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Radiation doses for Marshall Islands Atolls Affected by U.S. Nuclear Testing:All Exposure Pathways, Remedial Measures, and Environmental Loss of 137Cs

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INTRODUCTION

The United States conducted 24 nuclear tests at Bikini Atoll with a total yield of 76.8 Megatons (MT). The Castle series produced about 60% of this total and included the Bravo test that was the primary source of contamination of Bikini Island and Rongelap and Utrōk Atolls. One of three aerial drops missed the atoll and the second test of the Crossroads series, the Baker test, was an underwater detonation. Of the rest, 17 were on barges on water and 3 were on platforms on an island; they produced most of the contamination of islands at the atoll.

There were 42 tests conducted at Enewetak Atoll with a total yield of 31.7 MT (Simon and Robison, 1997; UNSCEAR, 2000). Of these tests, 18 were on a barge over wateror reef, 7were surface shots, 2 aerial drops, 2 under water detonations, and 13 tower shots on either land or reef. All produced some contamination of various atoll islands.

Rongelap Atoll received radioactive fallout as a result of the Bravo test on March 1, 1954 that was part of the Castle series of tests. This deposition was the result of the Bravo test producing a yield of 15 MT, about a factor of three to four greater than the predicted yield that resulted in vaporization of more coral reef and island than expected and in the debris-cloud reaching a much higher altitude than anticipated. High-altitude winds were to the east at the time of detonation and carried the debris-cloud toward Rongelap Atoll. Utrōk Atoll also received fallout from the Bravo test but at much lower air and ground–level concentrations than at Rongelap atoll. Other atolls received Bravo fallout at levels below that of Utrōk [other common spellings of this island and atoll (Simon, et al., 2009). To avoid confusion in reading other literature, this atoll and island are spelled in a variety of ways (Utrik, Utirik, Uterik or Utrōk).

Dose assessments for Bikini Island at Bikini Atoll (Robison et al., 1997), Enjebi Island at Enewetak Atoll (Robison et al., 1987), Rongelap Island at Rongelap Atoll (Robison et al., 1994; Simon et al., 1997), and Utrōk Island at Utrōk Atoll (Robison, et al., 1999) indicate that about 95- 99% of the total estimated dose to people who may return to live at the atolls today (Utrōk

Island is populated) is the result of exposure to ^{137}Cs. External gamma exposure from ^{137}Cs in the soil accounts for about 10 to15% of the total dose and ^{137}Cs ingested during consumption of local food crops such as drinking coconut meat and fluid (*Cocos nucifera L.*), copra meat and milk, *Pandanus* fruit, and breadfruit accounts for about 85 to 90%. The other 1 to 2% of the estimated dose is from ^{90}Sr, $^{239+240}Pu$, and ^{241}Am. The ^{90}Sr exposure is primarily through the food chain while the exposure to $^{239+240}Pu$, and ^{241}Am is primarily via the inhalation pathway as a result of breathing re-suspended soil particles.

2. BACKGROUND

Previous dose assessments for the ^{137}Cs component of the dose were made using only the radiological decay of ^{137}Cs ($T_{1/2}$ = 30.1 y). Since those assessments, significant research has been done to determine the rate of loss of ^{137}Cs from the atoll terrestrial ecosystem. This work was initiated because over a period of many years ^{137}Cs has been observed in the island ground water lens that lies about 3 to 3.5 m below the ground surface. When adequate rainfall occurs a certain amount of fresh water recharge occurs to the lens and a portion of the ^{137}Cs inventory in soil that is soluble is transported to the underlying ocean ground water lens. The ^{137}Cs-containing fresh water lies atop the denser ocean water and slowly mixes with the ocean water as a result of tidal cycles (Wheatcraft and Buddermeier, 1981; Buddemeier and Oberdorfer, 1988; Oberdorfer et al., 1990; Oberdorfer and Buddemeier, 1995). The mean residence time of the ground water, and therefore the soluble ^{137}Cs in the ground water, at coral atolls has been estimated to be between 5 and 15y (Buddemeier, 1981).

In 1995 four slotted ground water wells were installed across Bikini Island in order to determine the amount of standing fresh water in the ground water lens at four different locations. The standing fresh water in 1995 ranged from 1.2 to 1.6 m in the 4 wells. Beginning in October 1997 there was an unusually long drought of about 2.5 y where rainfall was inadequate to produce freshwater recharge of the lens. This is very unusual as in most years there is adequate rainfall to provide some recharge of the ground water lens (30 cm to 160 cm). Vegetation was under extreme stress during this time and had never looked worse. The slotted wells were monitored frequently for total standing fresh water during this time to determine the rate of loss of fresh water from the ground water lens (i.e. mixing with the ocean water). Results are shown in Fig. 1. Mean residence time of fresh water in the lens for the 4 wells is 5.3 y with 95% confidence limits of 5.6 y and 5.0 y, respectively. After April 2000 rainfall returned to normal conditions and the fresh water in the lens once again returned to pre-drought levels with a new input of ^{137}Cs.Thus, except for a year of extreme drought, there is a continuing loss of ^{137}Cs from the soil and the root zone of the fruit trees to the ground water and that ^{137}Cs is no longer available for uptake by island vegetation.

The question then was "what is the rate of loss of ^{137}Cs from the root zone of tree food crops to the groundwater". This loss-rate was evaluated using two independent methods (Robison et. al., 2003): (1) an indirect time-dependent study of ^{137}Cs concentration in drinking-coconut meat (*Cocos nucifera* L) and leaves of naturally occurring *Pisonia grandis*, *Guettarda specosia*, *Tournefortia argentea*, *Scaevola taccada* at the atolls over many years, and, (2) a direct evaluation of the ^{137}Cs/^{90}Sr production ratio at the time of the Bravo detonation compared with the ^{137}Cs/^{90}Sr ratio in integrated soil profiles from Bikini Island some 40 to 50 years after fallout occurred. Both approaches gave similar results. The mean environmental loss half-life (ELH) of ^{137}Cs at the atolls is 12 y with 95% confidence limits of 11 y and 15 y. When the ELH is combined with the radiological decay of ^{137}Cs, it leads to an effective half-life of 8.5 y with 95% confidence limits of 8.0 y and 12 y. The difference in the rate of loss of ^{137}Cs from only radiological decay and from effective decay is shown in Fig. 2.

Because ^{137}Cs accounts for such a large portion of the estimated dose for potential residents at contaminated atolls, a significant radioecology program was begun to determine if 137Cs could be eliminated from the soil or blocked from getting into the tree food crops. Many options were evaluated (Robison and Stone, 1998). The most effective and most easily implemented remedial measure was the addition of K to the soil surface. During periods of rainfall the added K dissolves and is subsequently absorbed by the trees and plants. This K treatment is effective because natural concentration of K in atoll coral soil is very low. Exchangeable K ranges from 20 to 80 mg K per kg soil in the upper 40 cm of soil and below 40 cm about it is about 2 to 5 mg K kg^{-1} soil. All plants are growing on the margin of K deficiency.

Thus, addition of about 2000 kg K ha^{-1} reduces 137Cs concentration in coconuts (and *Pandanus*) to about 5% of pretreatment concentration at Bikini Island (Robison and Stone, 1992; Robison et al., 2006). Moreover, ^{137}Cs concentration remains at this low concentration for at least 10 y after K is last applied (Robison et al., 2006). When additional K is available, trees absorb large quantities of K to the point that concentration of K in trunks of K-treated coconut trees is a factor of 5.6 greater than in trunks of control coconut trees that received no additional K (Robison et al., 2009). This high internal concentration of K in the trees reduces further uptake of ^{137}Cs from soil and reduces the amount of ^{137}Cs allocated to edible fruits. This will greatly reduce the radiation dose to people who will resettle the islands and consume local tree food-crops, and, importantly, K treatment is needed no more often than about every 10 y (Robison et al., 2009). This greatly reduces the remediation costs. Also, it and provides important assurances that reduction in ^{137}Cs is long term and that the radiation dose from consuming local fruit-tree foods will remain low upon resettlement. Treatment of annual garden-type food crops (leafy vegetables, corn, sorghum, squash, beans, melons, etc,) with K also reduces the ^{137}Cs concentration to very low levels (Stone and Robison, 2002).

3. METHODS

3.1 Pathways and databases

Details of the databases and dose methodology can be found in Robison et al., 1997. A brief description is given here for all exposure pathways for both internal and external dose. Natural background dose pathways include cosmic radiation, cosmogenic radionuclides, natural radionuclides in the body, and other background sources such as inhalation of radon in the U.S. and Europe and ingestion of ^{210}Po/^{210}Pb from consumption of fresh fish in the Marshall Islands (Table 1). Nuclear test-related radionuclides still present at any significant level at the atolls are ^{137}Cs, ^{90}Sr, $^{239+240}$Pu, and ^{241}Am. Pathways specific to contaminated atolls are external gamma exposure to ^{137}Cs in the soil, inhalation of re-suspended radionuclides, and consumption of terrestrial food-crops, marine foods, and ground water that contain test-related radionuclides. Extensive databases have been developed over the years and include external gamma measurements of ^{137}Cs on 25m grid spacing on several islands (Gudiksen et al., 1976; Robison et al., 1988, 1999; Rongelap unpublished data) and EG&G aerial surveys (Tipton and Meibaum, 1981) to determine the ^{137}Cs and ^{241}Am in soil an most all islands in the Northern Marshall islands. Other data bases include external beta particle exposure (Crase, et al., 1982; Shingleton et al., 1987), exposure from re-suspension of soil and radionuclides in air at Bikini Atoll (Shinn, et al., 1980; unpublished resuspension data for Rongelap and Enewetak atolls), radionuclide concentrations in terrestrial foods (Robison et al, 1982; 1987; 1988; 1994; 1997; 1999), marine foods (Noshkin et al., 1981a; 1981b; 1981c; 1986; 1988; 1997; Noshkin and Robison, 1997; Robison et al., 1981), cistern and ground water (Noshkin et al., 1975; 1977; 1981; Robison et al., 1988) These data provide the basic input for dose calculations along with a diet model (discussed section 3.2.3) and effective remedial actions developed from field studies at the atolls.

3.2 Dose Methodology

3.2.1 Natural background dose in the Marshall Islands (MI), U.S., and Europe

Sources contributing to the annual background dose of MI residents are listed in Table 1 along with the magnitude of their contribution. MI cosmic background exposure dose is 9.0×10^{-10} C kg^{-1} (or 3.5 μRh^{-1}) (Gudiksen et al., 1976). This value is essentially the same as that calculated from data in UNSCEAR 2000 for the cosmic ray field at ground level for latitudes of less than 30° N. Thus, the annual whole-body dose from cosmic radiation rate is 0.22 mSv y^{-1}. Cosmogenic produced radionuclides contribute 0.001 mSv y^{-1} and naturally occurring radionuclides in the body, ^{40}K and ^{14}C, contribute 0.18 mSv y^{-1} and 0.01 mSv y^{-1}, respectively (NCRP Report 94, 1987). External gamma radiation from naturally occurring radionuclide in the soil is only 0.01mSv y^{-1} because the natural U concentration in coral soil is very low (Robison et el., 2001). Thus radium, thorium, and radon isotopes that contribute a large fraction of the U. S., Canada, and Europe background dose are essentially non-existent in the Marshall Islands. As a result the external gamma exposure to non-test-related radionuclides is about 0.01mSv y^{-1}. The total background dose in the Marshall Islands from cosmic, terrestrial, and in-body sources is 0.42 mSv y^{-1}.

The major source of background radiation exposure to Marshall Islands inhabitants is the consumption of fresh fish. There has been considerable research work worldwide that has shown that ^{210}Po and ^{210}Pb contribute a significant fraction of the background dose from ingestion of foods in populations that have a high intake of fresh marine seafood (Holtzman, 1980; Pentreath and Alington, 1988; Noshkin et al., 1994; Carvalho, 1995). A more recent large-scale international study has reconfirmed that ^{210}Po contributes a major portion of the dose people receive from ingestion of foods when fresh marine foods are part of the diet (Aarkrog et al., 1997). Fish that might be frozen for an extended period would have lower concentrations of two radionuclides.

In this report the latest dose conversion factor for ^{210}Po of 1.26 x 10-6 Sv Bq^{-1} and for 210Pb of 6.9 x 10^{-7} Sv Bq^{-1} from the International Commission on Radiological Protection (ICRP, 1996) were used to calculate the dose from consumption fresh fish (Table 1). Doses calculated from using the above dose conversion factors for ^{210}Po and ^{210}Pb and the imports-available diet are 0.96 mSv y^{-1} for ^{210}Po and 0.55 mSv y^{-1} for ^{210}Pb for a total dose from consumption of fresh fish of 1.51 mSv y^{-1}. Total background dose in the Marshall Islands is, therefore, 1.51 mSv y^{-1} + 0.42 mSv y^{-1} for a total of 1.9 mSv y^{-1}. For comparison, the average background radiation dose in the U.S. is 3.0 mSv y^{-1} and for Europe and Canada about 2.4 mSv y^{-1} (NCRP Report 94, 1987). Previous dose assessments (Noshkin et al., 1994; Robison et al., 1997) were made using then current ICRP dose conversion factors (Sv Bq^{-1}) for ^{210}Po and ^{210}Pb that are lower than those currently used and consequently led to a lower estimate of the total background dose of 1.5 mSv y^{-1}.

3.2.2 External dose from nuclear test-related radionuclides

External exposure calculations for gamma radiation (primarily from ^{137}Cs in the soil) are based on detailed measurements made at Bikini and Eneu Islands, the two residence islands at Bikini Atoll, at Enjebi and Enewetak Islands at Enewetak Atoll, Rongelap Island at Rongelap Atoll, and Utrōk and Aon Islands at Utrōk Atoll by LLNL as identified in section 3.1 (Pathways and data bases). These data for the various atolls are decay corrected to year 2010 which is the assumed resettlement date in this report. This may not be a realistic resettlement date for all three atolls, and maybe none of them, so resettlement subsequent to 2010 would lead to lesser doses than given in this report. The conversion factor from C kg^{-1} h-1 to mSv y^{-1} is 1.6×10^{-5} (froṃµR h^{-1} to mSv y^{-1} it is 0.0624).External exposure to ^{90}Sr, $^{239+240}$PU, and ^{241}Am in the soil leads to insignificant dose (Robison et al., 1997).

Observation of peoples living habits during field missions over a 25 y period and discussions with community members and other knowledgeable people in the Marshall Islands led to the following average distribution of peoples time in various locations on the residence island and around the atoll for the purpose of calculating the external dose:

- Ten h d^{-1} are spent inside the house
- Nine h d^{-1} are spent outside around the house and village area
- Three h d^{-1} are spent in the island interior (that almost always has the highest ^{137}Cs concentration in the soil)
- Two h d^{-1} are spent on the beach or lagoon (the lowest ^{137}Cs activity concentrations on the island)

This is the distribution used in the 1997 Bikini Isalnd and 1999 Utrok Island dose assessments (Robison et al., 1997, 1999). In earlier reports for Enjebi and Rongelap Islands the time distribution was slightly different prior to the input mentioned above. The time distribution for Enjebi and Rongelap Islands has been updated to the current time distribution in this report.

Houses provide shielding from external gamma exposure. Measurements at Bikini Island show that houses reduce the open-air gamma exposure by a factor of 4 to 5 (Robison et al., 1997). These houses were built in 1970 using more modern construction methods using concrete walls and floors. Houses built on Enewetak and Medren Islands at Enewetak Atoll in the late 1970's and current community buildings and houses on Rongelap Island are also constructed with similar modern materials. These materials provide a much higher shielding factor than the historic old wooden or coconut frond structures. Thus, the 10 h spent indoors are at a reduced exposure level due to shielding of the buildings.

Further reduction in external dose can be obtained by removing the top 10-15 cm of soil within 10-15 m of houses and community buildings and adding crushed coral around all the buildings (a common practice in the Marshall Islands) at the time of construction. All the required heavy equipment needed to do the soil removal and add the crushed coral would be available during clearing of the island and construction of the houses and community buildings. This would reduce the external exposure to very low levels in the areas where people spend a great deal of their time (19 h d^{-1} in houses and outside around the houses and village area).

3.2.3 Internal dose from nuclear test-related radionuclides

Internal doses are calculated using ICRP methods and dose conversion factors (Robison et al., 1997) and they scale directly to the intake of: (1) radionuclides in terrestrial food crops grown on a contaminated island, (2) radionuclides in contaminated marine foods, (3) radionuclides in island ground water, and (4) inhaled radionuclides. As mentioned previously, 137Cs accounts for 88% or more of the total dose as a result of ingestion of terrestrial foods and about another 10% as a result of external exposure. Strontium-90, $^{239+240}$Pu, and ^{241}Am account for about 2% of the dose. Marine-food, inhalation, and cistern /ground water pathways are all very minor contributors to the 50 y integral dose (0.078%, 0.22%, 0.17%, respectively).

Diet models were developed with input from several groups to determine daily consumption of locally grown terrestrial foods, marine foods, and ground water. These daily consumption rates, g d^{-1}, of all the various foods and water resources, when multiplied the radionuclide concentration measured in all the food and water products at the islands, provides the daily intake of each of the radionuclides at each of the islands. A detailed listing of the daily intakes for the IA diet model and further discussion of the diet model can be found in (Robison et al., 1997). One diet model includes locally grown foods and the availability of imported foods [imports available diet (IA)]. Imported foods account for about 60% of the dietary intake in this diet and include canned meats such as chicken, spam, corned beef, in some cases frozen chickens, large quantities of rice, some potatoes, etc. The other diet model [imported foods unavailable diet (IUA)] consists only of locally grown food over a lifetime as a maximum case. In the Marshall Islands today the chance that people living on the contaminated atolls (Bikini.

Enewetak, Rongelap) would exist on "local foods only" for any extended period of time is very unlikely. Transport of foods to the atolls by air and ship are common if not routine. Imported foods have become an expected part of the daily diet, and when combined with intake of some local foods, provide a realistic diet in the Marshall Islands today.

The mean ^{137}Cs body burdens calculated using the IA diet model predict very well the actual mean body burdens for Rongelap and Utrok Atoll residents between 1977 and 1993 that were measured by whole body counting by Brookhaven National Laboratory (Robison and Sun, 1997). Moreover, the upper 95% confidence limit of inter-individual variability around the population mean value based on the environmental method is in excellent agreement with the whole body counting data (Robison and Sun, 1997). Diet models with higher intakes of local foods greatly overestimate the body burdens obtained by direct whole body counting (Robison and Sun, 1997). If a person were to consume only foods grown on the island for their entire lifetime (IUA diet with no imported foods ever available) then the initial annual dose would be higher by about a factor of four.

3.2.4 Dose calculation process based on previous assessments

As was discussed in the Background (2.0) section of this paper, all previous dose assessments included only the radiological half-life of ^{137}Cs when calculating time-dependent doses. Since that time the rate of loss of ^{137}Cs from the soil to the ground water has been determined and an "effective half-life" for ^{137}Cs that is much more rapid than just the radiological loss of ^{137}Cs, can now be used for time dependent calculations for the islands. The annual dose rate (DR) was calculated for a specific year in each of the previous dose assessment papers for Bikini (1999), Enjebi (1990), Rongelap (1995), and Utrōk (1999) Islands. In this paper those values were decay corrected to year 2010: $DR_{2010} = \int_0^t DR_t \times (e^{-\lambda_{eff} \times t})$ where "t" is the number of years from the year of DR to the year 2010 for each of the islands, $\lambda_{effective} = 0.0815\ y^{-1}$ [$\lambda_{eff} = \lambda_{radiolocical} + \lambda_{environmetal}$] and $\lambda_{radiological} = 0.023\ y^{-1}$ and $\lambda_{environmental} = 0.0578\ y^{-1}$]. The corresponding half-lives are $T_{1/2} = 30.1$ y and 12 y, respectively.

The 50 y integral dose, D_{50}, from 2010 to 2060 is calculated using the equation: D_{50} = $\int_0^{50} DR_{2010} \times (e^{-\lambda_{eff} \times t}) = DR_{2010}/(-\lambda_{eff}) \times \left[e^{-\lambda_{eff} \times t}\right]_0^{50} = (DR_{2010}/\lambda_{eff}) \times \left[1 - e^{-\lambda_{eff} \times t}\right]$.

3.3 Remedial options

Previously published dose assessments for islands at the atolls have included only the radiological half-life of ^{137}Cs of 30.1 y. As mentioned in the Background section of this paper, the environmental half-life of 12 y (95% confidence limits 11 and 15 y) for ^{137}Cs in atoll soil is much more rapid than the radiological half-life of ^{137}Cs (30.1 y). Thus, the loss of ^{137}Cs from the root zone of plants is much accelerated; the effective half-life is 8.5 y (95% confidence limits 8 and 9.8 y). Moreover, treatment with potassium (K) is very effective at reducing the concentration of ^{137}Cs if food crops for an extended period of time (Robison et al., 2006). A "Combined-Option" remedial-action-program has been recommended to the communities because of the effectiveness of both external and internal exposure remedial actions.

The "Combined-Option" program consists of removing the top 15 cm of soil around the housing and village area with the excavated area subsequently backfilled with crushed coral. Using crushed coral around the housing and village area is a common practice in the Marshall Islands. These two actions greatly reduce the external dose where people spend most of their time. The second part of the combined-option is the treatment of the coconut grove, breadfruit trees, *Pandanus* trees, and other agricultural areas with K. This part of the combined-option greatly reduces the internal dose resulting from consumption of locally grown foods. The doses presented in following tables and graphics reflect the use of the "Combined Option" and the effective half-life of ^{137}Cs.

4. RESULTS

The final percent reduction in ^{137}Cs concentration in tree food crops as a result of treatment with K is dependent on the concentration of ^{137}Cs in the soil (Fig. 3). A reduction of a factor of 20 (5% of the initial concentration) is observed for Bikini Island at Bikini Atoll where the highest ^{137}Cs concentrations in soil occur. The reduction factor is 7 to 8 (~13% of the initial concentration) for Eneu island at Bikini Atoll and Enjebi Island at Enewetak Atoll where ^{137}Cs concentrations in soil are less than at Bikini Island, and a factor of 3 (~33% of the initial concentration) for Rongelap Island at Rongelap Atoll where soil ^{137}Cs concentration is less than that of Eneu and Enjebi Islands. The lowest two data points in Fig. 3 are from Rongelap Island. The appropriate reductions have been included in the projected dose calculations for the effect of the K treatment at each atoll/island.

Results of the effect of K treatment and soil removal in the housing and village area (Combined-Option) for Bikini, Enjebi, and Rongelap Islands are shown in Fig. 4. The annual dose in year 2010 is reduced by about a factor of 9 for Bikini Island, and Enjebi Island and a factor of 5 for Rongelap Island. The dose for Utrok Island is for current conditions (no remediation). These doses are compared with the background radiation dose in the Marshall Islands in Fig. 5.

A further breakdown on the total doses at the atolls is shown in Fig. 6. Annual background dose for the year 2010 from the various sources discussed in 3.2.1 is given for the Marshall Islands where the dose from eating fresh fish is significant and for comparison the U.S. and Europe where the radon dose is significant. The nuclear test-related dose for the atolls is shown in red. The total annual background dose plus nuclear test-related dose in the Marshall Islands is less than the annual background dose in the U.S. and Europe.

As discussed previously, loss of ^{137}Cs from both radiological decay and environmental processes greatly reduces ^{137}Cs concentration in soil and food crops over time. In Fig. 7 the 50 y integral dose is listed for the Marshall Islands and for the U.S. and Europe. The background doses are shown in black and the nuclear test-related dose in the Marshall Islands is again shown in red. The difference between the 50 y integral background doses for the U.S. and Europe and the sum of the 50 y integral background dose plus nuclear-test dose for the Marshall Islands is greater than the difference in the annual dose summary in Fig. 6 as a result of the continuing loss of ^{137}Cs from both radiological and environmental processes. Comparisons of the 50 y integral doses for the atolls to various annual standards given by the ICRP, NCRP, United States Nuclear

Regulatory Commission (U.S.NRC), and the United States Environmental Protection Agency (U.S.EPA), multiplied by 50 years, are listed in Table 2.

5. DISCUSSION AND CONCLUSIONS

Population average doses presented in this paper are calculated for year 2010 using the effective half-life of ^{137}Cs at the atolls and by applying the effect of remedial measures at the time of resettlement (K-treatment of agricultural areas and limited soil removal in the housing and village areas). Year 2010 is the earliest resettlement could occur at Rongelap Island although this may be optimistic. Resettlement will not occur at Bikini or Enjebi Islands by this time. Thus, doses will be less, and maybe significantly less, than those presented here depending on the actual resettlement date for the islands.

The total annual dose (natural background dose plus nuclear test-related dose) calculated for each of the three islands for year 2010 using the IA diet model range from 65 to 70% of the average background dose in the U.S. Annual nuclear test-related dose at the islands in year 2010 as a percentage of the total annual island background dose is 8% for Bikini, 3.8% for Enjebi, and 1.5% for Rongelap. After the islands are resettled, whole body counting can be used to determine whether these dose estimates for the population are slightly underestimated or slightly overestimated.

The mean body burden of ^{137}Cs based on whole body counting data of residents of Rongelap and Utrok Atolls for the period 1977 to 1993, and the 95 % confidence limits for the BNL whole body-counting data, lie within the modeled confidence limits when using the dose calculation methods discussed in this paper and the IA diet model (Robison and Sun, 1997). This indicates that the IA diet model of both imported and local foods is very realistic in the Marshall Islands. Diet models with higher intakes of local foods greatly overestimate the body burdens obtained by direct whole body counting over the 17 y period. It also indicates that the average concentration of radionuclides in food crops used in this and previous dose assessments dose assessments is appropriate. Use of values from the upper end of the distribution of ^{137}Cs concentration in local foods will also greatly overestimate the observed dose.

Also, the modeled 95% confidence limits in inter-individual variability in the population average dose are a factor of 2.5 above and below the calculated mean value. For comparison, the upper 95% confidence limits based on the adult population average observed by BNL in the whole body counting data over the years at Rongelap and Utrōk are 1.6 and 2.1, respectively (Robison and Sun, 1997). This provides additional confidence in applying the environmental method to other atolls currently uninhabited but where resettlement might occur.

The most current data available for comparing dose estimates in this report that are based on environmental data, dose models, and diet models (referred to as the Environmental Method) with actual dose estimates based whole body counting (WBC) comes from Utrok Atoll. That is because there are currently being no permanent residents on Bikini and Eneu Islands at Bikini Atoll, Enjebi Island at Enewetak atoll, or Rongelap Island at Rongelap Atoll. There is a small permanent workforce on Rongelap Island that is supplied with a significant portion of their food and therefore may not be representative of a permanently settled population group. The mean annual dose at Utrōk Atoll in year 2010 is calculated to be only 0.011 ± 0.0076 mSv y^{-1} using the Environmental Method without any type of remediation. The mean dose for 120 Utrok residents measured by WBC in 2003 (25), 2004 (21), 2005/6 (74) (Hamilton et al, 2006, 2007), that has been decay corrected to 2010 for comparison with Environmental Method results, is 0.019 mSv y-1. These estimates by the Environmental Method and WBC method overlap at one standard deviation of the two data sets. Thus, the environmental method predicts very well the actual doses observed at Utrōk Atoll by WBC. This supports comparisons mentioned in the previous paragraph where the environmental method using the imports available diet model predicted very well the ^{137}Cs body burdens measured by whole body counting on Utrōk and Rongelap Atolls over the 17-year period from 1977 to 1993 when Rongelap Island was inhabited (Robison and Sun, 1997).

Risk associated with radiation exposure is proportional to total dose received regardless of the source. As mentioned above, the annual nuclear test-related dose plus natural background dose at the islands is significantly less than the annual natural background dose in the U.S. and Europe. This is true even if the maximum exposed individual dose, that is about 2.5 times greater than the population average dose (Bogen et al., 1997), is used for comparison (the red bars in Fig. 6 would be multiplied by 2.5). For this case, the island background plus nuclear test-related dose as a percentage of U.S. background dose are 79% for Bikini, 70% for Enjebi, and 67% for Rongelap.

The mean population 50 y integral-dose and the maximum exposed individual 50 y integral dose calculated for each of the atolls do not exceed ICRP, U.S. EPA, or U.S. NRC, annual guidelines multiplied by 50 years. This results from the continuing loss of ^{137}Cs from the atoll soil to the ground water in addition to the radiological decay of ^{137}Cs.

Potassium treatment of coconut, *Pandanus*, and, breadfruit trees at the islands greatly reduces the ^{137}Cs concentration in edible fruits and this in turn very significantly reduces the dose resulting from consumption of locally grown terrestrial food crops. The low concentration of ^{137}Cs in the fruits lasts for at least 10 y after K is applied. This provides important assurances to the communities that reduction in ^{137}Cs is long term and that radiation dose from consuming local fruit-tree foods, the largest component of the calculated dose, will remain low upon resettlement. Also, the long-term effect of the K treatment greatly reduces the long-term remediation costs in that application of K is necessary at a minimum of every 10 y.The concentration of ^{137}Cs in annual food crops is also greatly reduced if K is applied at the time of planting and is highly recommended to the communities.

Chemically, ^{90}Sr (radiological $T_{1/2}$ = 28.5 y) is in the same chemical group of the periodic table of the elements as Ca and is transported and deposited by and in plants in a similar manner to Ca. Although very little Sr is deposited in the edible fruits of the coconut, breadfruit, papaya etc., there is a higher deposition in the leaves of plants that are definite repositories of Ca. Thus, if leafy vegetables (lettuce, cabbages, mustards, mizuna, etc.) were to become more prominent in the diet at some point in the future (their use is very uncommon in the outer atolls today) then the dose from ^{90}Sr would increase relative to that from ^{137}Cs.

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Figure legends:

Figure 1. Mean residence time of fresh water in the ground water lens of Bikini Island at Bikini Atoll.

Figure 2. Loss of ^{137}Cs by radiological decay compared to the loss of ^{137}Cs from both radiological decay and environmental processes at Bikini Island (the effective half-life).

Figure 3. Percent reduction in ^{137}Cs concentration in drinking-coconut meat as a result of treatment with potassium (K) compared to the initial ^{137}Cs concentration in the drinking coconut meat. The initial ^{137}Cs concentration in coconut meat correlates to ^{137}Cs concentration in the soil.

Figure 4. Reduction in the annual effective dose as a result of applying the "Combined Treatment" remediation strategy and the effective half-life of ^{137}Cs for people who might resettle Bikini, Enjebi, and Rongelap Islands. The Utrōk dose calculation did not include the "combined-treatment" strategy but did include the effective half-life of ^{137}Cs.

Figure 5. Annual effective dose in year 2010 for Bikini, Enjebi, and Rongelap Islands, after applying the "Combined Treatment" remediation strategy and the effective half-life of ^{137}Cs, compared with the annual natural background dose in the Marshall Islands.

Figure 6. Sum of the annual natural background radiation dose in the Marshall Islands and the nuclear test-related annual dose for Bikini, Enjebi, Rongelap, and Utrōk Islands using the "combined option" remediation strategy (except for Utrōk Island) and the effective half-life of ^{137}Cs compared with the annual natural background dose in the United States and Europe.

Figure 7. Sum of the 50-year integral background dose and 50-year integral nuclear test-related dose at Bikini, Enjebi, and Rongelap Islands compared with the 50-y integral background dose in the United States and Europe.

Table 1. Background Dose in the Marshall Islands.

Source	(mSv y^{-1})
Cosmic radiation	0.22
Cosmogenic radionuclides	0.001
In the body	
^{40}K	0.18
^{14}C	0.01
External in soil	0.01
Consumption of fresh fish	1.51
Total background dose	1.9

Table 2. 50-y Integral dose at the Atolls starting in year 2010 Compared with Various Annual Guidelines for the general public multiplied by 50 y

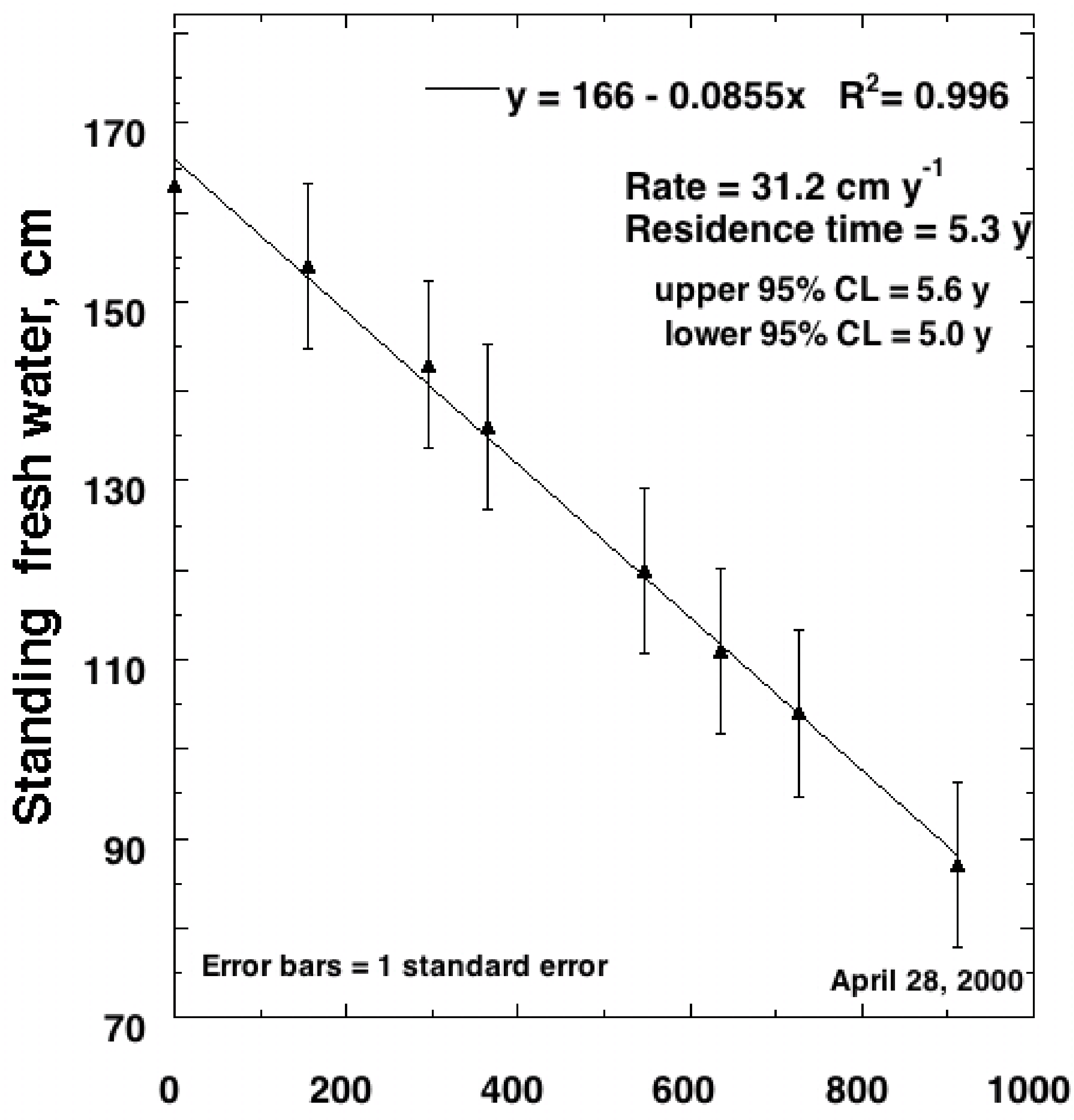
Atoll/Island	Test-related (mSv y^{-1}) (population average)	Test-related[a] (mSv y^{-1}) (maximum individual)	1.0[b] (mSv y^{-1}) (x 50 y)	0.15[c] (mSv y^{-1}) (x 50 y)
Utrōk				
Utrōk	0.2	0.5	50	7.5
Rongelap[d]				
Rongelap	0.4	1.0	50	7.5
Enewetak[d]				
Enjebi	0.8	2	50	7.5
Bikini[d]				
Bikini	2	5	50	7.5

[a]Factor for 95% confidence limits = 2.5.

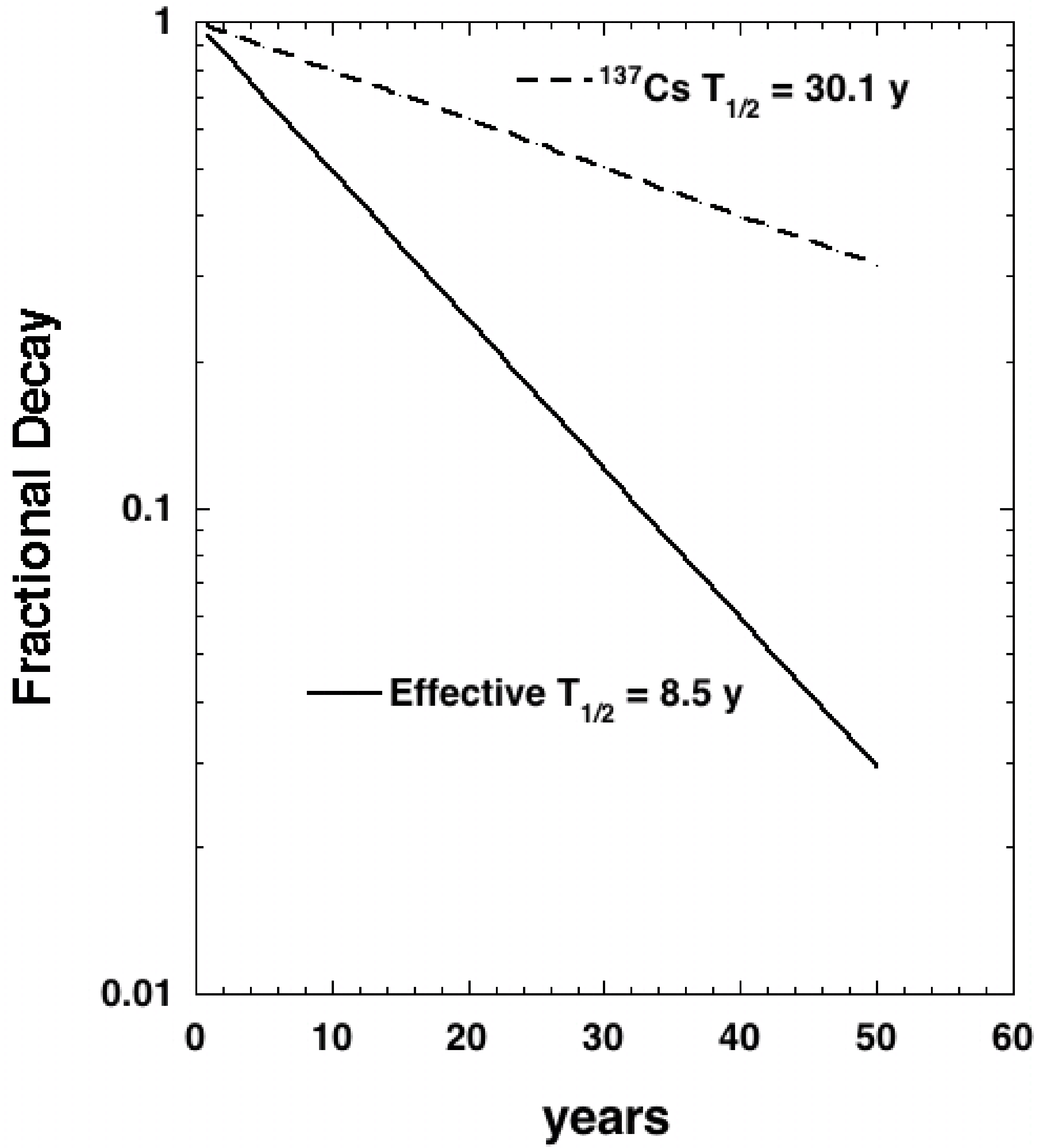
[b] International Commission on Radiological Protection (ICRP), Volume 36, No. 4, 2006 ; National Council on Radiation Protection and Measurements (NCRP), Report 116, 1993b; and U.S. Nuclear Regulatory Commission (U.S. NRC) guidance for the general public, Federal Register 10 CFR, part 20, Energy, 2008 .

[c]U.S. Environmental Protection Agency (U.S. EPA) guidance for CERCLA sites.

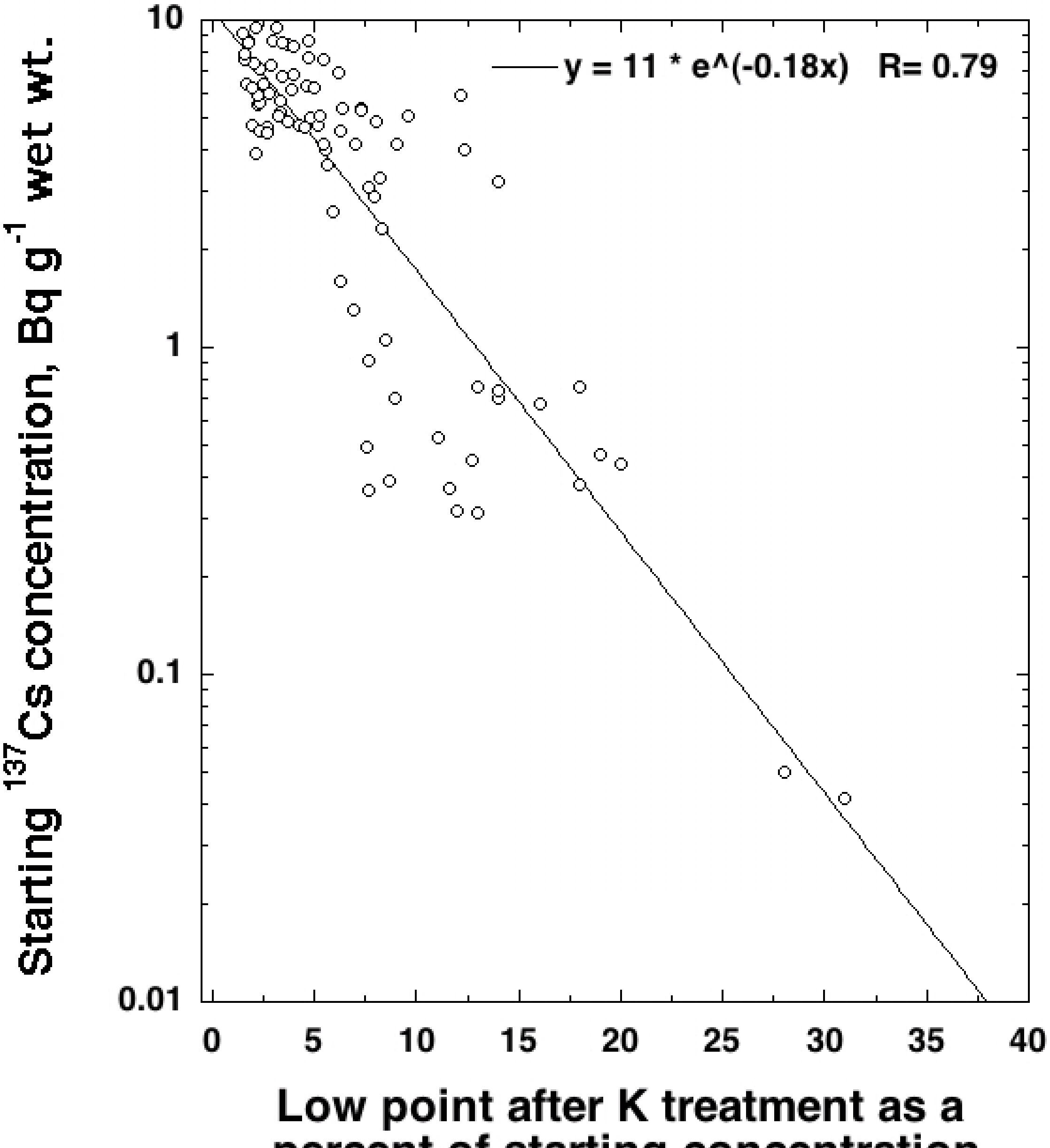
[d]Remediation using the combined option and the effective half-life.



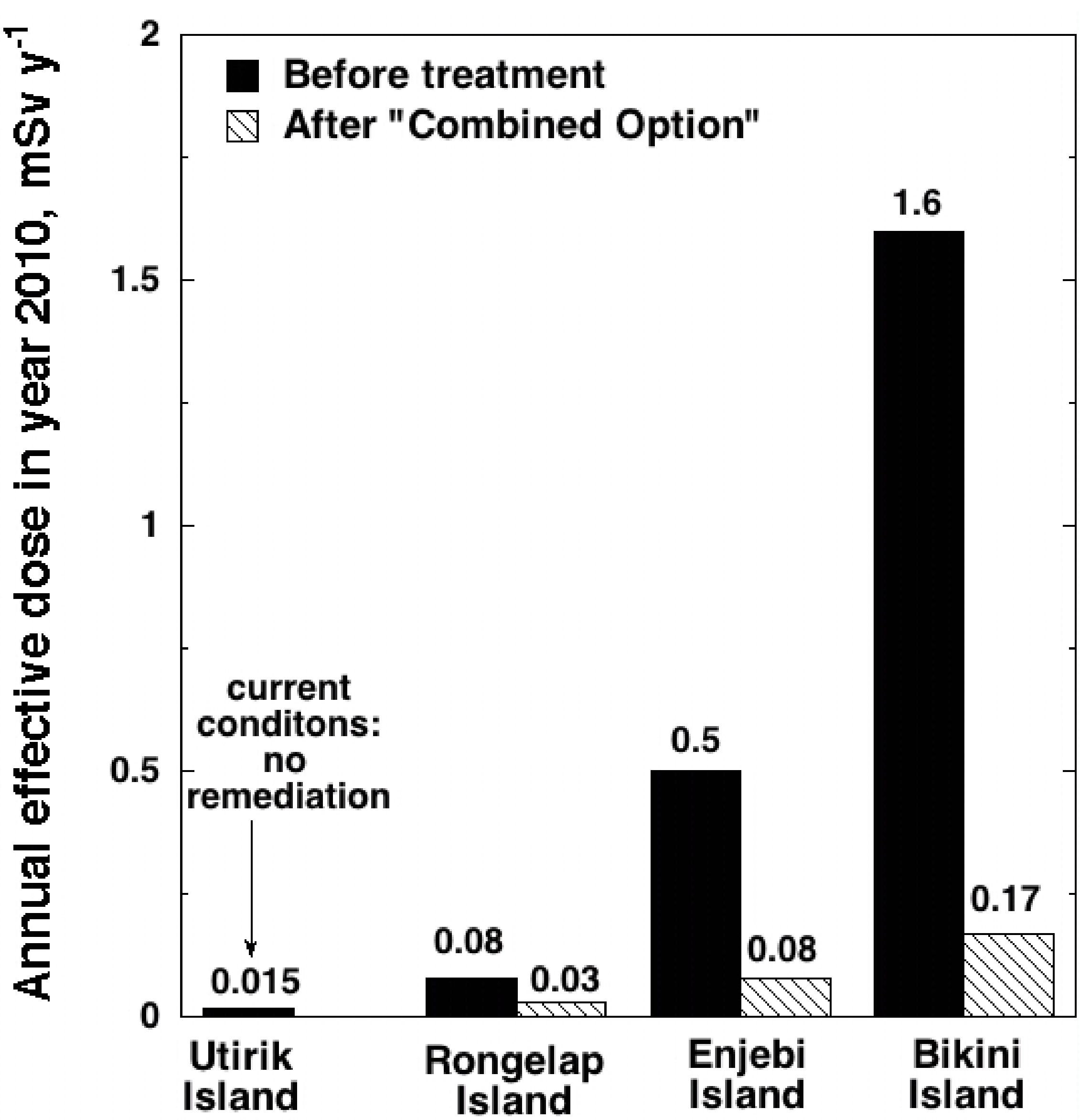
y = 166 - 0.0855x   R2= 0.996
Rate = 31.2 cm y-1
Residence time = 5.3 y
upper 95% CL = 5.6 y
lower 95% CL = 5.0 y
Error bars = 1 standard error
April 28, 2000
Standing fresh water, cm
170
150
130
110
90
70
0
200
400
600
800
1000
Days since October 30, 1997



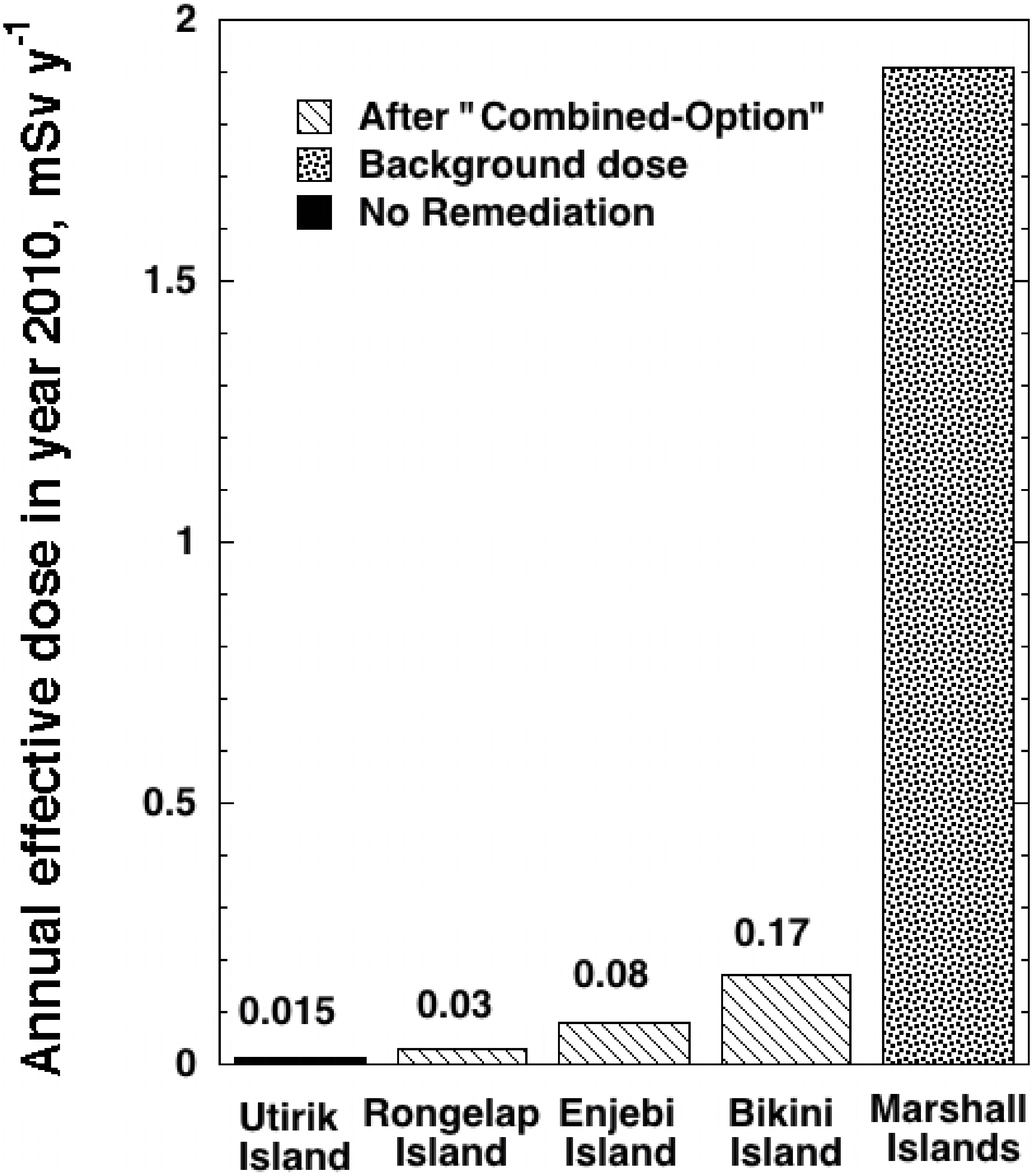
1
0.1
0.01
0
10
20
30
40
50
60
Fractional Decay
years
137Cs T1/2 = 30.1 y
Effective T1/2 = 8.5 y



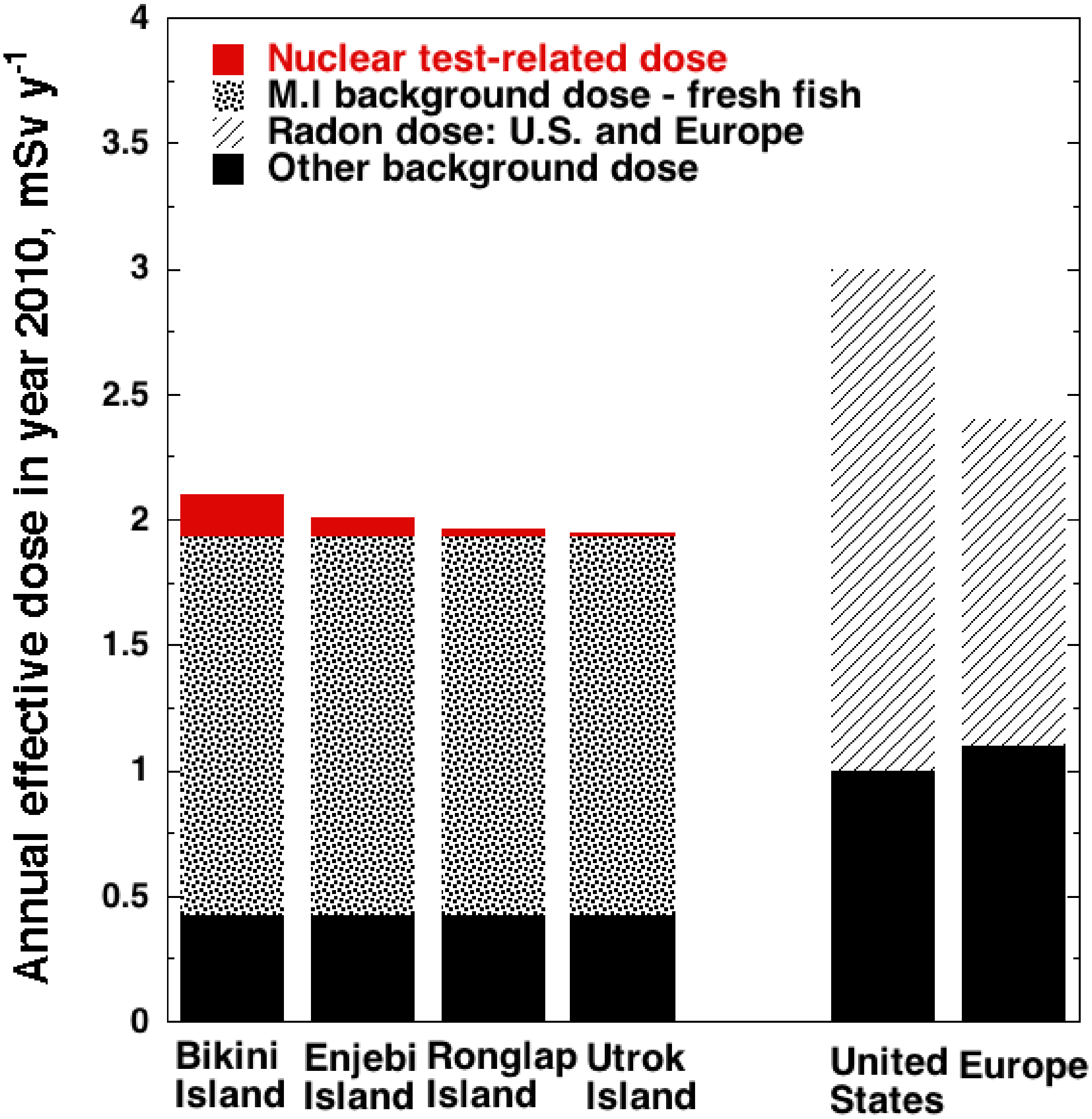
y = 11 * e^(-0.18x) R= 0.79
10
1
0.1
0.01
0
5
10
15
20
25
30
35
40
Starting 137Cs concentration, Bq g-1 wet wt.
Low point after K treatment as a percent of starting concentration



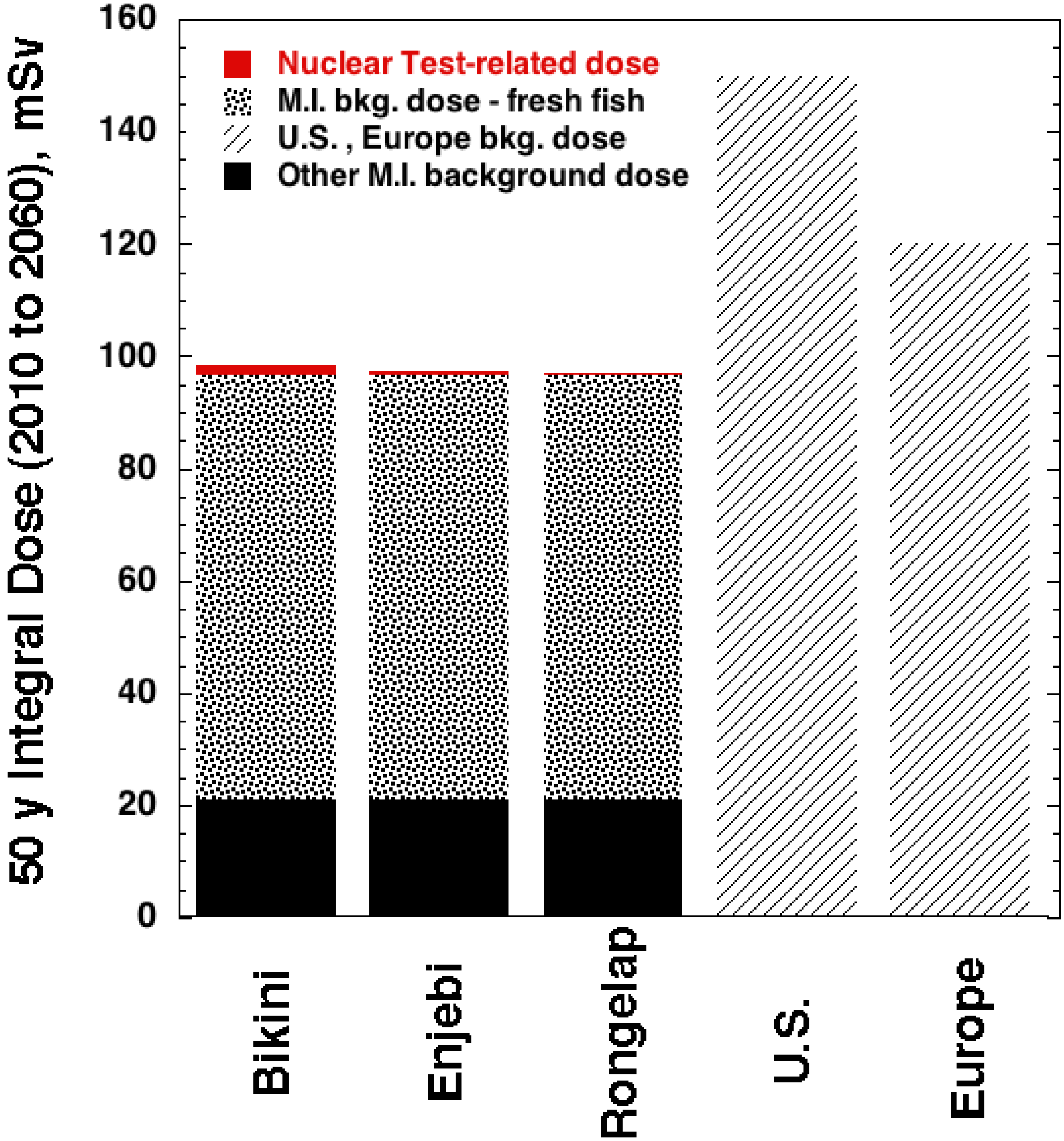
Annual effective dose in year 2010, mSv y-1
2
1.5
1
0.5
0
Before treatment
After "Combined Option"
1.6
0.5
0.08
0.03
0.08
0.17
0.015
current
conditons:
no
remediation
Utirik
Island
Rongelap
Island
Enjebi
Island
Bikini
Island


Annual effective dose in year 2010, mSv y-1
2
1.5
1
0.5
0
After " Combined-Option"
Background dose
No Remediation
0.015
0.03
0.08
0.17
Utirik Island
Rongelap Island
Enjebi Island
Bikini Island
Marshall Islands

A



Nuclear test-related dose
M.I background dose - fresh fish
Radon dose: U.S. and Europe
Other background dose
Annual effective dose in year 2010, mSv y-1
0
0.5
1
1.5
2
2.5
3
3.5
4
Bikini Island
Enjebi Island
Ronglap Island
Utrok Island
United States
Europe



Nuclear Test-related dose
M.I. bkg. dose - fresh fish
U.S. , Europe bkg. dose
Other M.I. background dose
50 y Integral Dose (2010 to 2060), mSv
0
20
40
60
80
100
120
140
160
Bikini
Enjebi
Rongelap
U.S.
Europe