 3.9E-02 | 4.9E-04 | 8.1E-05 |
| Wellwater[z] | 139 | 0.00 | 0.00 | 8.0E-04 | 1.8E-03 | 1.3E-05 | 7.5E-06 | 1.1E-01 | 2.5E-01 | 1.8E-03 | 1.0E-03 |
| Malolo[z] | 106 | 0.00 | 0.00 | 5.2E-04 | 1.9E-04 | 2.4E-06 | 3.9E-07 | 5.5E-02 | 2.0E-02 | 2.5E-04 | 4.2E-05 |
| Coffee/tea[z] | 190 | 0.00 | 0.00 | 5.2E-04 | 1.9E-04 | 2.4E-06 | 3.9E-07 | 9.8E-02 | 3.6E-02 | 4.5E-04 | 7.4E-05 |
| Total Local | 940 | | 492 | | | | | 761 | 11 | 0.15 | 0.061 |
| Fluids | 705 | | 7 | | | | | 68 | 0.42 | 0.0047 | 0.0028 |
| Solids | 235 | | 485 | | | | | 693 | 11 | 0.15 | 0.058 |

NOTE: Grams/d were taken from Table 1; footnotes for Tables A-1 through A-4 provided on page A-10; NR stands for no response.

Footnotes to Tables A-1 through A-4

[a] Data from Murai (1958).

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

[c] Specific activity from Robison et al. (1982a).

[d] Includes data from Robison et al. (1981).

[e] Specific activity used is that of reef fish.

[f] Specific activity calculated using the ratio (pCi/g shellfish tissue wet weight versus pCi/g fish tissue wet weight) from Bikini Atoll (Robison et al., 1982a).

[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 (pCi/g octopus tissue wet weight versus pCi/g fish tissue wet weight) from Bikini Atoll (Robison et al., 1982a).

[k] Specific activity calculated using the ratio (pCi/g turtle tissue wet weight versus pCi/g fish tissue wet weight) from Bikini Atoll (Robison et al., 1982a).

[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 in 1986 and 1987 by Dr. William Robison et al., Lawrence Livermore National Laboratory, Livermore, CA.

[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 (pCi/g bird eggs wet weight versus pCi/g bird muscle wet weight) from Bikini Atoll (Robison et al., 1982a).

[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 (pCi/g fruit wet weight versus pCi/g soil dry weight) from the outer atolls taken on the 1978 survey.

[v] Specific activity used is calculated using concentration ratios (pCi/g fruit weight versus pCi/g 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 from Noshkin et al. (1981).