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Bikini Atoll Rehabilitation Committee

Interim Report

Resettlement of Bikini Atoll: Feasibility and Estimated Cost of Meeting the Federal Radiation Protection Standards

Submitted to the U.S. Congress, House and Senate Committees on Interior Appropriations, pursuant to Public Law No. 97-257, Department of Interior Account No. TT-1587X08, Washington, D.C., November 23, 1983

BIKINI ATOLL REHABILITATION COMMITTEE

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THE FEDERAL RADIATION PROTECTION STANDARDS

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SUMMARY AND CONCLUSIONS

1. Bikini and Eneu, the chief islands of the Bikini Atoll, were contaminated in 1954 by radioactive fallout from US weapons-testing executed after the Bikini population had been removed (in 1946). Today the Bikinians number some 1,100 persons and there is strong sentiment for a return to their Atoll. Additional islands of the Atoll were affected by the 1954 shot as well as by other shots between 1946 and 1958.

2. The Bikini Atoll Rehabilitation Committee, set up in 1982 by Act of Congress (Public Law No. 97-257), will present its final report in 1984 on feasibility and cost. This interim report's principal findings are as follows.

3. Decontamination is technically feasible. At present, the major approaches are:
(a) Especially where radioactive contamination of soil is small, resettlement might be permitted with the proviso that no local foods except fish will be eaten during a specified period of years. (During the selected period, the soil's level of radioactive contamination declines spontaneously to a permissable level.)
(b) For any level of soil contamination, but especially for the greater ones, removal of contaminated soil is the method of greatest certainty or in some cases the only feasible one.

4. Assuming the legality of selected soil-disposal alternatives, the estimated approximate cost to meet Federal Radiation Protection Standards is of the order of $100 million and would require 2-4 years of on-site effort for the two major resettlement islands of Bikini and Eneu.

5. A major legal task associated with planning relates to the disposal of contaminated soil. At present, the law is unclear both with respect to where the ultimate authority for such disposal lies and what the specific requirements are.

1. THE PROBLEM

This is the interim report of the Bikini Atoll Rehabilitation Committee whose purpose, defined by Congress, is to determine the feasibility and estimated cost of a cleanup of Bikini Atoll (1). "Cleanup" as used here is equivalent to rehabilitation; "feasibility" will be evaluated in terms of cost, time, and environmental quality. Since no one plan may be ideal, several alternatives will be presented.

The Committee was set up by the Office of Territorial and International Affairs, Department of the Interior, working with the people of Bikini. Although funded by the Congress, this report is not a Government report; it has not been approved by any Government agency, and its contents are solely the responsibility of the Committee.

The Committee anticipates that its final report will be presented in mid-1984, when additional needed material will have become available. However, the trend of the Committee's findings already has become evident and therefore is reported now.

1.1 Background

In 1946 the US Government moved the 167 inhabitants of Bikini Atoll off their islands so that the atoll could be used for the testing of nuclear weapons. That program ended in 1958 after 23 tests. One of these, the 1954 Bravo shot of a thermonuclear device, showered Bikini and other atolls with radioactive fallout (2).

The Bikini people were moved first to Rongerik Atoll, then briefly to Kwajalein, and then in September 1948 to Kili Island, some 425 miles south of Bikini Atoll (3).

In 1968, President Johnson was advised by the Atomic Energy Commission that the main islands of Bikini Atoll were safe (but should be monitored in the future), and permission for resettlement was given. In 1969, therefore, the Department of Defense and the Atomic Energy Commission cleared the atoll of brush, debris, and abandoned equipment, and during 1970-73, thousands of coconut trees were planted on Bikini and Eneu Islands with the help of a number of Bikini people who had begun the resettlement (3).

The 1978 examination of the settlers by a team from Brookhaven National Laboratory revealed significant body burdens of the radionuclide cesium-137 (4). As of result of these and additional findings by the Department of Energy (5), the 139 settlers were evacuated in August 1978, and settlement has not been allowed since that time.

Studies by the Lawrence Livermore National Laboratory team, especially during the past 6 years, have accumulated extensive information on the excessive radioactivity of Bikini soil, plant products (6) and water (7). The validity of these data was questioned by the Bikini people on the basis that, coming from a Government laboratory, the testing may have been biased. However, a review in 1982 by independent consultants selected by the Bikini people (Epidemiology Resources, Inc.) confirmed the Lawrence Livermore findings and concluded that Bikini Island, judged by US radiation protection standards, should not be resettled (8).

The scarcity of land in the Marshall Islands and the cultural significance of land ownership make resettlement of Bikini Atoll a matter of overriding importance for the Bikini people. There are today approximately 1,120 Bikinians, of whom some 600 dwell on Kili Island, about 200 on Ejit Island in Majuro Atoll, and the rest elsewhere in the Marshalls. The Committee estimates that more than 75 percent of the population is under 30 years of age, and the majority is probably well under 20, perhaps even under 15. The population has been increasing at a rapid rate.

There are two aspects to the problem of Bikini Atoll resettlement. First, residence on the atoll must satisfy Federal radiation protection standards. Second, the atoll's physical and biological characteristics must meet the requirements of Bikinian tradition and of present-day Bikinian culture. This report, while primarily addressing the first of these aspects, does so with the second one in mind.

1.2 Geography and Political Status

Bikini Atoll is part of the Republic of the Marshall Islands, which has a total land area of about 170 km^2 (66 square miles) scattered over roughly 700,000 km^2 of the central Pacific Ocean (Figure 1). The Marshall Islands, together with the Caroline and Mariana Islands, comprise the Trust Territory of the Pacific Islands which the United States has administered since 1947 under a Trusteeship Agreement with the United Nations. On September 7, 1983, the voters of the Marshall Islands ratified a Compact of Free Association which, if passed by the US Congress, will define the Marshall Islands' future relationship with the United States and the international community.

The population of the Marshalls numbers some 33,000 persons. The principal population centers are on Majuro Island, the capital (Majuro Atoll), and Ebeye Island in Kwajalein Atoll, which is a missile range under the jurisdiction of the US Army.

Bikini Atoll is located 4,000 km (2,500 miles) southwest of Hawaii, at 11°35' N, 165°25' E. It comprises a ring of 23 islands with a total land area of 8.8 km^2 (3.4 square miles), including 1.6 km^2 (0.6 square miles) of intertidal area (Figure 2, Table 1). The lagoon of 630 km^2 (243 square miles) has an average depth of 45 m (148 feet); the maximum depth is 58 m.

The geological structure is that of a deep oceanic atoll. The islands are made of reef debris, primarily of sand and gravel size, and reef organisms. The reef is continuously being built and eroded, but under present conditions the islands and the passes that connect lagoon and ocean are fairly stable.

The atoll today is typical in appearance, and the principal islands of Bikini and Eneu are thickly covered with vegetation. The sandy soil supports a variety of plants, shrubby thickets along exposed coasts, and coconut plantations over most of the two larger islands. A variety of other food plants can be grown, but because of the long dry season, they are not likely to become staples.

1.3 Radiation Exposure and Control

Studies by the Lawrence Livermore National Laboratory monitoring group during recent years have shown that unrestricted settlement on some smaller islands would conform to Federal radiation protection standards now, or would do so within 15-30 years as a result of the spontaneous decay of the contaminating radionuclides (6). However, on the main island of Bikini, this would not be the case, as the Brookhaven National Laboratory team demonstrated by direct measurements on settlers in 1978 (4).

The radiation dose from resettlement today would result primarily from eating locally grown food (6). More than 90 percent of the dose would stem from the radionuclide cesium-137, and most of the rest would come from strontium-90. Coconut products would account for some 80 percent of the ingested dose, but neither cistern drinking water nor marine foods would make a quantitatively important contribution. As discussed later, contaminated ground water might be a formal problem.

It therefore appears that resettlement of the atoll under conditions that meet Federal radiation protection standards may require either or both of two lines of action: control of diet and/or decontamination of the soil.

If the Bikinians eat no local produce, resettlement might be permitted today or within a few years. If the Bikinians wait 100 years, spontaneous radionuclide delay alone will permit unrestricted resettlement of Bikini Atoll.

If, however, the settlers want to be free to consume local foods now, the radiation standards can be met only by taking major steps to render the soil innocuous. Five general methods are apparent:

(a) Chemical Treatment. Treat the contaminated soil to block the uptake of cesium-137 by plants.

(b) Removal and Replacement. Remove the top layers of contaminated soil and replace them with fresh soil.

(c) Topping. Cover the contaminated soil with a layer of fresh soil thick enough to contain most of the absorbing roots.

(d) Washing. Wash out the radionuclides with water.

(e) Biological Extraction. Remove cesium by cropping plants.

These methods are discussed generically in Section 4, followed in Section 5 by cost estimates for some examples of their application. The basis for employing them depends on the soil contamination data for the atoll as detailed in Section 2, and on the calculation of dose given in Section 3, which in turn is based on knowledge of the contamination level of atoll foods and on assumptions regarding diet. The interrelationships of these various factors are illustrated in the dose assessment model of Figure 3.

2. CONTAMINATION

The Bravo shot in 1954 deposited radioactive fallout unevenly throughout Bikini Atoll (Table 1). Today the contamination is less, owing to the spontaneous decay of the radionuclides involved (e.g., cesium has fallen 50 percent in 30 years), and in the case of the lagoon waters, also owing to a rapid exchange with the open sea.

The low "specific activity" of the radionuclide contamination in the Bikini Atoll is expressed in picocuries per gram (pCi/g) of soil or other substance. One picocurie per gram signifies that one atom in one gram of substance disintegrates and emits radiation every 27 seconds. A gram of soil contains more than 10^{21} atoms (1,000 billion billion).

2.1 Lagoon

Although the levels of contamination may have been high immediately after the 1954 Bravo shot, by 1972 the specific activity of lagoon water was low enough to meet the Federal drinking water standard for fresh water. The 1972 levels in pCi/g were: cesium-137, .0007; strontium-90, .0005; plutonium, .000007 (9). For comparison, the specific activity of potassium-40, a natural constituent of sea water, is 0.3 pCi/g (10, page 30).

The specific activity of the lagoon sediment (0-4 cm depth) is considered low although 1,000 times that of lagoon water. Cesium-137 activity is generally below 10 pCi/g (Figure 2), and on the lagoon bottom within 15 km of Eneu and Bikini Islands it is 0.1 - 1 pCi/g (11). The levels of other radionuclides in the Bikini-Eneu area are: cobalt-60, <1; plutonium, <5; americium-241, <5 pCi/g.

A study of specific activity in sediment down to depths of 100 cm or more is scheduled for the fall of 1983 with the cooperation of the

Lawrence Livermore team. It is anticipated that no increase with depth will be found, so that material dredged from the bottom should offer a large, relatively convenient source of backfill and landfill. While the sandy bottom is generally flat and thus suitable for dredging, numerous coral heads emerge, some of which may exceed 1 km in diameter and stand 30 or more meters high. There is also a forbidden area of sunken ships, from the 1946 tests, which poses a threat of oil (not nuclear) contamination from the ships' tanks.

2.2 Islands

The 21 islands of the atoll listed in Tables 1 and 2 vary greatly in size and in contamination. Only two of them are larger than 1 km^2--Bikini (2.4 km^2), and Eneu (1.2 km^2); two are 0.5 - 1 km^2, and a dozen are less than .11 km^2.

The major nutritional elements of the soil, judged by their distribution in depth, fall into two major classes. The concentrations of extractable potassium and of total phosphorus, nitrogen, and organic matter fall off with depth to become small below 50 cm (20 in.) as shown in Table 3. Cesium-137 follows this pattern (Tables 2 and 3) and is thought to be associated with the organic matter and with microorganisms. On the other hand, the concentrations of nonradioactive strontium and calcium are practically constant, and that of magnesium rises with depth. These tests, currently to 40 or 60 cm, are being extended at some sites to 100 cm.

Among the fallout elements associated with nuclear weapons, the transuranics--plutonium-239, -240 and americium-241--have turned out to be unimportant at Bikini because they are scarcely taken up by plants, and in addition, their specific activities in Bikini soil are relatively low, i.e., about 10 percent that of cesium-137 plus strontium-90 (12N*;

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* The N attached to the reference number signifies a note in the list of references.

Tables 3, 6, and 7 in Reference 6). They will be subject to further review in the final report for which we expect to have more detailed information from the Lawrence Livermore National Laboratory.

The two major contaminants today are cesium-137 and strontium-90, which are present in soil at roughly equal specific activities (Table 3). However, the total strontium in soil (non-radioactive plus radioactive) amounts to 2000-4000 parts per million, whereas cesium is less than 1.3 parts per million. The difference is not due to weapons testing.

Cesium-137 is by far the more important contaminant since it is readily taken up by plants, moving in much the same way as potassium, an essential element with which it might compete for uptake. Its specific activity varies in different foods, but in each case tends to rise and fall with the specific activity of the soil. Furthermore, plants may concentrate cesium by as much as three to five times over the soil level (6).

The specific activity of strontium in plants is low, in part because the great abundance of calcium in atoll soil tends to suppress the uptake of all strontium (both radioactive and non-radioactive), and also because the radioactive fraction of strontium is only a minute fraction of the non-radioactive strontium with which it "competes" for uptake. For the final report we expect to receive from the Lawrence Livermore National Laboratory more information on the distribution of strontium-90 than given in Table 3.

The cesium surface-contamination of the two most important islands for resettlement is: Bikini, 60 pCi/g; Eneu, 3.5 pCi/g (Table 1).

The following facts and impressions have emerged thus far concerning the distribution of cesium-137 on Bikini and Eneu. (It should be noted that cesium activities are dated and often are projected to 1987, the earliest year in which resettlement might seem likely to occur.)

(a) In Table 2, both median and mean values of cesium-137 activity are given for the pooled data of each island at each depth. The marked differences between the two statistics reflect the marked variation among the sampling sites. This is illustrated in detail by the frequency distributions in Table 4, where on Bikini at 50 cm average depth 47 percent of the sites are below 1 pCi/g, 26 percent are between 5 and 29 pCi/g, and 3 percent are 62-83 pCi/g.

(b) Since the sampling sites had not been chosen to represent the whole of Bikini or Eneu, a distributed island mean was calculated, i.e., each island was divided into 6 areas, the median value for each area was obtained, and the 6 medians were averaged to obtain a mean value for that island. The distributed means are plotted in Figure 4, where the smooth, roughly parallel curves show that the specific activity on Bikini is of the order of 10 times that on Eneu. For the surface zone (0-10 cm), the specific activities are: Bikini, 55 pCi/g; Eneu, 4.4 pCi/g (Table 2).

(c) For the so-called rooting zone of 0-40 cm, the distributed means for Bikini and Eneu are 32 pCi/g and 2.8 pCi/g, respectively (Table 2).

(d) For the 40-60 cm zone on Bikini Island (Table 4), the mean activity of cesium-137 is 3.2 pCi/g (excluding the two outliers). Therefore, removing the top 50 cm of Bikini soil would produce a new surface zone with less activity than that of the Eneu surface zone of 4.4 pCi/g.

(e) Although specific activity falls more or less smoothly with depth (Figure 4), there was a significant number of locations where this was not so or where an increase occurred (e.g., Table 4). Presumably such instances resulted from soil disturbances during cleanup and coconut planting, which began in 1969. Surprisingly, unlike cesium-137 on Eneu, the specific activity of strontium-90 (Table 3), of the plutoniums and of americium-241 do not appear to decline with depth as they do on Bikini (6).

During cleanup operations, therefore, it would be necessary to monitor each area after soil removal in order to take special measures in the case of residual pockets of high activity.

2.3 Water Supply

Any rehabilitation program must plan specifically for an adequate water supply. Although the variable rainfall is estimated to be in the range of 100-200 cm (40-80 inches) per year at Bikini Atoll, droughts are frequent. Water scarcity here as elsewhere in the Marshalls is relatively common even with the use of the customary cisterns. Cistern (rain) water, which is uncontaminated, is preferred to the more or less brackish ground water, and it accounts for the bulk of water consumed. Traditionally, coconut fluids make an important contribution to drinking needs.

Ground water accumulates in the following way. Rain water drains through the permeable soil and accumulates in the underlying porous rock and sand matrix as a roughly lens-shaped body of fresh water, floating on the denser salt water. Most of the fresh water is rapidly mixed with the underlying salt water by wave and tidal activity, leaving only a very thin fresh layer, usually in the central portion of the island. The smaller the island, the more rapidly mixing occurs, and hence the smaller the fresh-water body.

The quality of the ground water varies with time of day, season, location of well, and rate of withdrawal from the well. Only an initial sampling (1975) of four wells on Eneu and six on Bikini has been reported for radioactivity (13). The radionuclide content of the water was relatively low, but did not meet the Federal standard (Table 5, Section 3.3). The chloride and sulfate concentrations were in the range of 6-1800 ppm and 4-370 ppm, respectively.

The average ground water activities of Bikini Island were 4-12 times those of Eneu (cesium-137, 370 pCi/liter; strontium-90, 130 pCi/liter). Thus, they roughly paralleled the differences in soil activity, but were smaller. More information is needed on the causes of the great variation among wells and on the potentialities of the ground water system.

3. RADIATION EXPOSURE, DOSE, AND PROTECTION STANDARDS

Owing to natural terrestrial and cosmic sources of ionizing radiation, everyone on earth is irradiated, the average dose per person being approximately 0.2 rem per year. In the case of the Marshall Islanders, the natural dose is less than 0.1 rem (14 N, 15, 16).

Federal radiation standards (17-19) have been established to control radiation dosage from man-made sources (medical sources excepted), e.g., the overall average annual dose from man-made sources shall be no more than 0.17 rem (whole-body equivalent) or a total of 5 rem in 30 years (Table 6). From a practical point of view, the Bikini-resettlement, man-made annual dose would be the sum of two kinds of exposure, external from the radiations leaving the contaminated soil, and internal from the radiations emitted by radionuclides consumed in food and water or inhaled as gas or dust.

Cesium-137 would account for practically all man-made external dose (half-life, 30 years; 0.52 MeV beta, .66 MeV gamma.) It also would account for practically all internal dose excepting to bone marrow, which would receive an additional 5 percent from strontium-90 (half-life, 28 years; 0.54 MeV beta) (6).

The calculation of the external and internal doses depends on knowledge of soil contamination and food contamination, and on assumptions regarding the Bikini diet (Figure 3). Although the levels of contamination in the atoll may differ 100-fold, in no case will such estimated doses be great enough to induce a direct acute or subacute reaction in man (16, Annex J). In fact, the levels are low enough so that all islands may be visited now without risk. The dangers of exposure, if any, would be registered as a late effect, namely, a small increase in the lifetime risk of cancer, if sufficient, contaminated, island-grown food is eaten over one or more decades and sufficient time elapses for the cancer to appear (20).

In this interim report, the discussion of dose centers on Bikini and Eneu since these islands would be the primary sites of resettlement.

3.1 External Dosage

Calculated for 1987, the annual external doses for Eneu (.012 rem) and Bikini (.16 rem) will meet the Federal radiation protection standards in Table 6 of .17 rem (population average per year per individual), and of 5 rem (cumulative for 30 years) (Eneu .27 rem, Bikini 3.5 rem). Therefore, if no locally produced food is eaten, both islands are suitable for resettlement in 1987. (Note, however, the discussion on drinking water in Section 3.3, below.)

3.2 Internal Dosage

Dosage due to inhalation is trivial (6), so that food and water consumption are the primary considerations. Just what the Bikinians eat today and what they will eat tomorrow if they resettle Bikini Atoll is not clear. It is a difficult if not impossible task to project accurately the future Bikini diet. The Committee has arranged for a study of the dietary profile of the Bikinians who now reside on Kili.

The single most important factor in the diet is coconut consumption, which accounts for 80 percent or more of the internal dose (6). The Lawrence Livermore team assumed that dietary estimates for Enewetak people made by a Micronesian Legal Services investigator in 1979 would apply to the resettlement of Bikini. The Enewetak people at that time lived on Ujelang Atoll. On the other hand, the importance of the coconut appears to have decreased as imported foods play an increasingly prominent role in the Marshallese diet, and as the Marshallese life-style is affected by external cultures.

The Lawrence Livermore dose calculations indicate that Eneu may be resettled now without limitation of diet (Table 7). However, Bikini may be resettled only under very strict dietary control, otherwise the 30-year total doses would range from 17.7 to 30.7 rem under various conditions (Table 7, internal dose options a-d plus external dose).

The Lawrence Livermore dose calculations were reviewed in 1982 at the request of the Bikini people by Epidemiology Resources, Inc. (ERI), an independent consultant (8). In general, there was agreement, but ERI noted that some earlier observers had indicated greater coconut consumption or utilization (21 N, 22 N). ERI therefore proposed the use of an "index dose" that would be based on a kind of midpoint of estimates of coconut use. The index dose is defined as 2.5 times the Lawrence Livermore internal dose for the conditions "imports freely available 75 percent of the time," and in the present case equals 44 rem for the Bikini 30-year cumulative dose (Table 7). The index dose therefore is much more conservative hygienically, but it is not necessarily more accurate.

3.3 Drinking Water

Cistern (rain) water is practically uncontaminated, and is the chief source of drinking water. Radionuclide levels in ground water, though low, are notable because they exceed one of the two pertinent Federal standards (Table 6).

First, water consumption is regulated by the total-body Federal standard of 5 rem over 30 years. On Bikini and Eneu today, however, the ground water contribution would be less than 5 percent of the total, even when estimated on the unrealistically high consumption of 2 liters per day. Actual ground water consumption is estimated at about 0.25 liter per day by the Lawrence Livermore group.

Second, drinking water is regulated by a "practical" Federal standard (18) that sets activity limits for cesium-137 at 200 pCi/liter and strontium-90 at 8 pCi/liter (Table 6). When two or more nuclides are present, the standard for each is reduced proportionally.

In 1975, three or four test wells on Eneu exceeded the practical strontium standard, as did five of six wells on Bikini (13). None of the Bikini wells met the practical cesium standard (see Table 5).

Decontamination of Bikini Island soil should lead to a large reduction in ground water contamination. This follows from the fact that the specific activity of Eneu soil is of the order of one-tenth that of Bikini soil and the specific activity of its ground water is also lower. However, the marked variation among wells indicates the presence of complicating factors. The amount of published information on the subject is small and more is needed.

It should be noted that the potential problem of ground water quality would be largely if not entirely avoided by the construction of an adequate rainwater collection system.

It also is important to note that the very low practical standard for drinking water is flexible. The Environmental Protection Agency (EPA) may grant variances when it is established that health will not be affected thereby.

4. MEETING THE PROTECTION STANDARDS: GENERIC METHODS

Seven general approaches are available to solve the radiation protection problem. The first two deal with people:

(a) Delay resettlement until spontaneous decay of the radionuclides adequately reduces their specific activity, or

(b) Allow resettlement, but control the consumption of local produce.

The other five, as noted in Section 1.3, involve working with atoll soil. They are:

(c) Chemical treatment,

(d) Removal and replacement,

(e) Topping,

(f) Washing, and

(g) Biological extraction.

Before reviewing these methods, however, it is necessary to select the soil level of cesium-137 that is to be attained by their application.

4.1 Cesium-137: Liminal Activity

To permit resettlement, the average specific activity of the soil's rooting zone should be below a selected level, hereafter termed the liminal specific activity. The rooting zone is defined at present as the layer lying 0-40 cm below the surface. As a baseline, we shall begin with unrestricted conditions of resettlement. Furthermore, we shall focus on the liminal specific activity of cesium-137, since it is the overriding factor in contamination and since steps taken to control it will also mitigate the effects of other radionuclides.

Since the liminal activity cannot be estimated theoretically, it is fortunate that the Eneu data offer an empirical approach to its estimation, as follows. Two reasonable dose-estimates have been projected for the resettlement of Eneu, and they are within 40 percent of the 5-rem 30-year standard (Section 3.2, Table 7). Both assume the availability of imported food during 75 percent of the year and of local food throughout the entire year, but they differ on the precise details of the diet. We conclude therefore that the standard will be roughly met if the specific activity of cesium in soil is like that at Eneu.

The precise liminal level for planning will depend on which of the two estimates of dose is accepted (Section 3.2). The Lawrence Livermore estimate of 2.8 rem is 56 percent of the 5 rem Federal standard; therefore, the associated cesium-137 specific activity of 2.8 pCi/g in the rooting zone likewise would be 56 percent of a projected liminal soil value of 5 pCi/g.

The index-dose estimate of 6.4 rem is 28 percent above the standard (Table 7). On this basis, the soil level of cesium-137 (2.8 pCi/g) likewise must be 28 percent too high and should be reduced to a liminal value of 2.2 pCi/g or less. In doing so, we assume that dose is directly proportional to rooting-zone specific activity over a small range of extrapolation.

As noted, the two dose estimates depend on two different diets. When the results of the Committee-sponsored study of the diet currently used by Bikinians on Kili Island is reported, it may be necessary to consider a third possibility. Meanwhile for orientation, the liminal cesium-137 value lies between 2.2 and 5 pCi/g, the average being 3.6 pCi/g (23N). The corresponding average dose of the two estimates is 4.6 rem.

4.2 Spontaneous Decay

The annual rate of spontaneous decontamination is appreciable, since the half-lives of cesium-137 and strontium-90 are 30 and 28 years, respectively. The decay is about 2.3 percent of the radionuclide present at the beginning of each year, totalling 11 percent of the original amount in five years, 21 percent in 10 years, 37 percent in 20 years, and 50 percent in 30 years. Therefore, when a location's specific activity is close to the liminal value, it may be advantageous to decontaminate by delaying resettlement. On the other hand, in the case of Bikini Island a delay of about 100 years would be required.

By preventing the use of locally grown foods until spontaneous decay brings the specific activity down to the liminal level, resettlement might be allowed on all islands with the exception of B18 and B19, whose soil activities apparently exceed those of Bikini Island (Table 1). Such a plan would require importing almost all foods (fish excepted) on a reliable schedule, which in the past has been difficult. It would also require effective restraint to prevent the growth and consumption of local food.

4.3 Chemical Treatment

Recent exploratory experiments on Eneu by the Lawrence Livermore group (24) suggest that heavy applications of commercial NPK fertilizer might lead to the reduction of cesium-137 activity in existing coconut trees and grasses within 6 months. Such a reduction presumably is due to the fertilizer's high potassium content, which could reduce the plants' uptake of cesium.

In these experiments, the calculated ratio of potassium to cesium atoms in soil is gigantic--in the neighborhood of billions to one--as may be inferred from Table 3. Whether or not potassium can affect the higher (though still miniscule) levels of cesium on Bikini Island is also under test. Reports for both islands should be available in several months.

Such a chemical method, assuming that it becomes practical, would be of use in cases of marginal contamination, reducing plant uptake over 10 or 15 years while spontaneous decay brings the specific activity below the liminal level. Such treatment would avoid the productivity loss and the costs of revegetation entailed in soil removal. In fact, the application of potassium fertilizer to those soils already high in nitrogen and phosphorus (Table 3) should result in increased yields that might partly compenstate for treatment costs.

4.4 Soil Removal

Removal is the direct way to deal with contaminated soil. The work may be broken down into several sequential steps: clearing; excavation and hauling; and disposing of the contaminated soil (i.e., spoil) by dumping or using it as fill. We emphasize that the levels of contamination on Bikini Atoll are low. The spoil (excavated material to be disposed of) can be handled with practical impunity, so that adequate monitoring, but not costly and complex precautions, are necessary. However, inhalation of dust will require monitoring and for certains kinds of work masks might be required.

The process starts with clearing the land; thus, the vegetation is destroyed and must be reestablished later. Aside from the resulting loss of food supply and amenity, this destruction removes the shield that guards against excessive sunlight and the trade winds that blow almost constantly. Under favorably planned conditions (including fertilization), vegetation can be reestablished in 2-8 years, but effective shading and coconut fruit production are the slowest to reappear.

There are four locations for the disposal of spoil--the ocean, the lagoon, an unoccupied island, or a site for creating new land or a causeway. National and international laws and conventions will restrict dumping and are discussed in Section 6.

Whether or not to bag or otherwise immobilize the spoil before ocean or lagoon dumping is a question yet to be decided. Immobilization increases costs; dispersal is simpler.

For ocean or lagoon dumping, the specific activity of the spoil under discussion is so low and the dilution affected by such dumping so great that no radiation hazard is entailed. Various official bodies have suggested a de minimis level of 10^{-3} Ci/ton (10^{-2} - 10^{-4}) on material to be dumped (Section 6.3), i.e., a level so low that its radiation risks need not be considered. The specific activity of Bikini spoil (0-40 cm rooting zone) is less than 10 percent of the de minimis level, i.e., about 70 pCi/g for cesium-137, strontium-90 and the transuranic elements, or $\sim .7 \times 10^{-4}$ Ci/ton (Table 8).

The mass per se of the dumped spoil, however, may pose an ecological problem. The problem is minimized by dumping at selected non-sensitive locations or where dispersal is rapid.

The rate of fall in water of the dumped spoil and its eventual pattern of dispersal will depend on (a) rate of hydration in sea water, (b) particle-size distribution after hydration, and (c) density of particles. More than 90 percent of Bikini Atoll material consists of particles coarser than 0.05 mm (Table 3), the lower limit of very fine sand, which settle below 100 meters in about 12 hours.

Ocean dumping within the 3-mile limit of territorial waters is practical. The depth beyond the atoll reef falls rapidly to more than 1,300 meters. The 20-30 km round-trip from the lagoon loading docks to an ocean disposal site is comparable to that in the lagoon.

Lagoon dumping is convenient because the waters are tranquil and the sites close at hand. The monthly replacement of the lagoon water will prevent any accumulation of turbidity or dissolved contaminants. The material could be scattered, or it could be dumped into the Bravo crater (16 million m^3, 73 m deep, 910 m diameter).

Dumping on an unoccupied island, declared off-limits for food production, would be more costly than aquatic dumping, but would have the advantage (or disadvantage) of localizing the material.

The spoil could be used to build a causeway connecting Bikini and Eneu Islands and the smaller unused islands between them (Figure 2). Removing a layer 0.5 m thick from the whole of Bikini Island would provide 1.2 million m^3 of spoil (Table 8). This is sufficient for a causeway between Bikini and Eneu, 8 km long, 13 m surface width and 6.4 m deep. The argument for making more land available is a strong one in a culture where land is scarce. The cost would be greater than for aquatic dumping, especially since the causeway would require bridges and continuous riprapping.

The plans would have to consider the stability of the causeway and its maintenance over the years in the face of erosion by wind, wave, and tidal action, as well as by infrequent but periodic typhoons. Presumably, the present form of the atoll is the stable one for the forces acting on it.

The specific activity of the employed spoil would be relatively unimportant in causeway construction, since the road would cover a significant fraction of it, and food production would be minimal.

4.5 Soil Replacement

Since the average elevation of Bikini and Eneu Islands is only 3 m, and the rooting zone is 0-40 cm, the removal of more than several centimeters of soil should be followed by replacement. Sediment dredged from the lagoon bottom off of Eneu and Bikini (Figure 2) would be convenient and cheap. Alternatively, if only small quantities of backfill are required, it might be more convenient to take it from projecting sand spits.

The basic chemical nature of the sediment and sand is similar to that of the island soils, but the upper layers of the latter have accumulated considerable amounts of organic matter, nitrogen and sometimes phosphorus (Table 3), important substances for vigorous plant growth. In any case, the new land surfaces should be promptly seeded and fertilized to prevent wind erosion. Revegetation with desirable food or woody species could then be carried on (25N).

4.6 Topping

Instead of removing the rooting zone (0-40 cm) and replacing it with 40 cm of fresh soil, the rooting zone might be left in place but topped with 40-100 cm of fresh soil. Before topping, the vegetation in the contaminated rooting zone would be removed and disposed of. Topping therefore saves the cost of soil removal and its disposal.

An argument against topping is that the underlying soil would continue to contaminate the ground water as it does now. It also might contaminate the topping layer, but there is no experimental work or field experience to settle the latter objection.

A major uncertainty about topping is whether or not the root systems of the new vegetation would eventually penetrate down to the old buried surface and absorb appreciable amounts of cesium-137. It is probable that a program of frequent fertilizer application and the build-up of organic matter in the new surface would encourage the concentration of absorbing roots in the new surface layer.

4.7 Washing

An obvious possibility is to wash out the contaminating radionuclides with large quantities of water. However, 35 years of rain (perhaps 60 inches per year) have failed to accomplish this. The Lawrence Livermore group is now conducting tests on Eneu and Bikini with sea water, pumped intermittently every three months and some results should be available in January 1984 (24).

In these coralloid soils, the cesium is probably associated with the organic matter. This "bonding" is very much weaker than the cesium fixation on clay minerals, which occurs in most continental soils (26, 27). In them, cesium is held so tightly that it is used as a tracer to follow the movement of soil during erosion. It is conceivable that addition of suitable clay minerals to Bikini's soil could prevent plant uptake of cesium-137.

4.8 Biological Removal

Since cesium is taken up by plants and may be concentrated in their tissues several-fold over the level in soil, the possibility arises of removing cesium by cropping. The method does not seem practical. The top 40 cm (rooting zone) of Bikini soil weigh about 1.2 million metric tons and contain some 37 curies of cesium-137. Even if all plants concentrate cesium five-fold, then under the simplest model, approximately 200,000 metric tons of green plant material would have to be grown, harvested and moved off of the island to extract 83 percent of the cesium.

5. TYPE PLANS AND COSTS

Owing to variations in contamination level and to local circumstances in the field, several methods might be employed for the decontamination work. For orientation and comparison, we have estimated the costs of five "type plans" (Tables 9 and 10). Such estimates at best can only be approximate, but studies now in progress should make the estimates of the final report more precise. Also in the final report, we shall consider alternatives for the other islands of the atoll (Table 1).

In the case of Eneu and Bikini Islands, major physical parameters of the work (Table 8) can be estimated from the basic data in Tables 1 and 2 and the choice of 3.6 pCi/g as the liminal specific activity of the rooting zone (Section 4.1). For Bikini, using the distributed mean, about 1.2 million metric tons of soil are above liminal activity and carry a burden of 37 Ci of cesium-137. The total burden of all radionuclides would therefore be about 80 Ci. The comparable figures for Eneu are 0.14 million metric tons and 1.25 Ci.

Estimating the volume of soil for excavation or treatment is simple for a uniform depth over an entire island. In practice, however, such uniformity will not occur since the specific activity may vary greatly at different locations (Table 4). Isopleth maps for successive depths are being prepared that will allow planning to take such inhomogeneities into account when profitable to do so.

From a practical point of view, the type plans fall into two classes--those that involve digging on a large scale and those that do not. At present, some of the non-digging types involve steps that are frankly exploratory or even speculative, so that their true cost, including allowance for corrections due to unforeseen complications, can only be estimated very roughly. It does appear, however, that they tend to be cheaper than the digging types but require much more time for execution.

Moreover, a non-digging treatment does not entail costs for lost topsoil fertility and for revegetation, both of which must be added to the operational costs of the digging procedures in Tables 9 and 10. For example, the three soils analyzed in Table 3 show high levels of nitrogen (3,500 - 12,000 kg/hectare) in their top layers (0-15 or 25 cm) and exceptional levels of phosphorus for Bikini (10,000 - 30,000 kg/hectare). The net loss due to topsoil removal will depend on the nature of the replacement soil. Dredged material would probably be low in comparison, so that considering Bikini's area of 240 hectares, and the continental US cost of fertilizer nitrogen (60¢/kg) and phosphate rock (35¢/kg), the loss could be equivalent to some millions of dollars. Samples of dredged material will be analyzed later this year to study the problem more precisely.

5.1 Non-Digging Plans

Based on the discussion in Section 4, non-digging plans are better adapted for those situations where the level of contamination is marginal or relatively low. The non-digging plan does not directly eliminate contamination, but rather avoids radiation exposure while waiting for spontaneous decay alone to eliminate excess radioactivity.

Under such conditions, the simplest plan is to prohibit the use of locally produced foods, excepting fish (Table 10, Option 1). The cost would be that of the food supply over a period of perhaps 10-20 years at a roughly estimated annual cost of $1 million. Thinking in terms of the future, the plan eventually should involve stimulating the population to become at least partially self-sufficient.

An alternative plan, as yet unproven, that would permit agricultural work from the start is the application of potassium-rich fertilizer to prevent the uptake of cesium-137 by plants (Table 10, Option 6). The annual cost has been estimated at something like 50¢ per square meter, or about a million dollars for Bikini Island and a half-million for Eneu (if necessary). Monitoring the treatment should be included in the cost. As far as is now known, the treatment would extend over the same number of years called for by the dietary restriction plan, e.g., 15 years for Eneu under certain assumptions, and more than 100 years for Bikini.

5.2 Digging Plans

For those plans that involve digging, the various costs per step are listed in Table 9, starting with the clearing of the land and ending with its replanting (28-31); total costs are listed in Table 10. Option 2 for Bikini in Table 10 may be considered the standard of comparison. It involves digging up 0.5 m depth of soil, dumping it in the lagoon, and replacing it with 0.5 m of "clean" lagoon sediment, at an estimated cost for Bikini Island of $92 million. The actual working time might be 2-4 years.

Instead of dumping the soil, Option 3 calls for the construction of an 8-km causeway that would join Eneu and Bikini. The cost now rises to $115 million, including the expense for two bridges at $1.5 million each. An allowance for annual maintenance should be added to these figures, not only for roadway and bridge maintenance, but to repair the effects of continual marine erosion and eventual typhoon catastrophe.

Option 4 is based on the fact that excavation and disposal together are more expensive (per unit volume) than backfilling alone (Table 9). It therefore should be possible to save money by doing less excavating and more backfilling (and topping). In Option 2, 50 cm (depth) are removed and replaced with 50 cm of sediment at a cost of $92 million. Instead, one might remove 25 cm of soil and replace it with 75 cm of sediment at a cost of $88 million, a saving of $4 million. However, if a replacement layer of 125 cm is considered to be necessary (Section 4.6), the cost rises to $122 million.

The costs for Eneu would be less than for Bikini, since the island is only half as large and contamination is very much less. _If_ decontamination is necessary, Option 5 (Table 10) might be considered the equivalent of the standard plan for Bikini (Option 2); it involves removing .2 m (depth) of soil from one-third of the island at a cost of about $7 million. If the case of chemical treatment (Section 5.1) continued for a period of 15 years, the total cost would be about $7.5 million.

In conclusion, the range of costs for the rehabilitation of Bikini Island appears to be of the order of $90-120 million, that for Eneu, $7 million, each including an increment to take care of planning, staging and administrative costs. The work to be done appears to be quite feasible. The speed with which it can be done will depend initially on how fast the responsible parties can come to an agreement, the regulatory bodies grant approval, the bids are let, and the successful bidder musters his work force. These things having been done, an estimate to complete the physical work is two to four years for Bikini, and of course, less for Eneu.

6. LEGAL CONSIDERATIONS

Legal questions concerning the radionuclide cleanup of Bikini Atoll involve three sets of laws--Marshallese, United States, and International. The applicability of these laws might vary as the status of the Compact of Free Association varies at the times of planning, obtaining financial support from the US, and carrying out the project.

In addition, no doubt consideration will be given to the wishes of the Bikini people, both as a political subdivision of the Marshall Islands Republic and as a cultural entity.

The Interim Report of the Committee's legal consultants (32), given below in Sections 6.1 - 6.4, indicates that the precise interrelationships of the laws are yet to be clarified. For example, a major legal task relates to the disposal of contaminated soil. At present, the law is unclear both with respect to where the ultimate authority lies and what the specific requirements are. Therefore, the legality of any plan involving the movement of earth might be questioned at this time, although the plan is technically feasible and biologically acceptable. Legal considerations ultimately may be decisive in choosing one alternative over another and could materially increase the cost or the time to execute the project.

6.1 Ocean Disposal

Disposal of radioactive wastes at sea is governed by the 1972 London Dumping Convention and the Marine Protection Research and Sanctuaries Act (MPRSA), 33 U.S.C. § 1401 *et seq.*, the implementing legislation of the Convention. Although the Convention has not been extended to the Trust Territory, US Department of State, Treaties in Force 253 (1982), the MPRSA defines "United States" to include the Trust Territory, 33 U.S.C. § 1401 *et seq.*, and the statute will continue to apply to the Marshall Islands once the Compact of Free Association becomes effective. See Compact Section 161(a)(3).

The MPRSA authorizes the Environmental Protection Agency (EPA) to regulate disposal of wastes at any point seaward of the baseline from which the territorial sea is measured. Id. § 1402(b). Thus, disposal into waters between the baseline and the three-mile limit of the territorial sea, as well as disposal into international waters, is subject to EPA's jurisdiction under the MPRSA.

Disposal of low-level radioactive waste requires a permit from EPA. Id. § 1412(a). On January 6, 1983, however, Congress established a two-year moratorium on issuance of MPRSA permits for disposal of low-level radioactive wastes. During the moratorium, EPA may not issue such permits except as necessary to conduct research. After January 6, 1985, EPA may recommend issuance of a permit to Congress, but no permit can issue unless Congress passes a joint resolution authorizing the Administrator to grant the permit. Id. §§ 1414(h), (i).

The applicant for an MPRSA permit for disposal of low-level radioactive waste must submit with its permit application the equivalent of an Environmental Impact Statement on the environmental merits and demerits of the project, reasonable alternatives, an assessment of feasibility, and a broadly defined cost-benefit analysis.

Since no material is devoid of radioactivity, the signatories to the London Convention wished to set a "*de minimis*" level of specific activity below which a material would not be considered radioactive for the purposes of the Convention. The International Atomic Energy Agency, which serves as a consultant to the Convention, has not yet proposed such a level, but it has noted that various national and international agencies exempt radioactive materials with activity below 10^{-3} Ci/t. The average specific activity of the top 50 cm of Bikini Island soil is about

10^{-4} Ci/t, or about one-tenth of this guideline. At present, however, EPA does not have any regulations establishing a de minimus level of radioactivity that will exempt waste material from regulation under the MPRSA.

6.2 Disposal in the Lagoon (Including Causeway Construction)

While the US Government has not yet established a baseline for Bikini under the MPRSA, it is likely that the baseline from which the territorial sea would be measured for Bikini Atoll would be seaward of the lagoon. Thus, while lagoon disposal of spoil may not be subject to the MPRSA, it would be regulated under the Clean Water Act, which defines "State" to include the Trust Territory, 33 U.S.C. § 1362, and which will continue to apply to the Marshall Islands under Section 161(a)(3) of the Compact. Some of the same types of definitional problems will have to be resolved under this statute, which requires a permit from the Army Corps of Engineers for the discharge of "fill" material that "replaces portions of the 'waters of the United States' with dry land or which changes the bottom elevation of a water body for any purpose." 33 U.S.C. § 1344. The permit process must be preceded by an EPA review and a determination by the Corps of Engineers that granting the permit application is in the public interest.

6.3 Disposal on Land

Disposal of the spoil on land may also require the preparation of an Environmental Impact Statement. This activity may be regulated by Nuclear Regulatory Commission (NRC) under the Low-Level Radioactive Waste Policy Act of 1980, 42 U.S.C. § 2021b-3, although "atomic energy defense activities" committed to the Department of Energy are not subject to NRC regulation.

6.4 Marshallese Law

Under Marshallese law the bottom of Bikini lagoon is owned by the Bikini people, who also own the adjacent fast lands. Dumping spoil into the lagoon will therefore also require the permission of the Bikinians, and presumably the same would be true of dumping into the ocean within the 3-mile territorial limit. At the same time, a cleanup will require coordination with the Government of the Marshall Islands, since Article VII of the agreement implementing Section 177 of the Compact provides that "(t)he Government of the United States is relieved of and has no responsibility for, and the Government of the Marshall Islands, consistent with its constitutional processes, shall have and exericse responsibility for, controlling the utilization of areas in the Marshall Islands affected by the (US) Nuclear Testing Program."

7. REHABILITATION: DOMESTIC AND PUBLIC ARRANGEMENTS

The rehabilitation of Bikini and Eneu Islands will require plans that are worked out in conjunction with the Bikini people and that take into account the following items:

(a) Roads
(b) Housing
(c) Church and community building
(d) Schools
(e) Infirmary or dispensary
(f) Water supply: wells, cisterns
(g) Air strip
(h) Lagoon docking facility
(i) Reestablishment of the vegetation.

In addition, the Bikinians will have to decide whether the community will eventually reside on Bikini Island, Eneu, or both.

Whatever the ultimate plan, it should be noted that Eneu could be ready for domestic and public construction before Bikini, since its level of soil contamination is so much less. Furthermore, it is likely that Bikinians would like to be employed in the rehabilitation of their atoll, not only in the cleanup phase, but in the resettlement projects as well. An initial group of settlers on Eneu, for example, could participate in such work.

As one possibility, the overall plan might be carried out in three phases. The easiest job, the rehabilitation of Eneu, could be tackled first. Second, with Eneu established as a base, the physical rehabilitation of Bikini Island would be undertaken. Finally, the requirements for island life, such as housing, schools, community facilities, etc., would be constructed.

In conclusion, the Committee again emphasizes its incomplete or tentative treatment of certain topics and the illustrative rather than definitive nature of the plans and cost estimates. Although it is now clear that the two main islands of Bikini Atoll can be rendered safe for permanent occupancy, it is less clear which method or combination of methods might be recommended above all others. The Committee's final report will deal in greater detail with these problems.

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23. We emphasize again that the liminal value is largely dependent on the estimate of coconut consumption, whose trend in recent years apparently has been downward. A value of 3.6 pCi/gm could easily be 35% lower than necessary. A better estimate of present day coconut consumption may become available when the dietary survey requested by the Committee is completed.

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TABLE 1. ISLANDS OF BIKINI ATOLL: ISLAND AREA, EXPOSURE RATE, AND SOIL SURFACE SPECIFIC ACTIVITY OF CESIUM-137 AS OF 1987

		Exposure Rate (R/y)		Soil Activity, 0-10 cm Depth		
					Terrestrial Survey[d/]	
Island[a/]	Area (km^2)	Aerial survey[b/]	Terrestrial survey[c/]	Aerial survey[b/] (pCi/g)	No. of samples	median and (mean) (pCi/g)
B1 Nam	0.54	0.15	-	30	33	6.6 (28)
B2 Iroij	0.20	0.048	-	9.7	10	1.0 (5.7)
B3 Odrik	0.04	0.011	-	2.3	5	0.77 (0.73)
B4 Lomilik	0.22	0.15	-	30	16	1.7 (5.5)
B5 Aomen	0.17	0.033	-	6.6	9	1.1 (1.9)
B6 Bikini	2.41	0.22	0.23	45	118	60 (74)
B7 Bokantauk	0.09	0.00085	-	0.13	-	-
B8 Iomeler	0.03	0.0053	-	0.81	-	-
B9 Enaelo	0.02	0.00085	-	0.13	-	-
B10 Rojkere	0.08	0.11	-	22	3	0.088 (5.9)
B11 Eonjebi	0.03	0.00085	-	0.13	-	-
B12 Eneu	1.22	0.016	0.02	3.3	114	3.5 (4.9)
B13 Aerokojlol	0.41	0.00085	-	0.13	13	0.062 (0.12)
B14 Bikdrin	0.10	-	-	-	-	-
B15 Lele	0.23	0.0093	-	1.9	4	0.16 (0.26)
B16 Eneman	0.10	0.0093	-	1.9	6	2.5 (2.3)
B17 Enedrik	0.96	0.03	-	6.0	32	1.2 (3.2)
B18 Lukoj	0.14	0.26	-	54	3	19 (24)
B19 Jelete	0.17	0.31	-	63	2	38 (38)
B21 Oroken	0.05	0.078	-	16	-	-

a/ The islands of Bikini Atoll are numbered clockwise starting with Nam as B1.

b/ Tipton and Meibaum (2). The exposure rate and the specific activity calculated from it or measured in soil were primarily due to cesium-137.

c/ Gudiksen et al. (15)

d/ Robison et al. (6).

TABLE 2. BIKINI ATOLL: CESIUM-137 IN SOIL

			Specific Activity (pCi/g): Median and (mean) for 1987[b]					
Island[a]	Area (km^2)	No. of Sites	0-5 cm	5-10 cm	10-15 cm	15-25 cm	25-40 cm	0-40 cm
B1 Nam	0.54	33	8.9 (38)	4 (18)	4.6 (21)	5.1 (17)	2.2 (15)	5.4 (19)
B2 Iroij	0.20	10	1.3 (8.1)	0.71 (3.2)	0.58 (0.77)	1.2 (13)	0.58 (0.58)	1.1 (2.1)
B3 Odrik	0.04	5	0.89 (0.80)	0.63 (0.65)	0.45 (0.50)	0.42 (0.55)	0.28 (0.44)	0.53 (0.54)
B4 Lomilik	0.22	16	1.5 (7)	1.8 (4.1)	1.2 (2.7)	1.3 (1.8)	1.2 (1.2)	1.5 (2.6)
B5 Aomen	0.17	9	1.4 (2.5)	0.81 (1.3)	1.1 (1.5)	0.77 (1.1)	1.1 (2.4)	1.3 (1.9)
B6 Bikini	2.41	122	69 (83)	50 (65)	27 (44)	11 (32)	3.9 (20)	27 (39)[d]
distributed[c]			65	45	30	17	7.6	32
B12 Eneu	1.22	114	4.1 (5.9)	2.9 (3.9)	2.3 (3.2)	1.5 (2.2)	0.98 (1.5)	2.0 (2.8)
distributed[c]			5	3.8	2.5	2.0	1.4	2.8
B13 Aerokojlol	0.41	13	0.12 (0.15)	0.045 (0.097)	0.041 (0.065)	0.015 (0.039)	0.018 (0.034)	0.050 (0.061)
B15 Lele	0.23	4	0.22 (0.37)	0.097 (0.15)	0.11 (0.14)	0.089 (0.089)	0.089 (0.081)	0.12 (0.14)
B16 Eneman	0.10	6	2.7 (2.5)	2.4 (2.1)	1.8 (1.9)	1.9 (1.8)	1.5 (1.5)	2.0 (1.9)
B17 Enedrik	0.96	32	1.5 (4.4)	0.84 (2.1)	0.61 (1.5)	0.28 (1.1)	0.23 (0.7)	0.63 (1.5)
B18 Lukoj	0.14	3	33 (33)	4.6 (15)	6.5 (8.1)	8.9 (7.6)	1.2 (1.5)	8.1 (9.7)

a/ The islands at Bikini Atoll were numbered clockwise around the atoll starting with Nam Islands coded as B1.

b/ Robison et al. (6). For each depth-layer (0-5 cm, etc) the data for the entire island were pooled.

c/ For the distibuted mean, Eneu and Bikini were divided into 6 areas, the median for each area (at each depth) determined, and the island-mean of the 6 medians calculated.

d/ 114 sites.

TABLE 3. ANALYSIS OF SOIL FROM BIKINI AND ENEU ISLANDS[a/]

Island Location and Depth (cm)	pH[b/]	Cs-137 (pCi/g)	Sr-90[c/] (pCi/g)	Total[d/] Sr (%)	Ca (%)	Mg (%)	P[e/] (%)	N (%)	Organic matter[f/] (%)	Extractable K[g/] (ppm)	Particles sized < .05mm (%)
Bikini No. 1											
0-5	7.7	282	64	0.38	30.4	.95	1.35	0.64	14.4	79	} 11.5
5-10	7.8	85	73	.39	30.8	.89	1.28	.62	13.2	26	
10-15	7.9	35	63	.39	30.9	.89	1.29	.63	12.3	20	9.5
15-25	7.9	22	39	.40	31.9	.86	1.17	.50	10.6	23	11.7
25-40	8.3	3.5	24	.39	34.3	1.28	.67	.19	4.5	4	6.3
40-60	8.4	1.1	-	.31	34.5	2.05	.16	.11	1.6	3	0.6
Bikini No. 2											
0-5	7.8	119	64	0.40	31.0	1.02	0.82	0.49	10.7	50	5.7
5-10	8.0	55	73	.40	32.4	1.09	.71	.46	8.5	24	3.7
10-15	7.9	21	63	.38	33.1	1.18	.56	.35	7.4	24	3.3
15-40	8.2	4.2	32	.38	34.7	1.79	.32	.11	1.6	6	1.1
Eneu No. 1											
0-5	7.7	8	2.3	0.32	32.0	1.74	0.085	0.30	5.1	41	2.3
5-10	8.0	6.7	2.6	.34	32.6	1.76	.055	.35	5.6	20	1.6
10-15	8.0	2.5	2.7	.31	34.3	2.08	.037	.17	2.6	9	.8
15-25	8.4	.1	2.5	.28	34.0	2.40	.016	.06	0.9	1	.3
25-40	8.7	.1	2.4	.28	34.4	2.48	.014	.05	0.8	1	.2
40-60	8.9	.2	-	.30	33.3	2.37	.015	.03	0.6	< 1	.1

a/ Samples collected in May 1982 by Lawrence Livermore National Laboratory team and analyzed by Nelson Laboratories, Stockton, CA. Particle size was 2 mm or less (99.8%-83.6% total).

b/ pH in water.

c/ The strontium-90 activities are the mean of 55-63 sites on Bikini and 37-40 on Eneu. The activity at locations 1 and 2 on Bikini and Eneu Islands was not determined.

d/ Total cesium was below detection limit (1.3 ppm).

e/ High phosphorus values indicate ancient guano deposition.

f/ Organic matter by wet oxidation.

g/ Extractable in N NH_4 acetate.

TABLE 4. VARIATION OF CESIUM-137 ACTIVITY AT SPECIFIC DEPTHS, BIKINI ISLAND (1987)[a/]

Depth (cm)	Mean specific activity (pCi/g)	Per cent of sites with stated activity (pCi/g)					
		0-1	1-4	5-9	10-19	20-29	60-150
25-40	9.1[b/]	31	24	18	7	16	4
40-60	3.2[c/]	47	25	17	6	3	3

a/ Lawrence Livermore Laboratory pooled data (6) for 69 sites, each sampled at the 2 specified depths.

b/ Excludes three outlying points of 83, 125 and 141 pCi/g. Their inclusion would raise the mean to 22.3 pCi/g.

c/ Excludes 2 outlying points of 62 and 83 pCi/g. Their inclusion would raise the mean to 6.4 pCi/g.

TABLE 5. CESIUM-137 IN SOIL AND WATER

Material	Eneu (pCi/g)	Bikini (pCi/g)
Soil (1987)a/		
0-5 cm (surface zone)	5	65
0-40 cm (rooting zone)	2.8	32
50 (40-60 cm)	.2-.6	.9-2.1
Ground Water (1975)b/	.03c/ (.001-.07)	.37d/ (.23-.7)
Lagoon (1979)e/		
water	.001	.001
sediment (0-5 cm)	.01-.7	.01-.7

a/ Table 2.

b/ Section 2.1.

c/ Strontium-90: .03 (.001-.07) pCi/g.

d/ Strontium-90: .13 (.001-.26) pCi/g.

e/ Section 2.3.

TABLE 6. FEDERAL RADIATION PROTECTION STANDARDS

1. Whole-body[a]	
Population standards	
Mean annual dose	.17 rem per person
Maximum annual dose	.5 rem per person
Mean 30-year cumulative dose	5.0 rem per person
Occupational standard	
Annual dose	5 rem per worker (over 18 years old)
2. Drinking water[b], [c]	
Cesium-137	200 pCi/liter
Strontium-90	8 pCi/liter
Annual total contribution to whole-body dose:	.004 rem
30-year total contribution	.12 rem

a/ Whole-body equivalent doses (17).

b/ References: 18-19.

c/ For one radionuclide. When more than one is present, the standards are reduced proportionally. The total contribution to the whole-body equivalent dose shall not be more than .004 rem, annually.

TABLE 7. RESETTLEMENT WITHOUT DECONTAMINATION: 30-YEAR CUMULATIVE ADULT DOSE FOR ENEU AND BIKINI ISLANDS BEGINNING IN 1987

Exposure	Conditions	30-year dose (rem)a/ Eneu	Bikini
Externalb/	-	.27	3.5
Internal	Lawrence Livermore estimatesc/		
	a) Imported foods only	0	0
	b) Local foods only	3.7	27.2
	c) Both local and imported foods freely available	2.1	14.2
	d) Imports freely available 75% of the year	2.5	17.6
	Index-dose estimated/		
	Imports freely available 75% of the year	6.2	44

a/ The total dose equals internal plus external. The protection standard is 5 rem.

b/ Does not allow for shielding by buildings and by gravel spread around dwellings.

c/ Calculated from Reference 6, Tables 23, 24, 27, 28, which give the adult female dose, not the average adult dose.

d/ The index dose represents other dietary assumptions than those of the Lawrence Livermore Laboratory. See Section 3.2 and Reference 8.

TABLE 8. SOIL VOLUME, WEIGHT AND CESIUM-137 BURDEN (1987)

Factor	Eneu	Bikini
Area (km^2) a/	1.2	2.4
Volume ($10^6 m^3$) b/		
0.1 m depth	.12	.24
0.4	-	.96
Weight (10^6 metric tons) c/		
0.1 m depth	.14	.29
0.4	-	1.15
Cesium-137 activity (pCi/g) d/		
0.1 m depth	5	65
0.4	-	32
Total cesium-137 (curies) e/		
0.1 m depth	0.6	18.7
0.4	-	36.8

a/ 1 km^2 equals 100 hectares or .386 sq. miles.

b/ 1 m^3 equals 1.31 cubic yards.

c/ Bulk density, 1.2. A metric ton (10^6 g) equals 1.1 tons.

d/ 0 - .1 m is the layer in which the liminal specific activity of ceisum-137 (3.6 pCi/g) is exceeded on Eneu; 0 - .4 m is the layer of excess on Bikini.

e/ The total burden of strontium-90 and cesium-137 would be approximately twice that of cesium-137 alone. The transuranic radionuclides increase the total by about 10%.

TABLE 9. STEP-WISE COSTS[a]

Item	Unit Cost (dollars)	Step Cost Per km^2 ($ millions)	Subtotals Per km^2 ($ millions)
1. Vegetation			2.30
a. Clearing & Disposal	1.30/m^2	1.30	
b. Replanting	1.00/m^2	1.00	
		per .1 m depth[b]	
2. Excavation and hauling	19.00 /m^3	1.90	1.90
3. Disposal of soil in ocean or lagoon			0.74
a. Bagging and Loading	5.40/m^3	0.54	
b. Marine transportation[c]	2.00/m^3	0.20	
c. Dumping	(trivial)		
4. Backfilling with lagoon sediment			1.90
a. Dredging	11.00/m^3	1.10	
b. Hauling & Spreading	8.00/m^3	.80	
5. Causeway of spoil[d]	5800/m	5.80/km	5.80/km
6. Other Costs[e]	–	–	–

a/ The rounded costs are 2.4 times those for continental USA (28-31).

b/ For 1 km^2 dug to a depth of 0.1 m. It is assumed that doubling the depth will double the cost.

c/ For a round trip of 18 NM.

d/ The causeway has a trapezoidal cross-section with a 39 m base, 13.4 m top and 6.4 m height with .67 m of riprap on each exposed face. The cross-sectional area is 168 m^2.

e/ Other costs:

Base Camp Construction	6% of Construction Cost
Mobilization	$2 Million
Overhead (Engr, Contingency, etc)	32% of Construction Cost
Survey and Quality Control	$2,300 per day on site
Roads, airstrip, housing, etc	Not included for the present

TABLE 10. SOME ALTERNATIVES FOR BIKINI AND ENEU ISLANDS

Island	Option	Depth of Soil		Cost ($ Millions)
		Removal (m)	Replacement (m)	
Any Island	1. **Dietary Control;** Imported foods only	—	—	—[a]
Bikini	2. **Backfill:** Clear and dispose, evacuate and haul, bag and load, ocean/lagoon disposal, backfill, replant[b]	.5	.5	92
	3. **Causeway:** Same as option 2, except a causeway is constructed from Bikini to Eneu with the spoil	.5	.5	115[c]
	4. **Backfill plus topping:** Same as option 2, except more dredge-material is backfilled than soil removed so as to form a buffer over the contaminated soil	.25	1.25	88-122
Eneu	5. **Backfill:** Same as option 2, except only one-third of Eneu is cleared	.2	.2	6.7
	6. **Potassium Treatment:** Treat 50% of Island surface for 15 years to allow spontaneous decay to reduce the specific activity by 28%	—	—	7.5

[a] Per 1000 persons per year. To be determined.

[b] Refer to Table 9 for Unit Costs

[c] Two bridges may be required to permit proper circulation between the lagoon and ocean. Construction costs for these bridges have been included

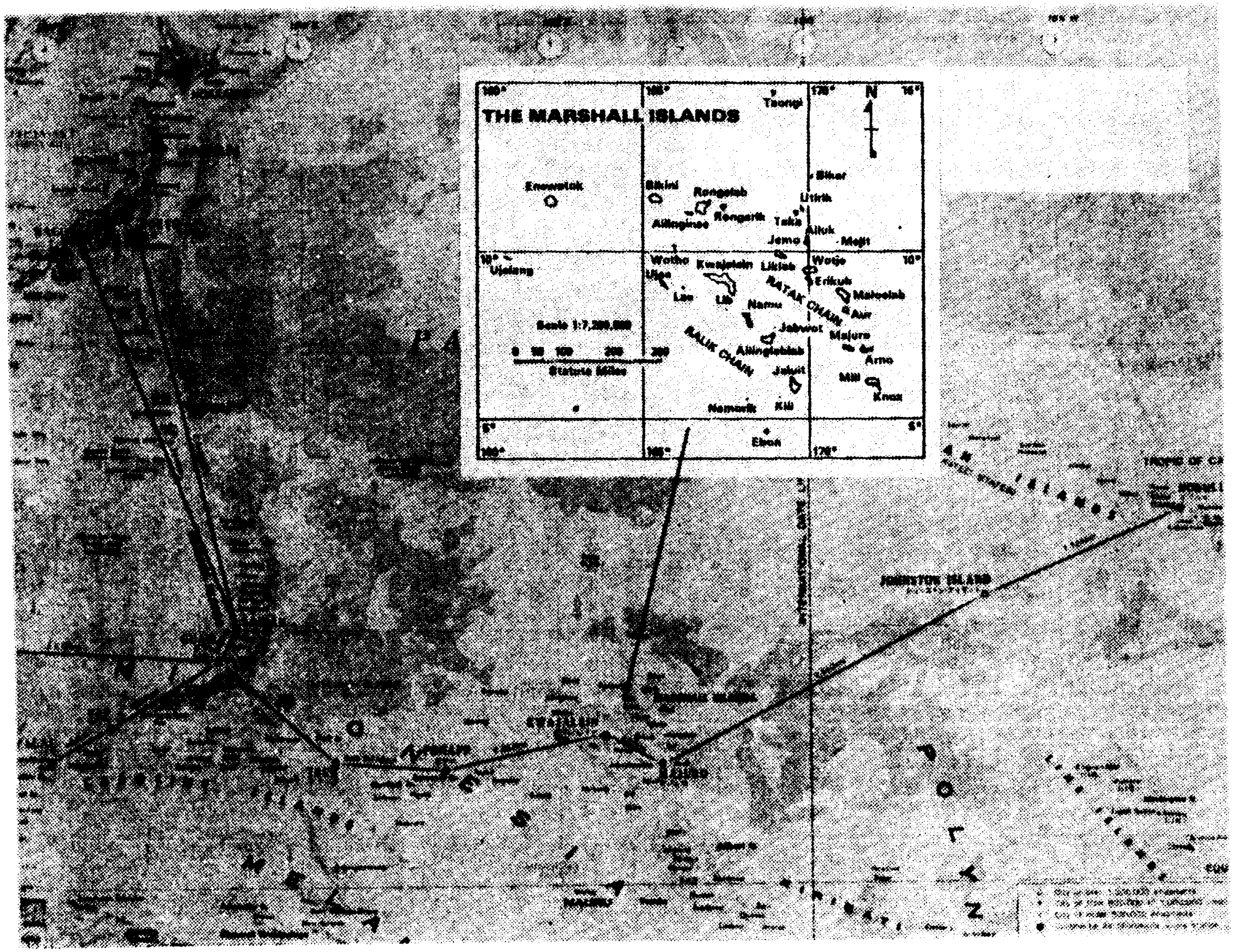
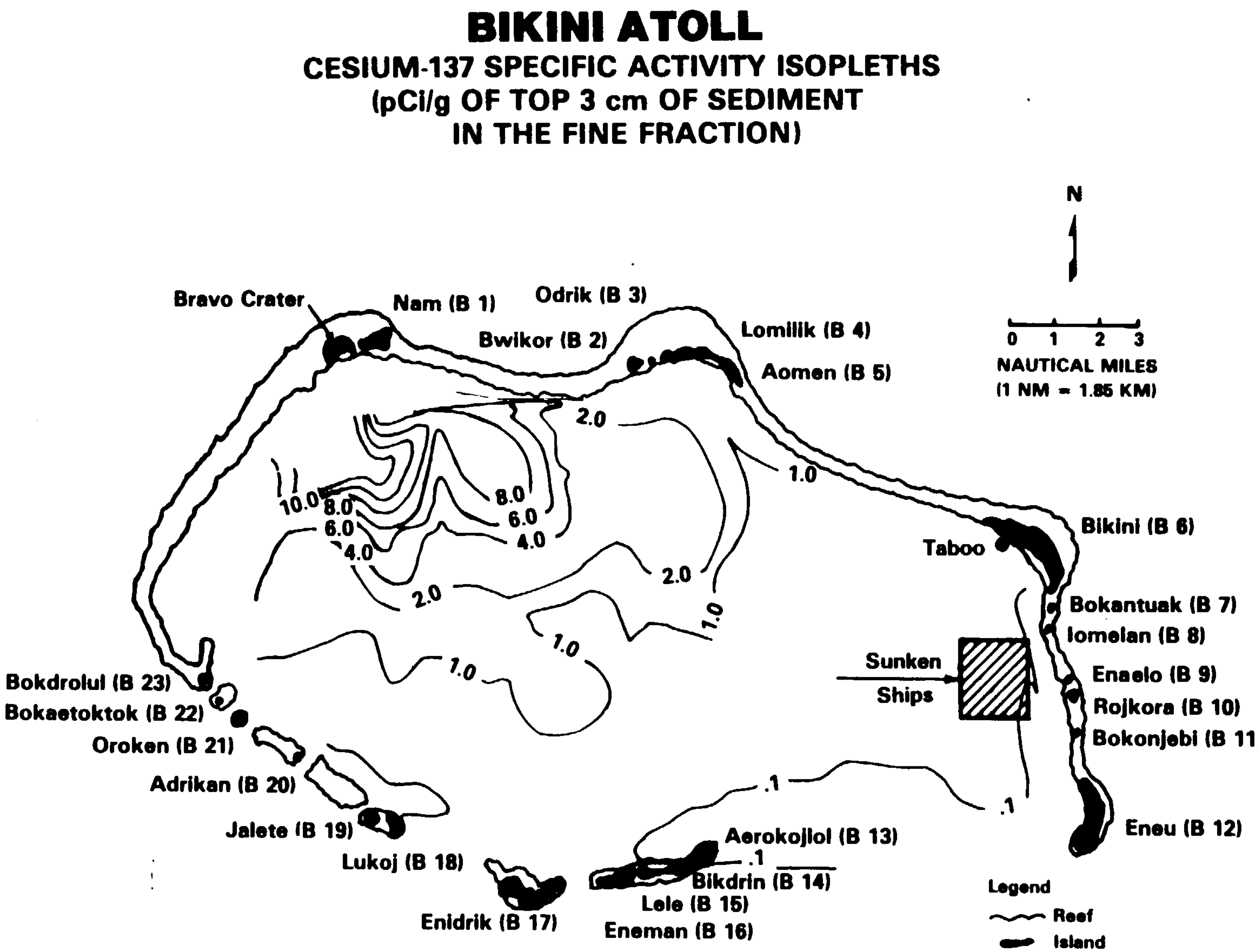


Figure 1. Location of the Marshall Islands



Note: The isopleths (pCi/g), based on sample stations 2.6 km apart, are for 1979, and will be published by V. E. Noshkin, Lawrence Livermore National Laboratory, Livermore, CA.

Figure 2. Bikini Atoll. Cesium-137 Specific Activity Isopleths (pCi/g of Top 3 cm of Sediment in the Fine Fraction)

DOSE ASSESSMENT MODEL

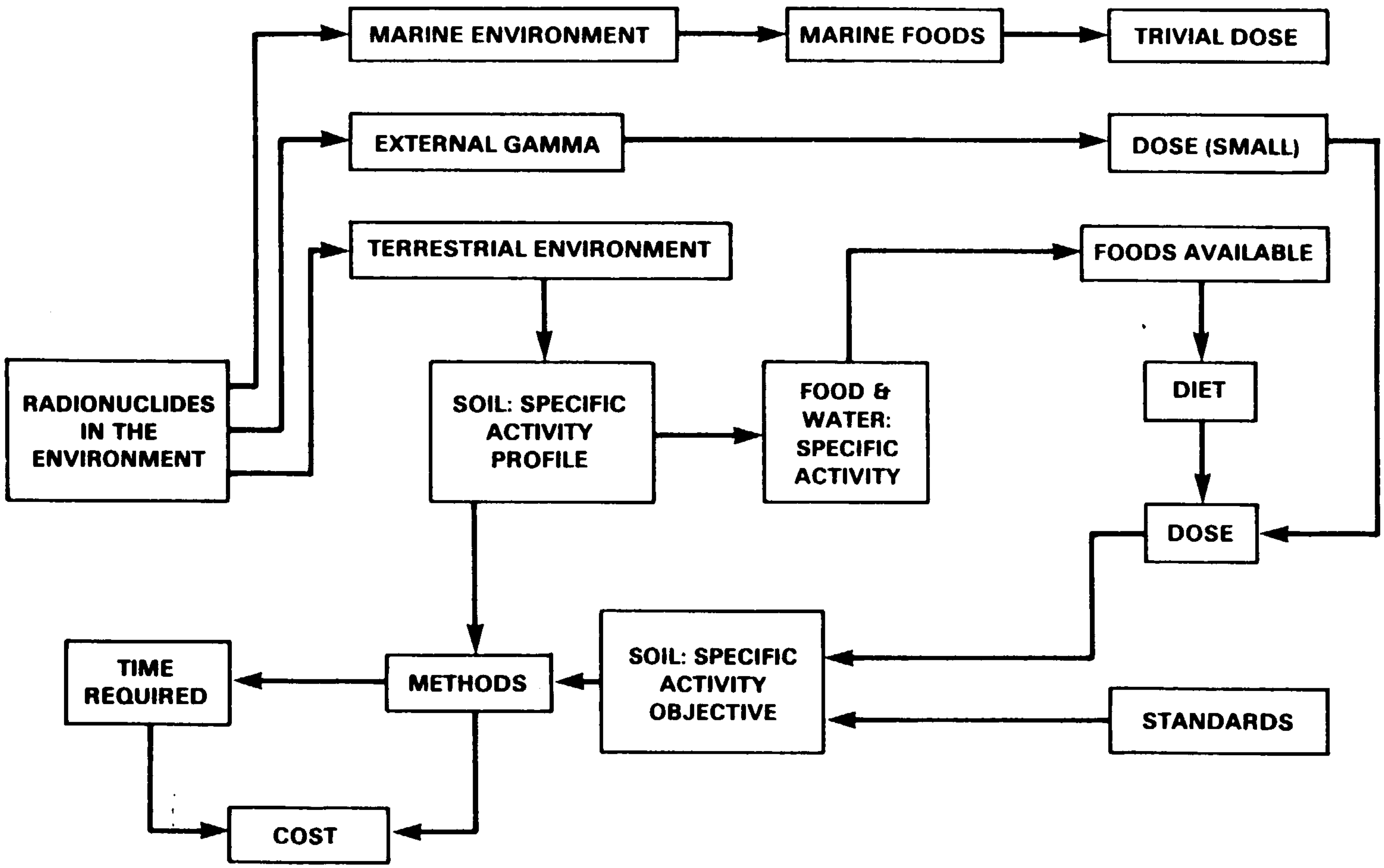


Figure 3. Dose Assessment Model

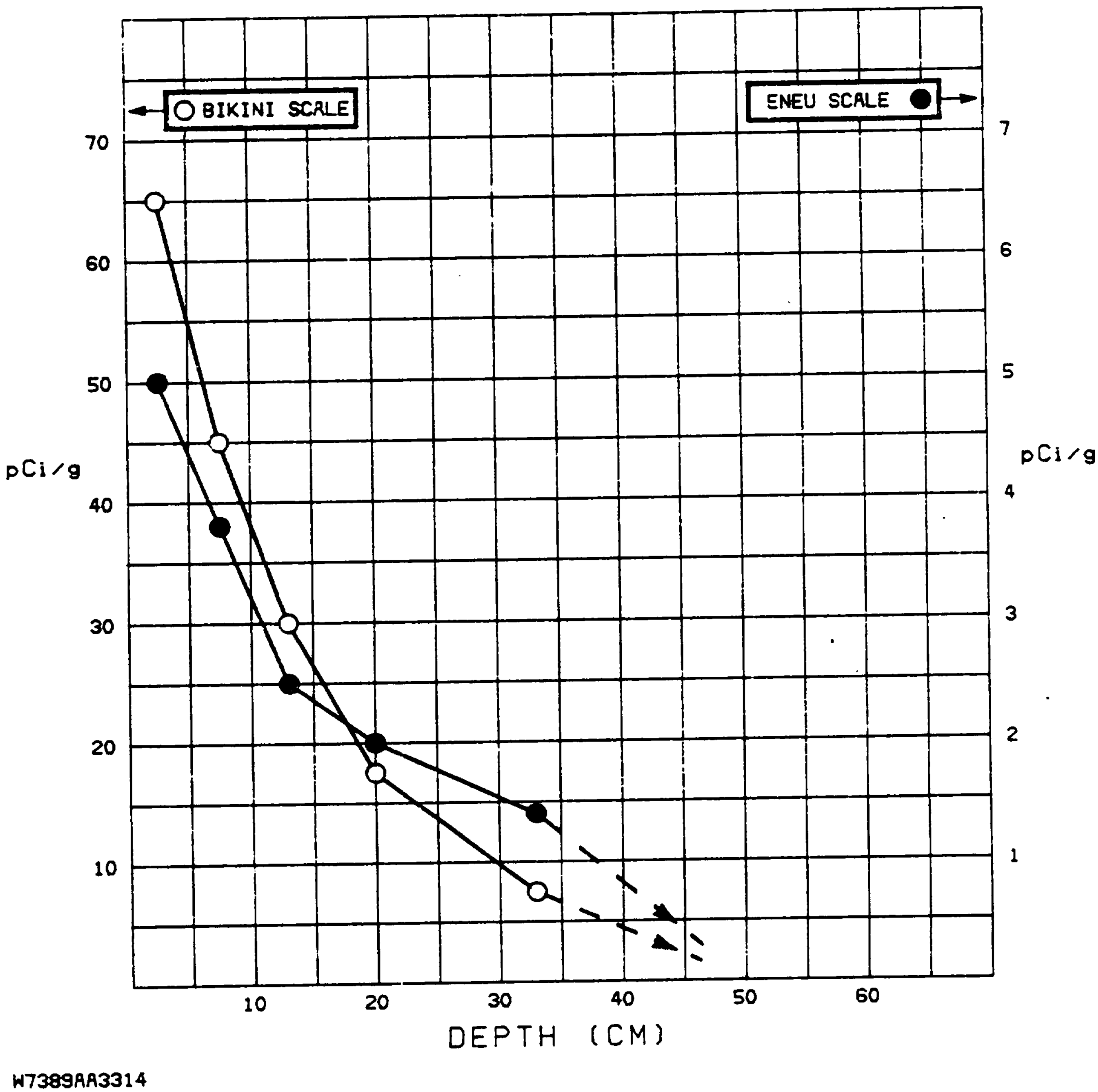


Figure 4. Cesium-137 (pCi/g, Projected to 1987) at Various Depths in the Soils of Bikini and Eneu Islands