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Overview of Radiological Conditions on Bikini Atoll

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Overview of Radiological Conditions on Bikini Atoll

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Summary

- Bikini Atoll is one of two sites in the Republic of the Marshall Islands that was used by the United States for testing of atmospheric nuclear weapons.
- The nuclear test program on Bikini Atoll produced close-in fallout contamination over much of the atoll forming a continuous source-term for remobilization of radionuclides into the marine and terrestrial environments. Of importance is the fact that long-lived fallout radionuclides were assimilated to different levels into plants, animals and other organisms used for human consumption.
- Residual levels of fallout radioactivity on the atoll have been well characterized, especially for the main residence islands. Today, the residual fallout radionuclides of potential radiological concern remaining on Bikini Atoll include cesium-137 (^{137}Cs) and strontium-90 (^{90}Sr) and, to a lesser extent, the plutonium isotopes and americium-241 (^{241}Am).
- A good understanding has also been developed on all the possible pathways for human exposure to radioactive fallout contamination on the islands and through the marine food chain. The most important pathway for human exposure is ingestion of ^{137}Cs contained in terrestrial foods such as coconuts, *Pandanus* and breadfruit. External gamma exposure provides the second most important radiation exposure pathway with only a minor contribution coming from inhalation of contaminated dust particles.
- The predicted annual effective dose for resettlement of Bikini Island without any form of remediation in 1999 ranges from 15 mSv (1500 mrem) for a local foods only diet to about 4.0 mSv (400 mrem) where imported foods are made available. The compares with the average natural background (unavoidable) dose in the Marshall Islands of about 1.5 mSv (150 mrem).
- In order to reduce the dose from exposure to radioactive fallout contamination on Bikini Atoll, Lawrence Livermore National Laboratory researchers have evaluated several methods for blocking the uptake of ^{137}Cs into plants and food crop products. The most effective and practical method for reducing the uptake of ^{137}Cs into locally grown foods is to treat agricultural areas with potassium fertilizer (KCl). The addition of potassium has the added benefit of increasing the growth rate and productivity of some food crops.
- Assuming imported foods are available and a resettlement date of 1999, the *combined* effects of treating the agricultural areas with potassium fertilizer and removing of the top 25-40 cm of contaminated soil in the village and housing area

where people spend most of their time, reduces the predicted population average annual effective dose on Bikini Island from about 4 mSv y⁻¹ to 0.41 mSv y⁻¹.

- In addition, environmental processes are naturally reducing the dose to hypothetical island residents over time by removing the amount of ¹³⁷Cs available to the plants. This *accelerated environmental-loss rate* of ¹³⁷Cs reduces the amount of ¹³⁷Cs in locally grown foods with an effective half-life of about 8.5 years compared with its radiological half-life of 30 years - or about 3.5 times faster than that predicted in existing dose assessments. Based on this new information, the population average effective dose on Bikini Atoll in 2010, after employing the prescribed remedial measures, will be around 0.17 mSv (17 mrem) or very close to the self-imposed cleanup standard of 0.15 mSv (15 mrem) above-background as adopted by the Republic of the Marshall Islands.
- To ensure that conditions remain below applicable safety standards and to provide assurances to the resettled population, we recommend establishing a post-resettlement radiation surveillance program on Bikini based on *whole body counting* and, if required, *plutonium urine bioassay*. A number of whole body counting facilities have already been established in other parts of the Marshall Islands and are operated by trained Marshallese technicians. *Whole body counting* provides a direct measure of the amount of ¹³⁷Cs in a person's body and does not rely on modeled assumptions associated with predictive dose assessments. This proposed individual radiation protection-monitoring program will also allow potential 'high-end' doses to be accurately tracked and assessed.

History

Bikini Atoll is one of two sites in the northern Marshall Islands used by the United States for testing of atmospheric nuclear weapons. Twenty-three nuclear devices were detonated on Bikini Atoll between 1946 and 1958 with a combined fission yield of 42.2 Megaton (Mt) (UNSCEAR, 2000). An additional forty-three atmospheric nuclear tests were conducted on Enewetak Atoll about 300 km to the west of Bikini Atoll. The most significant contaminating event in the Marshall Islands and the highest yield atmospheric nuclear test ever conducted by the United States involved the detonation of a high-energy experimental thermonuclear device on the northwest fringe of Bikini Atoll on 1 March of 1954. This ground-surface test was code named BRAVO and had an estimated explosive yield of 15 Mt (USDOE, 2000). It is estimated that about 50% of the fission yield associated with near-surface nuclear detonations was deposited on a local or regional scale (Hamilton 2004; UNSCEAR, 2000). The remainder of the debris from near-surface denotations and all the debris from high altitude airbursts entered the global environment producing a worldwide pattern of global-fallout deposition. Prior to BRAVO, little consideration was given to the potential health and ecological impacts of fallout contamination beyond the immediate 'boundaries' of the test sites. However, regional fallout from the BRAVO test unexpectedly caused widespread contamination of Bikini Atoll and forced the evacuation of Marshallese people living on Rongelap and Utrik Atolls (Cronkite et al., 1955).

The vast majority of radionuclides produced in nuclear weapons detonations are short-lived so potential acute-radiation exposure conditions at Bikini and neighboring atolls was most severe in the first few days following nuclear test events. It is important to note that the people of Bikini Atoll were relocated prior to commencement of the test program and were never directly exposed to *fresh* fallout. Today, the dominant radionuclides of radiological concern on the islands of Bikini Atoll include residual concentrations of cesium-137 (^{137}Cs), strontium-90 (^{90}Sr), and the transuranium elements (TRU), namely plutonium-239 (^{239}Pu), plutonium-240 (^{240}Pu), and americium-241 (^{241}Am). These radionuclides are long-lived with half-lives of 30 y, 28 y, 24,100 y, 6560 y, and 433 y, respectively, and are known to transfer continuously through environmental media within the atoll by different physical, chemical and biological processes. However, these longer-lived radionuclides make an insignificant contribution to the predicted total radioactivity burden and ambient dose rates in *fresh* fallout. Thus, from a radiological perspective, the manmade radiation environment on Bikini Atoll has changed dramatically since the early 1950s. Importantly, the acute-radiation exposure hazard that once existed on the atoll during and immediately following test events has declined to an insignificant level with decay of the short-lived *fresh fallout* radionuclides. At the same time, the longer-lived fallout radionuclides were remobilized and assimilated at different levels into indigenous terrestrial plants, fresh-water supplies, and aquatic organisms. The levels and transfer rates of these radioactive contaminants across environmental compartments will depend on the initial release conditions, as well as the mobility and biogeochemical cycling of the various radionuclides contained in the close-in fallout debris. Scientists from the Lawrence Livermore National Laboratory (LLNL) have played a critical role in developing an understanding of the unique relationships between coral atoll radioecology, and its role in controlling the fate, transport and exposure pathways of these residual long-lived fallout radionuclides in the environment.

Current Radiological Conditions

The following discussion provides an initial perspective of *current radiological conditions* on Bikini Atoll and its islands. It also addresses one of the most frequently posed questions concerning this atoll, which is "... to what degree was Bikini Atoll contaminated with radioactive fallout from the nuclear test program?" The degree of terrestrial fallout contamination on Bikini Atoll can most easily be assessed by comparing the measured inventory of specific radionuclides in soils with the expected latitudinal global-fallout deposit. For example, a typical soil profile on Bikini Island contains an average ^{137}Cs inventory deposit of around 80 kBq m^{-2} compared with about 0.5 kBq m^{-2} expected from integrated global fallout deposition (Robison et al., 1997a). This information tells us that close-in fallout debris from the nuclear-weapons testing program on Bikini Atoll has increased the present-day average ^{137}Cs radiation burden on Bikini Island by a factor of about 160. However, due to the heterogeneous nature of local fallout contamination, depositional densities of fallout radionuclides at specific locations on Bikini Island and elsewhere around the atoll may exceed the expected world-wide background deposit by a factor of 1000 or more. Accordingly, the predicted dose rates on

different islands of Bikini Atoll span several orders of magnitude due largely to variations in the original fallout deposit over the atoll, and the effects of post-depositional radionuclide redistribution processes such as weathering and physical disturbance.

The first radiological studies on Bikini Atoll were mostly concerned with gathering information on the effects of ionizing radiation upon fish and other resident marine organisms (1946-1977) (Donaldson, et al., 1997). Since the 1970s, the United States Department of Energy (DOE) has funded scientists from LLNL to conduct periodic missions to Bikini Atoll to monitor both the marine and terrestrial environments. Based on measurement data developed over the past three decades, LLNL scientists have been able to make more accurate predictions about *current radiological conditions* on the islands, and to model the chronic dose and risk to hypothetical Bikini residents. The experimental program on Bikini Island has also been used to develop possible cleanup options designed to minimize exposures of resident populations while having little or no detrimental impact on the environment. A summary of the findings of the Marshall Islands environmental program is presented below.

Early Environmental Characterization Studies and Resettlement of Bikini Atoll

The last series of tests on Bikini Atoll took place between May and July of 1958; however, a plan to resettle Bikini Atoll was not established until 1969 (AEC, 1971). Based on radiation survey data collected at that time, it was concluded that Bikini and Eneu Islands of Bikini Atoll could be used for continuous occupation and agricultural development. It was also believed that the largest contributor to the internal dose would come from ingestion of ^{90}Sr contained in locally grown foods. The rehabilitation program on Bikini Atoll was implemented by the United States and involved a general cleanup of contaminated debris, replanting of Bikini and Eneu Islands with coconut, breadfruit and other food crop products, and construction of 43 homes. About 40 people began living on Eneu Island in 1969 but by 1972 these people, along with an additional 20 women and children, had moved to Bikini Island. The resident population on Bikini Island slowly increased through 1975 until reports were released showing elevated radiation exposure conditions on the island. After a review of radiological data showed “higher levels of radioactivity than originally thought”, the Bikinians filed a successful lawsuit in the U.S. Federal Court in Hawaii to force the United States to postpone the resettlement until a more comprehensive pre-cleanup survey of the northern Marshall Islands could be performed. It was assumed that as newly planted food crops matured and the fruits became available for human consumption, ^{137}Cs body burdens of island residents would increase dramatically and that the resulting annual effective dose might eventually exceed federal guidelines for radiation protection (Robison et al., 1977). Meanwhile, more Bikinians continued to occupy the atoll and consume the locally grown food. In April of 1978, whole-body counting measurements performed by the Brookhaven National Laboratory (BNL) confirmed that many of the 139 people then living on Bikini Island had acquired ^{137}Cs body burdens well in excess of the maximal permissible levels (Greenhouse, 1978).

About 3 months later, the United States Department of Interior under the Administrator for Trust Territory of the Pacific arranged for island residents to be relocated. The Northern Marshall Islands Radiological Survey (NMIRS) began shortly after the people living on Bikini Island were moved back to their temporary home on Kili Island (about 700 km to the south). Following relocation, some infrastructure and housing were retained on Bikini Island to provide essential services to community members and other visitors to the island and to attract potential commercial interests in an effort to develop an economic base for a possible future resettlement of the atoll. Current operations on Bikini Island include a very successful diving and fishing tourist-venture that attracts several hundred paying visitors to the atoll each year. DOE also maintains a presence on Bikini Island to conduct ongoing scientific studies under an agreement between the DOE and Bikini Council and with the support of local Marshallese field workers.

Through the early 1980s, scientists from LLNL developed an extensive database of environmental measurements for Bikini Atoll, especially for soils and vegetation growing on Bikini and Eneu Islands. These detailed radiological monitoring studies were used to assess potential radiation doses from residual radionuclides in the marine and terrestrial environments. Wherever possible, the studies involved direct measurement of radionuclide concentrations in soil and associated food-crop products, as well as air, water resources, fish and resident marine organisms. These data were essential in helping to identify the critical radionuclides and radiation exposure pathways and in providing a scientific basis for improving dose-rate estimates, and helping DOE assist the Bikini Council in making more informed decisions about eventual resettlement of the atoll. During this period, predictive dose assessments for both Bikini and Enewetak Atolls clearly indicated that the most significant pathway for human exposure to *residual* fallout contamination in the Marshall Islands was ingestion of ^{137}Cs present in locally grown foods such as coconut, breadfruit, and *Pandanus* (Robison et al., 1980; 1982).

Remediation Options

The reason that ^{137}Cs plays such a key role in contributing to exposure is because coral soils are known to contain little or no clay material and very low concentrations of naturally occurring potassium—an alkaline earth element that shares similar properties with cesium. These conditions result in increased uptake of ^{137}Cs from soil and incorporation into plants relative to the rate of ^{137}Cs uptake from continental soils. This fact also helps explain why the importance of dietary intakes of ^{137}Cs was initially overlooked because early models in radioecology were based on continental type soils and exposure conditions. Knowledge of the unique behaviors and pathway of ^{137}Cs in potassium-poor coral soil environments was also instrumental in helping guide remediation experiments designed to reduce the potential dose delivered to resettled populations in a effective and environmentally protective manner.

During the 1980s, the first of a series of long-term field experiments was established on Bikini Island to evaluate potential remedial measures (Robison and Stone, 1998). Based on these field experiments, the most effective and practical method for

reducing the uptake of ^{137}Cs into food crop products was to treat agricultural areas with potassium fertilizer (KCl). The addition of potassium had the added benefit of increasing the growth rate and productivity of some food crops with essentially no adverse environmental impact. Excavation of the top 30 to 40 cm of soil also would be very effective in reducing soil ^{137}Cs but obviously this remedial method would be much more expensive to implement. Furthermore, this process carries away all the soil organic matter needed to maintain the water retention capacity of coral soils and supply essential nutrients to support plant growth. Soil excavation also necessitates a very-long term commitment to rebuild the soil and revegetate the land.

Large-scale field experiments on Bikini Island have also been used to optimize the required amount and application rates of potassium. The results from these experiments show that a single application of 2000 kg ha^{-1} of potassium can be effective in reducing the ^{137}Cs uptake in coconut meat (and juice) to about 5-10% of the pretreatment level. Multiple applications (over several months) of the same total amount of potassium produce even better and more consistent results. Moreover, the concentration of ^{137}Cs in the coconuts following such potassium treatment remains low for an extended period of time, so the need for continuous effort and retention of scientific and technical expertise is minimized (Robison et al., 2004). In fact, the use of potassium was adopted by the Rongelap Atoll Local Government (RALG) as part of a *combined option* for remediation and resettlement of Rongelap Island (Rongelap Atoll), about 180 km southeast of Bikini Atoll. The *combined option* consists of treatment of the entire agricultural area of the island with potassium to reduce the uptake of ^{137}Cs into plants and the replacement of contaminated surface soil around the village and housing areas by crushed-coral fill, to minimize external exposure rates in areas where people spend most of their time. This same type of approach would be applicable to reducing ambient dose rates on Bikini Island.

Based on the latest published dose assessment by LLNL researchers (Robison et al., 1997b; also refer to the *Bikini Fact Sheet*—Appendix I), the estimated population average annual effective dose for living conditions on Bikini Island during 1999, assuming no remediation and a mixed diet that includes both local and imported foods, is around 4 mSv y^{-1} (400 mrem y^{-1}). The 30-, 50- and 70-y integral effective doses were also determined at 91 mSv ($9,100 \text{ mrem}$), 130 mSv ($13,000 \text{ mrem}$), and 150 mSv ($15,000 \text{ mrem}$), respectively. The combined effects of adding potassium to agricultural fields and replacing contaminated soil in the village and housing areas with crushed-coral fill could reduce the population average annual effective dose to about 0.41 mSv y^{-1} (41 mrem y^{-1}) (Robison et al., 1997b). Using this scenario, where imported foods are available (the most likely dietary scenario), a detailed uncertainty analysis for these dose estimates shows that no additional cancer fatalities attributable to radiation exposure would likely arise in a cohort of 200 people living on Bikini Island (Bogen et al., 1997). Also, the estimated *maximum* annual effective dose received by Bikini residents under this scenario would be around 2 mSv y^{-1} (200 mrem y^{-1}) compared with about 8 mSv y^{-1} (800 mrem y^{-1}) where only local foods are consumed. For comparison, the worldwide average annual effective dose due to radiation from natural sources is around 2.4 mSv

(240 mrem) (Appendix II). There are, however, large variations in doses from natural sources and it is not unusual to find people living in regions of the world where the annual doses exceed 10 mSv (1000 mrem). In contrast, the estimated annual dose from background radiation in the Marshall Islands at around 1.4 mSv y⁻¹ (140 mrem y⁻¹) is lower than the world average by about half. Over 70% of the natural background dose in the Marshall Islands is delivered by dietary intakes of fresh fish that contain naturally occurring polonium-210 (²¹⁰Po).

Based on the cleanup of contaminated soil near buildings, the use of potassium remediation, and a realistic diet consisting of both local and imported foods, exposure to fallout contamination on Bikini Island after cleanup would increase the average annual effective dose in the resident population by about 30% above background [i.e., (1.4 mSv + 0.41 mSv)/1.4 mSv].

Cleanup Guidance and International Radiation Standards

Currently, there is no explicit international guidance for establishing action levels associated with chronic exposure situations, such as a dose standard or concentration limit for exposure to residual fallout contamination resulting from nuclear weapons testing. However, the Republic of the Marshall Islands (RMI) has adopted a cleanup standard based on an annual effective dose of 0.15 mSv y⁻¹ (15 mrem y⁻¹) using guidance provided by the U.S. Environment Protection Agency (EPA). As discussed above, it appears that the present-day population average annual effective dose on Bikini Island will result in a residual exposure level (~0.41 mSv y⁻¹), which will likely exceed the dose level adopted by the RMI of 0.15 mSv y⁻¹ (15 mrem y⁻¹).

However, it must be emphasized that generic standards or remedial action levels selected for chronic exposure situations need not be applied rigidly. For example, the increased radiation dose delivered to a hypothetical resident population on Bikini Island (and the associated health risk) will fall within the variance of the natural background dose so any decision to resettle Bikini should also consider potential social and economic factors. Simply put, the prospects of reuniting the community and for people to live a much more desirable lifestyle on Bikini Atoll could be viewed as more important or beneficial compared with the risk associated with low-level chronic radiation exposure. Readers are referred to the exposure guidelines for controlling the prospective dose to members of public, with reference to resettlement of Bikini Atoll, as outlined in Appendix II.

Prospects for Resettlement of Bikini Island

Radiological dose assessments for Bikini Island have been developed from samples collected and analyzed as part of a continuing environmental monitoring program on Bikini Atoll (1975-1994). These on-going studies have concentrated on assessing the uptake and remediation of ¹³⁷Cs in terrestrial plants because ¹³⁷Cs delivers, by far, the largest fraction of the radiation dose. Using empirical data from our annual or semi-annual monitoring program of selected trees on Bikini and Eneu Islands we have recently demonstrated that the environmental half-time of ¹³⁷Cs is more important than

radiological decay in controlling the fate and distribution of ^{137}Cs in coral soils (Robison et al., 2003). For example, the estimated effective half-life of ^{137}Cs on Bikini, Enewetak and Rongelap Atolls is around 8 to 9.8 years (95% confidence) compared with its radiological half-life of 30 years. These findings suggest that our existing dose estimates using simple radiological decay-corrected measurement data and prospective integral doses may not be applicable to *current or future radiological conditions* on the atoll. With this knowledge, LLNL scientists have directed their environmental studies towards quantifying the rates of environmental loss of ^{137}Cs using lysimeter collections and measuring the amount of ^{137}Cs washed out of the soil into the underlying groundwater. We have also developed an understanding of the residence time of the fresh water supply and associated contaminants leached into groundwater on Bikini Island. It is also probable that any labile soil ^{137}Cs is slowly being incorporated into more resistant mineral phases and, through aging effects, is becoming less available for soil-to-plant uptake. The lysimeter studies will be completed during 2005. Although the mechanisms involved and the effects of adding potassium on ^{137}Cs mobility are not yet fully understood, the data being collected by LLNL investigators will enable more accurate dose predictions to be developed for various resettlement and cleanup scenarios on Bikini Island. Applying a mean effective ^{137}Cs half-life of 8.5 years for the data developed for the 1999 Bikini dose assessment (Robison et al, 1997b; also refer to the *Bikini Fact Sheet*—Appendix I), the predicted population average effective dose for resettlement of Bikini in 2010, where imported foods are available, is about 0.17 mSv y^{-1} (17 mrem y^{-1}) or very close to the self-imposed cleanup standard adopted by the Republic of the Marshall Islands. With this understanding and the fact that exposure conditions on Bikini are improving at an accelerated rate, early resettlement of Bikini Atoll may become much more plausible and cost effective.

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Appendix I

Bikini Fact Sheet

Bikini Fact Sheet

(Resettlement Date = 1 January 1999)

Predicted dose rates on Bikini based on existing conditions				
<i>scenario</i>	Annual effective dose in mSv y ⁻¹	30-y integral effective dose in mSv	70-y integral effective dose in mSv	Cited literature
Local food only (IUA model diet)	15	350	560	Robison et al. (1997b)
Imported Foods Available (IA model diet)	4	91	150	

1 millisievert (mSv) = 100 millirem (mrem)

Predicted dose rates on Bikini after cleanup[#]				
<i>scenario</i>	Annual effective dose in mSv y ⁻¹	30-y integral effective dose in mSv	70-y integral effective dose in mSv	Cited literature
Local food only (IUA model diet)	1.2	31	50	Robison et al. (1997b)
Imported Foods Available (IA model diet)	0.41	9.8	16	
Interindividual variability and uncertainty analysis[§]				
<i>scenario</i>	Expected individual effective dose in mSv y ⁻¹	Maximum expected individual effective dose in mSv y ⁻¹	Expected population- average 70-y effective dose in mSv	Expected interindividual 70-y effective dose in mSv
Local food only (IUA model diet)	1.4	8.2	52 (30 to 87) ^a	52 (12-180) ^a
Imported Foods Available (IA model diet)	0.45	2	16 (11 to 24) ^a	16 (6.5-45) ^a

1 millisievert (mSv) = 100 millirem (mrem)

[#] The proposed cleanup of Bikini Island involves limited soil removal around the housing and village area and addition of potassium to the agricultural fields; [§] after Bogen et al., 1997 (assumptions : population size = 200 people; ^a uncertainty limits are given by the 2.5th to 97.5th percentile range).

Predicted dose rates on Bikini after cleanup and incorporating effects of the environmental-loss rate of cesium-137				
<i>Date</i>	Annual effective dose in mSv y ⁻¹	30-y integral effective dose in mSv	70-y integral effective dose in mSv	Cited literature
<i>1999 (previous estimate)</i>	0.41	9.8	16	Calculated from Robison et al. (2003)
1999 (revised estimate incorporating environmental loss of ¹³⁷ Cs) [§]	0.41	5.1	5.6	
2004 (predicted) [§]	0.27			
2010 (predicted) [§]	0.17			
2020 (predicted) [§]	0.07			

1 millisievert (mSv) = 100 millirem (mrem)

[§] Assumes that 100% of the post-1999 dose is due to ¹³⁷Cs, and that the effective environmental half-life of ¹³⁷Cs is 8.5 years.

Information Notes

- Today, the residual fallout radionuclides of potential radiological concern on Bikini Atoll include cesium-137 (^{137}Cs) and strontium-90 (^{90}Sr) and, to a lesser extent, the plutonium isotopes and americium-241 (^{241}Am).
- The predicted annual effective dose for resettlement of Bikini Island in 1999 for current conditions was estimated at 15 mSv for a local foods only diet (IUA model diet) and 4.0 mSv when 60% imported foods are made available (IA model diet). Under the latter dietary scenario, the ingestion of ^{137}Cs contributed about 90% of the estimated total annual effective dose. External exposure for occupancy of Bikini Island in 1999 contributed about 0.42 mSv or about 10% of the total annual effective dose.
- LLNL scientists have evaluated several methods for reducing the uptake of ^{137}Cs into plants and food crop products in order to help reduce the radiation dose from ingestion of ^{137}Cs . The most effective and practical method for reducing the uptake of ^{137}Cs into food crop products is to treat agricultural areas with potassium fertilizer (KCl). The addition of potassium has the added benefit of increasing the growth rate and productivity of some food crops.
- Assuming imported foods are made available and a resettlement date of 1999, the *combined* effects of treating the agricultural areas with potassium fertilizer and removing of the top 25-40 cm of contaminated soil in the village and housing area where people spend most of their time, reduces the estimated population average annual effective dose on Bikini Island from about 4 mSv y^{-1} to 0.41 mSv y^{-1} . In addition, environmental processes are naturally reducing the dose to hypothetical island residents with increasing time by removing the amount of ^{137}Cs available to the plants. This *accelerated environmental-loss rate* of ^{137}Cs reduces the amount of ^{137}Cs in locally grown foods with an effective half-life of about 8.5 years compared with its radiological half-life of 30 years - or about 3.5 times faster than that predicted in existing dose assessments. Based on this new information, the population average effective dose on Bikini Atoll in 2010, after employing the prescribed remedial measures, will be around 0.17 mSv (17 mrem) or very close to the self-imposed cleanup standard of 0.15 mSv (15 mrem) above-background as adopted by the Republic of the Marshall Islands.
- To ensure that conditions remain below applicable safety standards and to provide assurances to the resettled population, we recommend establishing a post-resettlement radiation surveillance program on Bikini based on *whole body counting* and, if required, *plutonium urine bioassay*. A number of whole body counting facilities have already been established in other parts of the Marshall Islands and are operated by trained Marshallese technicians. *Whole body counting* provides a direct measure of the amount of ^{137}Cs in a person's body and does not rely on modeled assumptions associated with predictive dose assessments. This proposed individual radiation protection-monitoring program will also allow potential 'high-end' doses to be accurately tracked and assessed.

Appendix II

Exposure Guidelines for Controlling the Prospective
Dose to Members of the Public

Guidance for controlling the prospective radiation dose to members of the public[#]		
Agency	Annual effective dose in mSv y⁻¹	Guiding principles
National Council on Radiation Protection and Measurement (NCRP) (NCRP, 1987)	1.0	Applies to controlling practices and the prospective dose from operations such as the nuclear industry, uranium mining, and storage facilities, etc., that may have potential for exposing the general public. Usually applied to the above-background (or the avoidable) population average dose.
International Commission and Radiological Protection (NRC) (ICRP, 1990)	1.0	Applies to controlling practices and the prospective dose from operations such as the nuclear industry, uranium mining, and storage facilities, etc., that may have potential for exposing the general public. Usually applied to the above-background (or the avoidable) population average dose.
Basic Safety Standards (FAO et al., 1996; ICRP 1993; ICRP 1984)	10	The principles of radiation protection in the Basic Safety Standards were developed by the ICRP and the International Nuclear Safety Advisory Group (INSAG) to the International Atomic Energy Agency (IAEA). The provisions of the Standards provide generic guidance for balancing risks and benefits in seeking to reduce radiation exposures or the existing likelihood of incurring an exposure. These standards are not considered part of a controlled practice, and are termed 'interventions'. There is no explicit international guidance on generic action levels for chronic exposure situations associated with previous activities or events such as nuclear weapons testing. According to Basic Safety Standards, some form of intervention would normally be required if dose rates are greater than 10 mSv per year, during emergency situations or when the lifetime dose cannot be reduced by other means and is projected to exceed 1000 mSv. Below this level, the Basic Safety Standards encourage decision makers to use a value judgement under a guiding principle that any action should cause 'more good than harm', i.e., any intervention must be justified in terms of costs, and the impacts and benefits to individuals, the environment or on society compared with the health-related risks posed by a pre-existing radiologic conditions.
United States Environmental Protection Agency (EPA) (EPA, 1989; 1992)	0.15	The U.S. EPA favors a risk based radiation protection approach with emphasis on protecting <i>reasonable</i> maximal exposed individuals. The EPA considers a risk factor of 1 in 10,000 to be potentially excessive.
Republic of the Marshall Islands Claims Tribunal	0.15	Adopted from the U.S. EPA guidance for cleanup of Superfund sites

[#] Usually applied to the above-background (or the avoidable) dose

Radiation Terms and Exposure Guidelines

- A millisievert (mSv) is the SI (International System of Units) measure of dose equivalent—a standardized quantity used to measure the biological effects of radiation. It is defined as the product of the energy deposited (absorbed dose) and the effectiveness of the type of radiation (quality factor). The traditional term millirem (mrem) is still used; 1 mSv = 100 mrem.
- Radiation exposures in excess of 4000 Sv can cause death within days or weeks of exposure¹. Short duration exposures of 2000 Sv can affect normal cell function, and may lead to infections and temporary sterility. Doses in excess of 300 mSv (i.e., 30,000 mrem) are known to cause cancer. A typical routine chest X-ray delivers about 0.06 mSv or 6 mrem.
- The National Council on Radiation Protection and Measurements (NCRP) and the International Commission on Radiological Protection (ICRP) recommend annual dose limits for public exposures to manmade radiation sources, other than for medical reasons, of 0.1 mSv (100 mrem) for continuous exposure and 0.5 mSv (500 mrem) for infrequent exposures. For occupational exposures, the NCRP recommends the use of a 50 mSv (5000 mrem) annual dose limit. Exposures should always be lower than the specified limits, and under the principles of ALARA (As Low As Reasonable Achievable), they should be much lower. These guidelines are developed for controlling prospective dose above background for practices such as the nuclear industry and do not directly apply to chronic exposure situations such as pre-existing conditions associated with fallout contamination from nuclear weapons testing.
- Within the United States, authority for administering federal radiation standards is shared between the Nuclear Regulatory Commission (NRC) and United States Environmental Protection Agency (EPA). The NRC implements radiation standards to regulate civilian sources of radiation including decommissioning of nuclear facilities. The EPA issues public protection standards and administers the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (Superfund) governing cleanup of federal and nonfederal facilities. Both agencies have historically differed over how restrictive radiation standards should be and what determines an acceptable risk for cleanup sites. Generally, radiation protection strategies used by different regulators imply that even the smallest radiation exposure carries some risk under the assumption of a linear, no-threshold hypothesis or model, and that radiation standards should provide all-pathway protection. The EPA applies more restrictive standards using a risk-based radiation protection approach especially when groundwater protection for drinking water is involved. The EPA favors an all-pathway public radiation protection standard of 0.15 mSv y⁻¹ (15 mrem y⁻¹) with additional limits for drinking water, while the NRC has set a single all-pathways limit of 0.25 mSv y⁻¹ (25 mrem y⁻¹). In theory only the avoidable dose above background is considered in comparisons with proposed actions levels.
- There is no explicit international guidance on generic action levels for chronic exposure situations associated with previous activities or events such as nuclear

weapons testing. However, the principles of radiation protection as described under the Basic Safety Standards developed by the International Commission and Radiological Protection (ICRP) and the International Nuclear Safety Advisory Group (INSAG) to the International Atomic Energy Agency (IAEA), state that remedial actions in chronic exposure situations are not normally necessary unless appropriate (generic) action levels are exceeded. In this instance, decision makers are encouraged to make a value judgment on the relative benefits and risks associated with an intervention strategy, taking into account social, environmental, and economic factors. For example, it is probable that the prospects of people living a more enjoyable and culturally acceptable lifestyle on Bikini Atoll may overshadow societal fear of radiation and the potential radiation detriment caused continuous exposure to low-level fallout contamination on the atoll after resettlement.

- The annual effective dose that people unavoidably receive from natural background radiation is, on average, about 2.4 mSv world-wide and about 3.0 mSv in the United States. Medical procedures such as X-ray and the use of nuclear medicine contribute another 0.5 mSv (50 mrem) or about 17% of the total population average annual effective dose equivalent in the United States.

Naturally Occurring Background Radiation[#]		
<i>Location</i>	Annual effective dose in mSv y ⁻¹	Critical radioisotopes and exposure pathways
World-wide (UNSCEAR, 1993)	2.4	<i>Cosmic</i> radiation (app. 22 mrem y ⁻¹ at sea level) <i>External</i> - ⁴⁰ K, ⁸⁷ Rb, and the ²³⁸ U & ²³² Th decay series radionuclides in the environment, construction materials, other <i>Internal/diet</i> - ¹⁴ C, ⁴⁰ K, ⁸⁷ Rb, ²¹⁰ Po in food and water <i>Inhaled</i> - greater than 50% of the total annual effective natural background dose delivered to the world's population can be attributed to radon and radon decay products.
United States (NCRP, 1987)	3.0	<i>Cosmic</i> radiation (app. 22 mrem y ⁻¹ at sea level) <i>External</i> - ⁴⁰ K, ⁸⁷ Rb, and the ²³⁸ U & ²³² Th decay series radionuclides in the environment, construction materials, other <i>Internal/diet</i> - ¹⁴ C, ⁴⁰ K, ⁸⁷ Rb, ²¹⁰ Po in food and water <i>Inhaled</i> - greater than 50% of the total annual effective natural background dose delivered to the United States population can be attributed to radon and radon decay products.
Marshall Island (Noshkin et al., 1994)	1.4	<i>Ingestion</i> ~1 mSv y ⁻¹ from the intake of polonium-210 (²¹⁰ Po) contained in fresh fish and other marine products

[#] Dose that people unavoidably receive from natural sources of radioactivity in the environment

