RADIOLOGICAL ASSESSMENT REPORTS SERIES

RADIOLOGICAL CONDITIONS AT BIKINI ATOLL: PROSPECTS FOR RESETTLEMENT

INTERNATIONAL ATOMIC ENERGY AGENCY

RADIOLOGICAL CONDITIONS AT BIKINI ATOLL:

PROSPECTS FOR RESETTLEMENT

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SUDAN
SWEDEN
SWITZERLAND
SYRIAN ARAB REPUBLIC
THAILAND
THE FORMER YUGOSLAV REPUBLIC OF MACEDONIA
TUNISIA
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FOREWORD

At the present time there are many locations around the world affected by radioactive residues. Some are the result of past peaceful activities, such as the processing of radium for use in medicine and luminizing, and the mining of uranium and other ores. Others result from activities during the Cold War, for example, residues from arms production activities and from the testing of nuclear weapons. With the improvement of relations between the major countries in the world and stimulated by the new and general concern about the state of the environment, attention in many countries has turned to remediating the areas affected by radioactive residues.

Some of the residues from uranium mining and weapons testing are located in countries where there is an absence of the infrastructures and expertise necessary for evaluating the significance of the radiation risks posed by the residues and for making decisions on remediation. In such cases, governments have felt it necessary to obtain outside help; in other cases, it has been considered to be socially and politically necessary to have independent expert opinions on the radiological situation caused by the residues. As a result, the IAEA has been requested by the governments of a number of Member States to provide assistance in this context. The assistance has been provided by the IAEA in relation to its statutory obligation "to establish...standards of safety for protection of health...and to provide for the application of these standards...".

The present assessment was requested by the Government of the Republic of the Marshall Islands within whose territory there are residues of nuclear weapon testing conducted over a 13 year period immediately following the Second World War. The Marshall Islands Government wished to have an independent view of the situation in order to provide a basis for a decision on whether the former inhabitants of Bikini Atoll should be permitted to return to their home island. For this purpose the IAEA convened a meeting of international experts chaired by K. Lokan of Australia in December 1995 to review the available information on the subject. Subsequently, and at the request of the Government of the Marshall Islands, the radiological data which formed the technical basis for the conclusions were corroborated through a monitoring mission to Bikini Island conducted by an IAEA team in May 1997. This report is issued in the Radiological Assessment Reports Series.

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1. SUMMARY

1.1. PREAMBLE

An international Advisory Group met at IAEA Headquarters in Vienna on 11–15 December 1995 for the purpose of reviewing the current radiological conditions at Bikini Atoll, Republic of the Marshall Islands, and advising on the prospects for rehabilitation of the atoll and resettlement of its indigenous population. The Advisory Group was convened by the IAEA in response to a request for technical assistance from the Government of the Marshall Islands within the framework of IAEA technical co-operation project MHL/9/003, 'Radiological Monitoring in Bikini Atoll'.

Tests related to nuclear weapons were carried out in the territory of the Marshall Islands between 1946 and 1958. In this period, 23 such tests, with a total yield equivalent to around 70 million tonnes of trinitrotoluene (TNT), were performed at Bikini Atoll (the remainder were conducted at Enewetak Atoll). The population of Bikini Atoll, at that time 167 people, was evacuated before the testing was begun and could not return owing to the residual radioactive materials remaining in the atoll as a result of the fallout from the explosions. The Bikinian population, which has since grown significantly, is now mainly residing on the island of Kili and on the island of Ejit in Majuro Atoll, far away from Bikini Atoll.

Since the testing was terminated, a number of assessments have been made of the radiological conditions at Bikini Atoll, including a nationwide study commissioned by the Government of the Marshall Islands.[1] Over the years, the Bikinian people received differing advice on the feasibility of resettling their atoll. The Marshall Islands — which in 1994 became a Member State of the IAEA — turned to the IAEA for confirmation, requesting a peer review of the various assessments made of the radiological conditions at Bikini Atoll and of the recommendations made for its rehabilitation.

[1] In July 1997, the official journal of the Health Physics Society, 'Health Physics', devoted a special edition to the 'Consequences of Nuclear Weapons Testing in the Marshall Islands'. Fifteen of the papers contained in this edition are relevant to the subject of this report and to the history of health physics studies related to Bikini Atoll.

The IAEA has a statutory responsibility to establish standards for protection against radiation exposure, and its Statute also authorizes its Secretariat to provide for the application of the standards upon the request of a Member State. While the IAEA standards are established for the peaceful uses of nuclear energy, their basic protection criteria can also be applied in principle to the particular radiological situation at Bikini Atoll.

The primary aim of this review was to assist the Bikinian people to form their own judgement on the radiological conditions at their atoll and on the prospects for resettling there, should they so desire. At the meeting, the Advisory Group benefited greatly from the participation of a delegation from the Marshall Islands.

At the request of the Government of the Marshall Islands, the international review was limited to Bikini Atoll and did not extend to other atolls, islands and islets affected by radioactive fallout from the testing. Moreover, within Bikini Atoll, it was concentrated on Bikini Island, where the Bikinian population formerly resided.

The review relates to the prevailing radiological circumstances and their implications for the future habitability of the atoll. It is not intended to include the retrospective assessment of the past radiological impact of nuclear testing. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has routinely estimated, and reported to the United Nations General Assembly, radiation levels and effects attributable to nuclear weapon testing — including the tests carried out in the territory of the Marshall Islands. Some of the UNSCEAR estimates have been included in the report, but only for the sake of completeness.

1.2. CONCLUSIONS

Important conclusions of the review are that "no further independent corroboration of the measurements and assessments of the radiological conditions at Bikini Atoll is necessary", but that "the Bikinian community might be reassured about the actual radiological conditions at Bikini Atoll by a limited programme of monitoring of radiation levels there, which should involve some participation of members of the community."

On the basis of the information provided for the review it is concluded that "permanent resettlement of Bikini Island under the present radiological conditions without remedial measures is not recommended in view of the radiation doses that could potentially be received by the inhabitants from a diet of entirely locally produced foodstuffs." However, it is noted that "in practice, doses caused by a diet of locally derived foodstuffs are unlikely to be actually incurred under the current conditions, as the present Marshallese diet contains — and would in the near future presumably continue to contain — a substantial proportion of imported food which is assumed to be free of residual radionuclides." Thus it is concluded that "provided certain remedial measures are taken, Bikini Island could be permanently reinhabited."

Two types of remedial measures were considered in detail, namely the use of potassium fertilizer to limit the uptake of caesium — the main chemical element in the residual radionuclides at Bikini — and a comprehensive surface soil scraping strategy. In this context the following conclusions were reached: "While no definite recommendations are given on which strategy to follow, it is considered that the strategy using potassium fertilizer is the preferred approach" and "the results expected from the strategy using potassium fertilizer are consistent with international guidance on interventions to avoid doses in chronic exposure situations and, therefore, the strategy would provide a radiologically safe environment permitting early resettlement." Moreover, "the alternative strategy, i.e. soil scraping — stated to be the alternative preferred by the Bikinian people — would be very effective in avoiding doses caused by the residual radionuclides, but it could entail serious adverse environmental and social consequences."

On the assumption that the proposed strategy is undertaken, it is further recommended that "regular measurements of activity in local foodstuffs should be made to assess the effectiveness of the measures taken" and that "a simple local whole body monitor and training in its use should be provided as a further means of enabling potential inhabitants to satisfy themselves that there is no significant uptake of caesium into their bodies."

Should the Bikinians decide to resettle Bikini Island after taking the recommended remedial measures, the radiation doses for the people living on the island would be higher than the doses prevailing before the testing started and also than the global average doses due to natural sources of radiation. However, total doses will still be lower than natural background radiation doses in large areas of the world where many people lead healthy lives. Moreover, people inhabiting Bikini Island could be assured that their radiation doses would be acceptable in terms of international standards and that their health would be adequately protected against radiation exposure due to the residual radioactive materials at Bikini Atoll.

1.3. ADDENDUM

This report was presented to and discussed with the late President of the Republic of the Marshall Islands, His Excellency Amata Kabua, who was accompanied by the Honourable Thomas Kijiner, then the Republic's Minister of Health and Environment, during the President's official visit to Tokyo on 14 October 1996. Immediately after this, on 17 October 1996, the report was formally submitted to the Government of the Marshall Islands in Majuro through the requesting office, the Ministry of Foreign Affairs. The report was also presented to the Bikinian community through the Office of the Local Government of Kili/Bikini/Ejit in Majuro on 18 October 1996. The report was finally officially accepted by the Government of the Republic of the Marshall Islands through a letter from its Ambassador to the United States of America on 18 September 1997.

At the meeting on 14 October 1996, President Kabua suggested that an independent corroboration by IAEA experts of the available environmental data relating to the residual radioactive materials on Bikini Island, which had served as the basis for the report's assessment, would be desirable. It had been concluded that no further independent corroboration of the measurements and assessments of the radiological conditions on Bikini Atoll was necessary. However, taking into account the need for the Bikinians to be reassured about the situation, the IAEA agreed to carry out the requested corroboratory monitoring.

Therefore, an IAEA environmental monitoring team carried out a limited programme of environmental measurements and sampling during the period 7–22 May 1997. Measurements were made of the absorbed dose rate in air and of the concentration of the most radiologically significant radionuclides in representative soil and foodstuff samples on Bikini Island. The results obtained by the IAEA monitoring team provided good corroboration of earlier measurements made by other expert teams and are attached to the report as an Addendum.

2. THE MARSHALL ISLANDS

The Republic of the Marshall Islands (see Fig. 1) consists of two archipelagic island chains of 29 atolls (Ailinginae, Ailinglaplap, Ailuk, Arno, Aur, Bikar, Bikini, Ebon, Enewetak, Erikub, Jaluit, Knox, Kwajalein, Lae, Likiep, Majuro, Maloelap, Mili, Namorik, Namu, Rongelap, Rongerik, Taka, Taongi, Ujae, Ujelang, Utirik, Wotho and Wotje) and five separate reef islands (Jabat, Jemo, Kili, Lib and Mejit), comprising 1152 islands and islets in total. Kwajalein is the largest of the group — indeed, the largest atoll in the world. The islands are situated some 4000 km southwest of Honolulu, about halfway between Hawaii and Papua New Guinea, in tropical waters of the northern Pacific Ocean, north of the equator and west of the international date line, between latitudes 4° and 15° N and longitudes 161° and 173° W. The land area adds up to only 181 km^2, but the total sea territory is vast, stretching over 3000 km between its northwestern and southwestern extremes. The capital is Majuro, in Majuro Atoll, towards the southeast.

There is evidence that the Marshall Islands have been populated for almost 4000 years. The indigenous inhabitants are mainly Micronesian, primarily of Australoid and Polynesian descent. The islanders speak two major Marshallese dialects from the Malayo-Polynesian family. The official language is English, which is universally spoken. The current population is about 56 000, with nearly half living in Majuro. It is a young and fast growing population: more than half of the Marshallese are under 14 years old and the population growth rate is nearly 4% per year, with a birth rate of around 4.6% per year, a death rate of around 0.75% and a total fertility rate of nearly seven children on average born per woman.

Agriculture and tourism are the mainstays of the Marshallese economy. Agricultural production is concentrated in small farms. The main commercial crops are coconuts, tomatoes, melons and breadfruit, and there is some pig raising. Small scale industry is limited to handicrafts, fish processing and copra, the dried coconut flesh from which coconut oil is extracted, which is the main export product of the islands. More recently, there have been plans to exploit phosphate resources. The islands have few natural resources and are occasionally subject to typhoons. Land and fresh water are highly valued resources; in addition to the Republic's small land area, the supply of potable water is inadequate. Since the average height above sea level of the islands is only about two metres, the possibility of global climate changes and potential rises in sea levels constitute a major issue for the Republic.

The Marshall Islands derive their name from Captain William Marshall, a British sea captain of the East India Company, who sailed through the islands in the 1780s. However, the archipelago was never formally a British colony. In 1885, Germany declared the islands a German protectorate. When Japan entered the First World War in 1914, the islands fell to Japan. After the war, the whole of Micronesia, including the archipelago, was mandated to Japan by the League of Nations.

In the Second World War, the Marshall Islands archipelago came under the military control of the USA. In 1947, the islands came under the trusteeship of the USA as part of the Trust Territory of the Pacific Islands, which also included the Caroline Islands and the Mariana Islands. The Marshall Islands became self-governing in 1979, with a constitution, a president and an elected legislature ('Nitejela') in Majuro. Each atoll sends at least one delegate (senator) to the Nitejela. A Compact of Free Association with the USA came into effect in 1986. The trusteeship of the USA was formally dissolved by the United Nations Security Council in 1990 and the Republic of the Marshall Islands was admitted to the United Nations in 1991. The Republic became a Member State of the IAEA in January 1994.

2.1. BIKINI ATOLL

Bikini Atoll, located 850 km northwest of Majuro on the northern fringe of the Marshall Islands and remote from the other atolls, comprises more than 23 islands and islets. Bikini, Eneu, Nam and Enidrik Islands account for over 70% of the land area. Bikini and Eneu are the only islands of the atoll that have had a permanent population. Most of the atoll's other islands are rather small or narrow, and also tend to be infertile, prone to storms and swept by sea water in high winds and high seas. Besides Bikini and Eneu, only Aerokojlol and Jelete Islands have edible crops, mainly coconut.

In 1946, Bikini Atoll was the first site in the Marshall Islands used for nuclear weapon testing. From 1948, Enewetak Atoll, a neighbouring atoll, replaced Bikini Atoll as the test site. From 1954, Bikini Atoll was reactivated as a test site until nuclear weapon testing was terminated in the Marshall Islands in 1958.

The Bikinians have their own dialect of Marshallese and are seen as a distinct Marshallese population. Before nuclear weapon testing started, the population of Bikini Atoll — at that time 167 people — was evacuated and resettled, first on Rongerik Atoll and eventually on the isolated island of Kili, about 800 km southeast of Bikini Atoll. Some were then resettled on the island of Ejit in the Majuro Atoll. They continue to live on these two islands. A Council of the Kili/Bikini/Ejit local government represents them in Majuro.

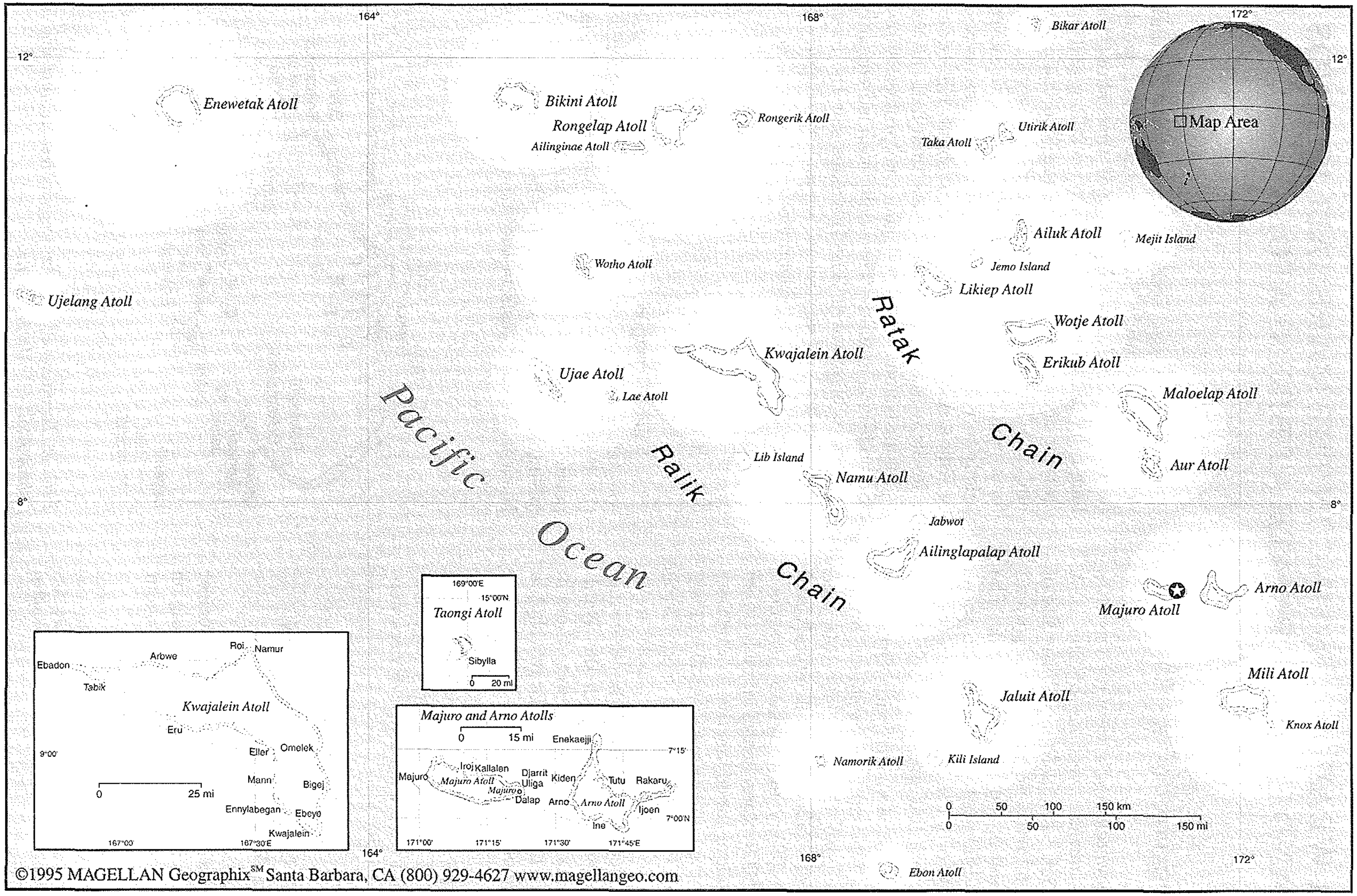

FIG. 1. The Republic of the Marshall Islands (*: national capital).

3. BACKGROUND: NUCLEAR WEAPON TESTING IN THE MARSHALL ISLANDS AND ITS AFTERMATH AT BIKINI ATOLL

3.1. NUCLEAR WEAPON TESTS

Bikini and Enewetak Atolls were used as sites for tests related to nuclear weapons by the USA between 1946 and 1958.[2] Bikini Atoll was the site of 23 of the 66 tests conducted under water, at ground level and above ground in the Marshall Islands. The yields of the tests at Bikini Atoll amounted to about 72% of the total yield of 1.1×10^5 kilotonnes (kt) of TNT equivalent for both test sites [1].

Testing at Bikini Atoll started with 'Operation Crossroads' in 1946. This experiment staged by the US Navy, which included the so-called 'Able' and 'Baker' shots, involved 242 ships, 156 aircraft and more than 42 000 military and civilian personnel, and used more than 5000 experimental animals. From July 1946, Bikini Atoll remained inactive as a test site and tests were conducted on Enewetak Atoll in 1948, 1951 and 1952. Then, in February 1954, Bikini Atoll was reactivated as a test site with the 'Castle' series of tests. They continued in 1956 with the 'Redwing' series and were terminated in 1958 with the 'Hardtack I' series. The tests of highest yield were those in the 'Castle' series, which included the 'Bravo' shot, a thermonuclear device of 15 megatonnes (Mt) equivalent yield of TNT.

Table I presents data for the trials at Bikini Atoll (see also Refs [2–7]). Figure 2 shows approximately where in Bikini Atoll the nuclear devices were detonated [3–5].

3.2. EVACUATION OF THE POPULATION FROM BIKINI ATOLL

Prior to the Able test in 1946, the first nuclear test in Bikini Atoll, the 167 Bikinians then living on Bikini Island were evacuated to Rongerik Atoll, about 200 km to the east, seemingly to reside there until an unspecified future date when the testing would be completed. (Knowledge at that time about the long term consequences of radioactive fallout and the transfer of radionuclides through the food chain was limited.) The Bikinians remained on Rongerik Atoll for a period of two years. In 1948, they were moved briefly to Kwajalein Atoll and later in the same year to Kili, a small (0.8 km^2) isolated island. Kili Island is fertile, with rich soil, but is less than half the size of Bikini Island. It has no lagoon, no protective reef and no fishing grounds. The small beach is frequently subject to high waves. The Bikinians saw the move to Kili as a temporary relocation and were reluctant to change from being fishermen to being farmers.

3.3. SUSPENSION OF TESTING

Nuclear weapon testing in the Marshall Islands was terminated in July 1958. On 31 October 1958, the USSR, the United Kingdom and the USA suspended atmospheric nuclear weapon testing under an international moratorium. The Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer

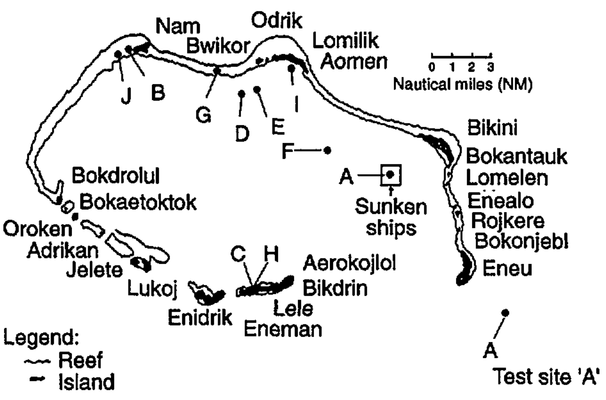

FIG. 2. Locations of nuclear weapon test detonations at Bikini Atoll (1NM=1.85 km).

[2] A few of the nuclear weapon tests in the Pacific Ocean were conducted by the USA outside the Marshall Islands, near Johnston Atoll and Christmas Island (the latter Kiribati, formerly the Gilbert Islands); however, these tests were limited to high altitude explosions.

TABLE I. NUCLEAR WEAPON TESTS CONDUCTED AT BIKINI ATOLL

Test series	Shot name	Date	Type	Yield (kt TNT equivalent)	Map reference (see Fig. 2)
Crossroads	Able	30 June 1946	Air drop	23	A
Crossroads	Baker	24 July 1946	Underwater	23	A
Castle	Bravo	28 February 1954	Surface	15 000	B
Castle	Romeo	26 March 1954	Barge	11 000	B
Castle	Koon	6 April 1954	Surface	110	C
Castle	Union	25 April 1954	Barge	6 900	D
Castle	Yankee	4 May 1954	Barge	13 500	D
Redwing	Cherokee	20 May 1956	Air drop	3 800	E
Redwing	Zuni	27 May 1956	Surface	3 500	C
Redwing	Flathead	11 June 1956	Barge	365	F
Redwing	Dakota	25 June 1956	Barge	1 100	F
Redwing	Navajo	10 July 1956	Barge	4 500	D
Redwing	Tewa	20 July 1956	Barge	5 000	G
Hardtack I	Fir	11 May 1958	Barge	1 360	B
Hardtack I	Nutmeg	21 May 1958	Barge	25.1	H
Hardtack I	Sycamore	31 May 1958	Barge	92	B
Hardtack I	Maple	10 June 1958	Barge	213	I
Hardtack I	Aspen	11 June 1958	Barge	319	B
Hardtack I	Redwood	27 June 1958	Barge	412	I
Hardtack I	Hickory	29 June 1958	Barge	14	H
Hardtack I	Cedar	2 July 1958	Barge	220	B
Hardtack I	Poplar	12 July 1958	Barge	9 300	J
Hardtack I	Juniper	12 July 1958	Air burst	65	H

Space and Under Water was signed in Moscow on 5 August 1963.[3]

3.4. RESTORATION AND RESETTLEMENT

In August 1968, following a number of radiological surveys [8] that had been carried out since 1958 to assess the impact of the USA's programme of nuclear weapon testing, President Lyndon Johnson publicly announced that Bikini Atoll was safe for habitation and approved the resettlement of the Bikinian people on the atoll. From February to October 1969, the atoll was cleared of debris. Fruit trees, including coconut, breadfruit, pandanus, papaya and banana, were replanted. A further radiological survey of Bikini Atoll was carried out in 1970.

Initially, in 1970, three Bikinian families and about 50 Marshallese workers returned to the atoll. Eventually, 139 Bikinians would resettle there. However, the Bikinian people remained unconvinced of the safety of the atoll, and in 1975 they initiated a lawsuit against the Government of the USA to terminate the resettlement effort until a satisfactory and comprehensive radiological survey had been carried out.

3.5. RADIOLOGICAL REASSESSMENT

In 1975, a further radiological assessment of Bikini Atoll was conducted [9]. However, at that time the trees planted in 1969 had not yet grown to maturity and few samples were available for reliable estimates to be made of radionuclide concentrations in food crops. In 1976, an external radiation survey programme for five northern atolls, which included some measurements at Bikini, was conducted. A continuing sampling and analytical programme was begun at Bikini Atoll in 1978 to gather additional data as a basis for more precise radiation dose estimates for the residents of Bikini and Eneu Islands. Radioanthropometry (whole body radiation measurements)

[3] A comprehensive ban on nuclear weapon testing was adopted by the United Nations General Assembly in September 1996.

for the purpose of estimating the intake of radioactive materials by Bikinian residents had begun in April 1977.

In 1978, it was determined that for the inhabitants of Bikini Atoll a tenfold increase in the body content of the radionuclide ^{137}Cs had occurred [10]. This increase was the result of a combination of the coconut trees starting to bear fruit and a drought that led to increased consumption of coconut fluid for want of fresh water. Apart from assessments of the long term impacts on the Bikinians, studies have been conducted on service personnel and Japanese fishermen exposed, in particular, as a consequence of the Castle Bravo test [11–14].

3.6. SECOND RELOCATION

In August and September 1978, in response to the high uptake of caesium in the population — then composed of the 139 Bikinians who had returned to Bikini Atoll — officials of the Trust Territory decided to relocate the Bikinians again from their atoll, back to Kili Island and to Ejit Island at Majuro Atoll.

3.7. FURTHER RADIOLOGICAL REASSESSMENTS

At the time of the second relocation, a new radiological survey in 11 northern atolls of the Marshall Islands, sponsored by the USA (Department of Energy), was started. The survey used detectors mounted in helicopters which were flown in parallel flight lines in order to plot external gamma dose rate contours [15]. Also, samples of vegetation, marine foods, animals and soil were collected and analysed [16, 17]. Revised radiation dose evaluations were published in 1980 and 1982 [18, 19] which indicated that — should the Bikinians decide to resettle their island — the terrestrial food chain would be the most significant exposure pathway. This dose assessment was most recently updated in 1995 on the basis of a continued measurement programme at the atoll [20, 21]. Additional information on radiological surveys is reported in Ref. [22].

3.8. ATTEMPTED REHABILITATION

The Congress of the USA created a 'Resettlement Trust Fund for the People of Bikini Atoll' for the purpose of improving living conditions on Kili. It also set up the 'Bikini Atoll Rehabilitation Committee' to study and report on the feasibility and cost of rehabilitating the atoll. In 1984, this Committee issued its first report, stating that Bikini could be resettled provided that no locally grown foodstuffs or groundwater would be consumed. The Committee also considered other courses of action, including the removal of topsoil from the islands.

In January 1986, a Compact of Free Association between the Governments of the USA and the Marshall Islands was signed into law. This provided for the payment of compensation to the people of Bikini, Rongelap, Enewetak and Utirik Atolls. An additional trust fund was established for the cleanup and resettlement of Bikini Atoll.

3.9. NATIONWIDE RADIOLOGICAL REASSESSMENT

A separate radiological assessment — the Republic of the Marshall Islands Nationwide Radiological Study (NWRS) — was commissioned by the Government of the Republic of the Marshall Islands. By this means, Bikini Atoll, as well as all other atolls in the Republic, was to be monitored for radioactive residues. Oversight was provided by a Scientific Advisory Panel of well known and respected scientists [23]. Laboratory quality control programmes were implemented to ensure that the NWRS surveys could provide accurate measurements. In general, the study confirmed the findings of earlier measurement programmes. The findings of the NWRS were published and a report on Bikini Atoll was released in February 1995 [1, 24]. In August 1995, six months after the NWRS issued its report on Bikini Atoll, the Nitejela of the Marshall Islands considered the NWRS findings but did not accept them.

3.10. REQUEST FOR AN INTERNATIONAL REVIEW

The Republic of the Marshall Islands was accepted as the 122nd Member State of the IAEA on 26 January 1994. The Marshall Islands Government subsequently requested the IAEA to conduct an independent international review of the radiological conditions at Bikini Atoll, and to consider and recommend strategies for the resettlement of the atoll. The IAEA responded to this request by convening an Advisory Group, which met in Vienna on 11–15 December 1995. The Group was convened under the framework of IAEA technical co-operation project MHL/9/003, 'Radiological Monitoring in Bikini Atoll'.

4. THE INTERNATIONAL REVIEW

4.1. OBJECTIVES OF THE REVIEW

There were three main objectives of the international review:

- To assess the radiological conditions on Bikini Atoll in the Republic of the Marshall Islands, taking into account the information submitted by the Republic's government;
- To ascertain whether any corroboration of the available information on the current radiological conditions at the atoll is needed;
- To determine whether any intervention to take remedial actions for the purpose of radiation protection is required and, if so, the form, scale and duration of such an intervention.

4.2. TECHNICAL FRAMEWORK

The framework for the review were the interagency 'International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources' (the 'Basic Safety Standards'). The Basic Safety Standards are jointly sponsored by the Food and Agriculture Organization of the United Nations (FAO), the IAEA, the International Labour Organisation (ILO), the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (OECD/NEA), the Pan American Health Organization (PAHO) and the World Health Organization (WHO). They were issued by the IAEA as Safety Series No. 115 [25] in 1996. The Basic Safety Standards were mainly used to establish the radiation protection criteria (see Section 8) for judging the prospects for resettlement of the Bikinian people in their homeland.

The international review took full account of all the available data from the Republic of the Marshall Islands NWRS [1], as well as of a large number of assessments made by scientists from around the world, mainly from Lawrence Livermore National Laboratory (LLNL), USA,[4] and to some extent from the Forschungszentrum für Umwelt und Gesundheit (GSF), Germany.[5]

4.3. CONCERNS OF THE BIKINIAN PEOPLE

The sentiments and concerns of the Bikinians were presented by Senator Henchi Balos, their elected representative for the past 16 years to the Marshall Islands Nitejela [27]. One of their major fears is a recurrence of the events of the late 1960s. At that time, advice was given by scientists in the USA that Bikini Atoll was safe for habitation; however, eight years later the inhabitants were informed that they had ingested amounts of ^{137}Cs far in excess of the expectations of the scientists and that they had to be relocated from the atoll.

Prior to 1978, communication with the Bikinians about the potential hazards associated with radiation exposure was reportedly sparse and uninformative. Although the population has grown considerably, there is no individual from the community with expertise in matters relating to radiation. The Bikinians have come to consider peer review by independent scientists as crucial to their acceptance of the findings of scientific studies. Their representatives expressed their appreciation at the formation of the international Advisory Group.

Senator Balos said that children everywhere play in the dirt and that "this is why we have said that the soil in the village must be scraped". For those areas of Bikini Atoll which may not be scraped, the representative voiced the continuing fear about the radioactive "poison" in the soil. Moreover, the community fears that no one will assume responsibility for the continued application of countermeasures intended to reduce the uptake of radionuclides into food crops.

4.4. UNDERTAKING OF THE IAEA

The Director General of the IAEA, Hans Blix, addressing the Advisory Group and the Bikinian

[4] The assessments made by LLNL were submitted by W.L. Robison.

[5] The assessments made by GSF were submitted by H. Paretzke [26].

delegation [28], reviewed the various locations around the world which during the arms race had been sites for the testing of nuclear devices. In addition to the Marshall Islands, these locations include Algeria, Australia, China, Kazakhstan, Mururoa and Fangataufa Atolls in French Polynesia, the Russian Federation and the USA.

Mr. Blix observed that, although the world was hopeful that a comprehensive nuclear test ban treaty would soon be achieved, there were some consequences of past nuclear testing that remained to be dealt with. Moreover, many people as a result continued to feel fear, resentment and a sense of injury, and were looking for answers about their health and safety in the future and the health of their environment.

The Director General noted that it was a duty of the IAEA to provide technical assistance to the Marshall Islands, now a Member State. Furthermore, he reiterated the IAEA's commitment to helping the Marshall Islands and other areas of the world to deal with residual radionuclides in the environment.

5. RADIOLOGICAL CONCEPTS IN THE CONTEXT OF NUCLEAR WEAPON TESTING

This section provides the context for the following sections on assessment of the radiological conditions at Bikini Atoll by introducing the most important radiological concepts, quantities and units used in the report — where the term *radiological* is used to mean radiation related — by providing a summary of the releases of radioactive materials and subsequent worldwide radiation exposures that resulted from global atmospheric nuclear weapon testing, and finally by briefly describing the health effects that can be caused by exposure to ionizing radiation.[6]

5.1. RADIOLOGICAL QUANTITIES AND UNITS

Radiation is the transport of energy through space. In traversing material, radiated energy is absorbed. In the case of ionizing radiation, which is the type of radiation of current concern in relation to nuclear weapon testing in the Marshall Islands, the absorption process consists in the removal of electrons from the atoms, producing ions. Ionizing radiation (hereinafter referred to as *radiation*) is inherent in the universe. It originates from the cosmos; it is also produced in manufactured devices such as X ray tubes; and it results ubiquitously from the disintegration of radioactive atoms of matter (or *radionuclides*) — the phenomenon that is called *radioactivity*. Radionuclides occur naturally; they may also be produced artificially, for instance in nuclear explosions such as those with which this report is concerned. As the radionuclides disintegrate, they transform into other (radio-)nuclides. The time required for the transformation of one half of the atoms of the radionuclide concerned is a constant usually termed the *half-life* of the radionuclide.

The Basic Safety Standards have adopted the international system of radiation quantities and units recommended by the International Commission on Radiation Units and Measurements (ICRU). The main physical quantities of the system are the *activity*, or rate of nuclear transformation of radionuclides emitting radiation, and the ***absorbed dose***, or energy absorbed per unit mass of matter from the radiation to which it is exposed. Thus:[7]

— The activity of a radioactive material is the number of nuclear disintegrations of radionuclides within that material per unit time; the unit of activity being the reciprocal second, termed the *becquerel* (Bq);
— The absorbed dose is the mean energy imparted by ionizing radiation to matter per unit mass; the unit of absorbed dose being the joule per kilogram, termed the *gray* (Gy).

Although the absorbed dose is the basic physical dosimetric quantity, it is not entirely satisfactory for radiation protection purposes since the effectiveness of radiation in damaging human tissue differs for different types of ionizing radiation. Consequently, the absorbed dose averaged over a tissue or organ is multiplied by a radiation weighting factor to take account of the effectiveness of the given type of radiation in inducing health effects. The resulting quantity is termed the *equivalent dose*.

The quantity equivalent dose is used when individual organs or tissues are irradiated. However, the likelihood of injurious late effects owing to a given equivalent dose differs for different organs and tissues. Consequently, when the whole body is irradiated, the equivalent dose to each organ and tissue must be multiplied by a tissue weighting factor to take account of the differing radiosensitivities of different organs of the body. The sum total of such weighted equivalent doses for all exposed tissues in an individual is termed the *effective dose*.

The unit of equivalent dose and that of effective dose is the same as that of absorbed dose, namely the joule per kilogram (or gray), but the term *sievert* (Sv) is used in order to avoid confusion with the

[6] This information has been derived from the Basic Safety Standards [25] and the latest UNSCEAR reports [29, 30].

[7] Since the becquerel is a unit expressing a very small activity, the following multiples are used in this report: 1000 Bq or kilobecquerel (kBq); 1 million Bq or megabecquerel (MBq); 1×10^9 Bq or gigabecquerel (GBq); 1×10^{12} Bq or terabecquerel (TBq); 1×10^{15} Bq or petabecquerel (PBq); 1×10^{18} Bq or exabecquerel (EBq).

TABLE II. NUMBER AND YIELD OF ATMOSPHERIC NUCLEAR EXPLOSIONS FOR WEAPON TESTING: WORLDWIDE AND AT BIKINI ATOLL

Year(s)	Worldwide		Bikini Atoll	
	Number	Estimated yield (Mt)	Number	Estimated yield (Mt)
1945–1951	26	0.8	2	0.05
1952–1954	31	60	5	46.5
1955–1956	44	31	6	18.2
1957–1958	128	81	10	12
1959–1960	3	0.1		
1961–1962	128	340		
1963	0	0.0		
1964–1969	22	12.2	No further tests	
1970–1974	34	12.2		
1975	0	0.0		
1976–1980	7	4.8		
1981–	0	0.0		

unit of absorbed dose. This report commonly uses the *millisievert* (mSv), a subdivision of the sievert which is equal to a thousandth of a sievert. (For the purpose of comparison, the average annual individual effective dose that the world's population incurs as a result of exposure to cosmic rays and radiation arising from naturally radioactive materials in the biosphere is about 2.4 mSv.)

In general, unless otherwise stated, the term *dose* is used in this report to mean effective dose when it refers to the whole body or equivalent dose when it refers to body organs.

When radionuclides are taken into organs of the human body, the resulting dose is received by the exposed individual throughout the period of time during which their activity continues in the body. The *committed dose* is the total dose delivered during this period of time, and is calculated as a specified time integral of the rate of receipt of the dose. Dose assessments in this report are based on the committed dose from the intake.

Nuclear weapon test explosions in the atmosphere introduced time elements that made the source of radiation different from previously known sources in the sense that, although the period of practice was limited, the period of exposure has been very protracted. After each test, some long lived radionuclides were released which will persist in the biosphere for many years, causing radiation exposure to future populations. Therefore, to quantify the situation more precisely, UNSCEAR introduced the concept of *dose commitment*, defined as the integral over infinite time of the per caput dose rates delivered to the world's population as a result of a specific nuclear explosion or series of explosions. The exposure is presumed to occur over a period of many years after the explosions have taken place and the individuals who are presumed to receive the resulting doses therefore include those not yet born at the time of the explosions.

The total impact of the radiation exposure due to a given practice or event, such as nuclear weapon testing, depends on the number of individuals exposed and on the doses they receive. The *collective dose*, defined as the summation of the products of the mean dose in the various groups of exposed people and the number of individuals in each group, may therefore be used to characterize the radiation impact of a practice or event. The unit of collective dose is the *man-sievert* (man·Sv).

The old units of activity, absorbed dose and (equivalent and effective) dose are the curie (Ci), rad and rem, respectively, which have the following equivalences: 1 Ci = 3.7×10^{10} Bq; 1 rad = 0.01 Gy; and 1 rem = 0.01 Sv. These old units and their

TABLE III. ACTIVITY OF RADIONUCLIDES RELEASED AND GLOBALLY DISPERSED BY ATMOSPHERIC NUCLEAR EXPLOSIONS

Radionuclide	Half-life	Estimated activity (excluding local fallout)			
		Normalized release (PBq/Mt)		Total activity	
		Fission	Fusion	From worldwide testing (EBq)	From testing in Bikini Atoll (EBq)[a]
^{3}H	12.32 a	0.026	740	240	33.6
^{14}C[b]	5730 a	[b]	0.67	0.22	0.03
^{54}Mn	312.5 d	—	15.9	5.2	0.73
^{55}Fe	2.74 a	—	6.1	2	0.28
^{89}Sr	50.55 d	590	—	91.4	12.8
^{90}Sr	28.6 a	3.90	—	0.604	0.08
^{91}Y	58.51 d	748	—	116	16.2
^{95}Zr	64.03 d	922	—	143	20.0
^{103}Ru	39.25 d	1540	—	238	33.3
^{106}Ru	371.6 d	76.4	—	11.8	1.65
^{125}Sb	2.73 a	3.38	—	0.524	0.07
^{131}I	8.02 d	4200	—	651	91.1
^{137}Cs	30.14 a	5.89	—	0.912	0.13
^{140}Ba	12.75 d	4730	—	732	103
^{141}Ce	32.50 d	1640	—	254	35.6
^{144}Ce	284.9 d	191	—	29.6	4.14
^{239}Pu	24 100 a	—	—	0.006 52	<0.001
^{240}Pu	6560 a	—	—	0.004 35	<0.001
^{241}Pu	14.4 a	—	—	0.142	0.02

[a] Based on a fission/fusion yield ratio of 0.14. Since the yield ratio for the Bikini tests is unknown, it is assumed in this table that the same fission/fusion ratio applies at Bikini Atoll as for total worldwide atmospheric testing of nuclear weapons.

[b] For simplicity, it is assumed that all ^{14}C is due to fusion.

submultiples (millicurie, microcurie, picocurie; millirad, microrad; millirem and microrem) are widely used in the reports on the radiological conditions at Bikini Atoll.

5.2. RADIOLOGICAL IMPACT OF ATMOSPHERIC NUCLEAR WEAPON TEST EXPLOSIONS

5.2.1. Releases of radionuclides to the environment

Nuclear explosions in the atmosphere were carried out at several sites, mostly located in the northern hemisphere, between 1945 and 1980. The periods of most active testing were 1952–1958 and 1961–1962. In all, 520 tests were carried out, with a total fission and fusion yield of 545 Mt. The number and yield of worldwide atmospheric nuclear explosions have been estimated by UNSCEAR and are summarized in Table II, together with data for tests undertaken in Bikini Atoll.

Since the Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space and Under Water was signed in Moscow on 5 August 1963, most nuclear test explosions have been conducted underground. Some gaseous radionuclides were unintentionally vented during a few underground tests, but the available data are insufficient to allow an assessment of the radiological impact. The total explosive yield of the underground tests is estimated to have been 90 Mt, much smaller than that of the earlier atmospheric tests. Although most of the underground

TABLE IV. DOSE COMMITMENT AND COLLECTIVE DOSE TO THE WORLD'S POPULATION FROM ATMOSPHERIC NUCLEAR WEAPON TESTING

Radionuclide	Dose commitment (mSv)		Collective effective dose (man·Sv)	
	From all tests	From tests at Bikini Atoll[a]	From all tests	From tests at Bikini Atoll
^{14}C	2.58[b]	0.36	25 800 000	3 612 000
^{137}Cs	0.47	0.07	1 890 000	265 000
^{90}Sr	0.11	0.02	435 000	60 900
^{95}Zr	0.09	0.01	278 000	38 900
^{106}Ru	0.07	0.01	222 000	31 100
^{54}Mn	0.06	0.008	189 000	26 500
^{144}Ce	0.05	0.007	181 000	25 300
^{131}I	0.05	0.007	165 000	23 100
^{3}H	0.05	0.007	164 000	23 000
^{95}Nb	0.04	0.006	131 000	18 300
^{125}Sb	0.03	0.004	88 000	12 300
^{239}Pu	0.02	0.003	58 000	8 120
^{140}Ba	0.02	0.002	53 000	7 420
^{241}Am	0.02	0.002	51 000	7 140
^{103}Ru	0.01	0.002	41 000	5 740
^{240}Pu	0.01	0.002	39 000	5 460
^{55}Fe	0.008	0.001	26 000	3 640
^{241}Pu	0.005	0.001	17 000	2 380
^{89}Sr	0.003	0.0005	11 000	1 540
^{91}Y	0.003	0.0005	8 900	1 250
^{141}Ce	0.001	0.0001	4 700	660
^{238}Pu	0.001	0.0001	2 300	320
Total (rounded)	3.7	0.52	30 000 000	4 180 000

[a] Based on a fission/fusion yield ratio of 0.14. Since the yield ratio for the Bikini tests is unknown, it is assumed in this table that the same fission/fusion ratio applies at Bikini Atoll as for total worldwide atmospheric testing of nuclear weapons.
[b] For simplicity, it is assumed that all ^{14}C is due to fusion.

debris remains contained, it is a potential source of human exposure. Underground nuclear weapon testing has never been conducted in the Marshall Islands. The earlier atmospheric tests, including those undertaken in Bikini Atoll, remain the principal source of worldwide exposure due to nuclear weapon testing. Table III shows UNSCEAR's estimates of the activity of radionuclides released and globally dispersed in all atmospheric nuclear testing and of those released in tests undertaken at Bikini Atoll.

The radioactive debris from an atmospheric nuclear test is partitioned between the local ground or water surface and tropospheric and stratospheric regions, depending on the type of test, location and yield. The subsequent precipitation or falling out of the debris is termed *local fallout* when it is locally dispersed, and *tropospheric fallout* and *stratospheric fallout* when it is globally dispersed.

Local fallout can comprise as much as 50% of the production for surface tests and includes large radioactive aerosol particles which are deposited within about 100 km of the test site. The northern islands of Bikini Atoll were severely contaminated by local radioactive fallout, and concentrations of ^{137}Cs and ^{90}Sr remain relatively high, together with lesser amounts of $^{239+240}Pu$ and ^{241}Am.

Tropospheric fallout consists of smaller aerosols which are not carried across the tropopause after the explosion and which deposit with a mean residence time of up to 30 days. During this period the debris becomes dispersed, although not well mixed, in the latitude band of injection following trajectories governed by wind patterns. From the viewpoint of human exposures, tropospheric fallout is important for nuclides with a half-life of a few days to two months, such as ^{131}I, ^{140}Ba or ^{89}Sr.

TABLE V. COLLECTIVE DOSE COMMITMENT BY THE WORLD'S POPULATION FOR CONTINUING PRACTICES AND FOR SINGLE EVENTS

Source	Basis of commitment	Collective dose (million man·Sv)
Natural sources	Current rate for 50 years	650
Medical exposure	Current rate for 50 years	
Diagnosis		90
Treatment		75
Nuclear weapon testing	**Completed practice (all nuclear weapon tests)**	**30**
	Completed practice (nuclear weapon tests at Bikini Atoll)	**4.2**
Nuclear power	Total practice to date	0.4
	Current rate for 50 years	2
Severe accidents	Events to date	0.6
Occupational exposure	Current rate for 50 years	
Medical		0.05
Nuclear power		0.12
Industrial uses		0.03
Defence activities		0.01
Non-uranium mining		0.4
Total (all occupations)		0.6

Stratospheric fallout, which comprises a large part of the total fallout, is from those particles which are carried to the stratosphere and later give rise to worldwide fallout, the major part of which is in the hemisphere of injection. Stratospheric fallout accounts for most of the worldwide residues of long lived fission products. Exposure of humans to fallout activity consists of internal irradiation (inhalation of radioactive materials in surface air and ingestion of contaminated foodstuffs) and external irradiation from radioactive materials present in surface air or deposited on the ground.

5.2.2. Radiation exposures

The contributions of the radionuclides released by atmospheric nuclear testing to the total dose commitment and the collective dose to the world's population have been estimated by UNSCEAR and are reported in Table IV, together with the contribution from testing undertaken at Bikini Atoll.

The summary in Table IV shows that the long lived radioisotope ^{14}C is the dominant contributor to the total effective dose commitment, accounting for 70% of the effective dose commitment to the world's population. However, if only 10% of the ^{14}C dose commitment is included in the comparison, i.e. if the dose commitments are truncated approximately to the year 2200, by which time all other radionuclides will have delivered effectively all of their doses, ^{14}C contributes only 19% to the truncated effective dose committed to the world's population.

The dose commitment to the world's population over infinite time from all atmospheric testing is about 3.7 mSv. The contribution from the tests undertaken at Bikini Atoll is about 0.5 mSv. Both figures are comparable to the effective dose from a single year of exposure to natural sources of radiation.

The total collective effective dose to be hypothetically incurred by the world's population over an infinite time period, attributable to the full series of atmospheric tests of nuclear weapons, is approximately 30 million man·Sv, of which about 4 million man·Sv are attributable to tests undertaken at Bikini Atoll. About one quarter of the collective dose will have been delivered by the year 2200; the remainder, due to ^{14}C, will be delivered over approximately the next 10 000 years. In comparison, the global collective dose attributable to natural sources over 50 years is 650 million man·Sv.

Some further perspective on these figures is provided in Table V. Although atmospheric testing of nuclear weapons represents the human-made source resulting in the largest collective dose, this is considerably smaller than the collective dose delivered unavoidably in a lifetime by exposure to natural background radiation.

These global estimates include a contribution from the doses to people close to the sites used for atmospheric tests. Although this contribution is small in global terms, some local doses have been substantial. The thyroid equivalent doses to children near the Nevada test site in the USA may have been as high as 1 Sv and it has been reported that thyroid equivalent doses to some children in Utah may have been as high as 4 Sv [31]. Similar high thyroid doses were incurred between 1949 and 1962 in settlements bordering the Semipalatinsk test site in the former USSR. Ground activity near Maralinga, Australia, the site of nuclear tests carried out by the United Kingdom, has been sufficient to restrict subsequent access. Some individual doses in the Marshall Islands were also high, mainly due to the Bravo test in 1954 and because the wind turned towards inhabited islands following the explosion.

The Bravo test is now widely known to have caused significant human radiation exposures at atolls east of Bikini [12, 13]. Owing to a sudden and unusual change in the wind direction on the day of the test, predominantly from the west rather than the east, people were exposed to radiation on at least three atolls: Rongelap, Ailinginae and Utirik. In particular, high radiation doses were received by the inhabitants of Rongelap Island (about 210 km from Bikini Atoll) and by some Rongelap Islanders temporarily residing on Ailinginae Atoll (about 150 km away). Lesser doses were received by the people of Utirik Atoll (about 570 km away). The other tests had no comparable radiological consequences.

Eighty-two individuals were evacuated from Rongelap 51 hours after the explosion and 159 persons were removed from Utirik within 78 hours. Effective doses as a result of external exposures, mainly from short lived radionuclides, ranged from 1.9 Sv on Rongelap (67 persons, including three in utero) and 1.1 Sv on nearby Ailinginae Atoll (19 persons, including one in utero) to 0.1 Sv on Utirik Atoll (167 persons, including eight in utero) [32]. The collective effective dose was of the order of 160 man·Sv. Equivalent doses to the thyroid, caused by several isotopes of iodine and tellurium and by external gamma radiation, were estimated to be 12, 22 and 52 Sv on average and 42, 82 and 200 Sv maximum to adults and children of 9 years and 1 year, respectively, on Rongelap Island [32].

The people of Bikini Atoll, while relocated on Kili, were not exposed to local fallout but mainly to the stratospheric fallout resulting from nuclear weapon testing in different parts of the northern hemisphere, including the Marshall Islands.

5.3. HEALTH EFFECTS OF RADIATION EXPOSURE

It has been recognized since the time of the first studies on X rays and radioactive minerals that exposure to radiation at high levels can cause early clinical damage to the tissues of the human body which, if extremely severe, can lead to death. In addition, long term epidemiological studies of populations (both human and animal) exposed to radiation, particularly the survivors of the atomic bombing of Hiroshima and Nagasaki in Japan in 1945, have demonstrated that exposure to radiation also has a potential for the delayed (or late) induction of malignancies and, plausibly, for hereditary effects.

5.3.1. Early effects

Exposure leading to very high radiation doses can cause effects such as nausea, reddening of the skin or, in severe cases, more acute syndromes that are clinically expressed in exposed individuals within a short period of time after the exposure. These effects can be clinically diagnosed in the exposed individual and attributed to the individual's dose. They are called *deterministic effects* because they are certain (predetermined) to occur if the dose exceeds a threshold level. Deterministic effects are the result of various processes, mainly cell death and impaired cell division, caused by exposure to radiation. If these processes are extensive enough, they can impair the function of the exposed tissue. The higher the dose is above the threshold for the occurrence of a particular deterministic effect in an exposed individual, the more severe is the effect. The threshold dose levels depend on the type of effect, the organ affected and also the duration of exposure. For doses delivered in a short period of time, deterministic effects can be expected at equivalent doses of the order of 1000 mSv. Death caused by acute radiation syndrome may occur at an effective dose of several thousand millisieverts.

The levels of equivalent doses and effective doses from the residual radionuclides from past nuclear weapon testing to be expected at present in Bikini Atoll (see Section 7) would be far below the threshold levels for the deterministic effects and no health effects of this type could conceivably occur in people living there now.

5.3.2. Late effects

As already stated, radiation exposure can also induce effects, such as malignancies, which are expressed after a relatively long latency period. Also, experimental studies in animals and plants have shown hereditary effects from radiation. Although hereditary effects have not been observed in humans, it is considered prudent for the purposes of setting standards to assume that they do occur. These radiation induced malignancies and hereditary effects are termed *stochastic effects* because of their aleatory and probabilistic nature. The induction of stochastic effects is assumed to take place over the entire range of doses, without a threshold level. Under certain conditions, primarily of relatively high doses and/or large numbers of people exposed, stochastic effects may be epidemiologically detectable in the exposed population as an increase in their natural incidence.

Stochastic effects may ensue if an irradiated cell is modified rather than killed. It is presumed that modified somatic cells may, after a prolonged process, develop into a cancer. If the cell modified by radiation exposure is a germ cell, whose function is to transmit genetic information to progeny, it is conceivable that hereditary effects of various types may develop in the descendents of the exposed individual. The body's repair and defence mechanisms make stochastic effects a very improbable outcome in the case of small doses; nevertheless, there is no evidence of a threshold level of dose below which stochastic effects cannot result from radiation exposure. Their probability of occurrence is higher for higher doses; however, the severity of any stochastic effect that may result from irradiation is independent of the dose sustained. Thus, the likelihood of stochastic effects is presumed to be proportional to the dose received, without a dose threshold. The proportionality factor is known as the nominal probability coefficient for the stochastic effect. For radiation protection purposes, the International Commission on Radiological Protection (ICRP) has recommended the use of the following nominal probability coefficients within the whole population: for fatal cancers, 5% per sievert, or 5 in 100 000 per millisievert; for non-fatal cancers, 1% per sievert, or 1 in 100 000 per millisievert; and for severe hereditary effects, 1.3% per sievert, or 1.3 in 100 000 per millisievert.

Stochastic effects attributable to the residual radionuclides in Bikini Atoll may theoretically occur in a population exposed to these radionuclides. However, because of the relatively low level of doses to be expected (see Section 7) and the small size of the population, any such effects would be undetectable.

6. PRESENT ENVIRONMENTAL RADIOLOGICAL CONDITIONS AT BIKINI ATOLL

The significant residual radionuclides from the nuclear tests that remain in the soil and surroundings of Bikini Atoll are ^{137}Cs, ^{90}Sr, $^{239+240}Pu$ and ^{241}Am. They are found to varying degrees in both the terrestrial and marine environments. Although this section refers to the radiological conditions in the whole of Bikini Atoll, it concentrates on Bikini Island, which was the previous permanent habitation of those people who were evacuated. It should be noted, however, that all the islands of Bikini Atoll have been thoroughly investigated, in particular in the NWRS [1] and by LLNL [33]. The results of measurements are available, in addition to Bikini Island, for the islands of Eneu, Rochikarai, Romurikku, Vorikku, Yurochi, Nam, Chieerete, Rukoji, Enidrik, Eniman, Reere, Bigiren and Airukiraru. Moreover, the NWRS investigated all atolls and reef islands in the Marshall Islands and found that Bikini Island has the highest residual activity of ^{137}Cs.

6.1. ACTIVITY IN SOIL

The coral soil of Bikini Atoll is composed mostly of calcium carbonate ($CaCO_3$), with some magnesium carbonate ($MgCO_3$) and essentially no clay. The soils are highly alkaline, with a potential of hydrogen (pH) ranging from 7.7 to 9.0. The surface horizons are high in organic matter (as much as 14%), although the organic matter in the soils drops markedly with depth in the soil column. As a result, most of the natural nutrients and the water retention capacity of the soil are confined to the top 25–40 cm of the soil column. The soils are low in exchangeable potassium (generally less than 50 parts per million) and marginal in phosphorus and trace mineral content. Some native plant species and most introduced species show definite signs of potassium deficiency. In fact, most introduced food crops and ornamental plants show very limited growth without the addition of potassium, phosphorus and trace minerals.

The unique composition of coral soil, which is primarily $CaCO_3$ with no clay, produces a pattern of availability to plants of ^{137}Cs and ^{90}Sr very different from that for which most data are reported in the literature, which correspond to aluminium silicate clay soils, as found in the Americas and Europe.

Bikini Island, the primary island for habitation at Bikini Atoll, has the highest concentrations of ^{137}Cs per unit mass of soil and vegetation in the atoll. The average ^{137}Cs concentration varies over a considerable range between the atoll's islands. The average ^{137}Cs concentration in soil and vegetation on Eneu Island, the other main island of residence, is about 10–13% of that of Bikini Island. Nam Island, one of the two other islands large enough for possible residence, has a ^{137}Cs concentration in soil of about 70% of that of Bikini Island; the ^{137}Cs concentration in soil at Enidrik Island, the other large island, is about 15% of that of Bikini Island.

The concentrations of transuranic radionuclides ($^{239+240}Pu$ and ^{241}Am) and their ratios to concentrations of ^{137}Cs and ^{90}Sr vary around the atoll, reflecting the difference in the design of the nuclear devices used in the detonations near the various islands. The concentrations of transuranic radionuclides in the soil on Nam Island exceed those on Bikini Island, while those on Enidrik Island are somewhat lower than those on Bikini Island. In general, the radionuclide concentrations decrease rapidly with depth in the soil column, although there are exceptions in parts of some islands. The activities of radionuclides per unit dry weight of soil in Bikini Island are shown in Table VI [20].

6.2. ACTIVITY IN FOODSTUFFS

Samples of various locally available foods and water have been collected and analysed in several studies for their content of residual radionuclides. Table VII presents the activity per unit mass of ^{137}Cs in these foodstuffs, measured as part of the NWRS [1] and other studies [20]. The activity was assessed from direct measurements on foodstuffs where this was feasible; otherwise they were predicted from concentration ratios at locations for which there were no measurements. The highest ^{137}Cs concentrations were found in coconut and some other fruits such as pandanus and breadfruit. It should be noted

TABLE VI. MEDIAN (AND MEAN) ACTIVITIES[a] OF ^{137}Cs, ^{90}Sr, $^{239+240}$Pu AND ^{241}Am PER UNIT DRY WEIGHT OF SOIL ON BIKINI ISLAND (Bq/g) [20]

Soil depth (cm)	^{137}Cs	^{90}Sr	$^{239+240}$Pu	^{241}Am
Interior of island				
0–5	2.3 (3.0)	1.7 (2.1)	0.32 (0.42)	0.26 (0.30)
5–10	1.2 (1.8)	2.0 (2.4)	0.29 (0.44)	0.19 (0.27)
10–15	0.58 (1.0)	1.5 (2.3)	0.15 (0.34)	0.081 (0.18)
15–25	0.19 (0.48)	0.73 (1.4)	0.053 (0.16)	0.026 (0.11)
25–40	0.071 (0.19)	0.47 (0.77)	0.0081 (0.061)	0.012 (0.051)
40–60	0.018 (0.019)	0.32 (0.65)	0.011 (0.035)	0.017 (0.073)
0–40	0.70 (0.91)	1.1 (1.5)	0.17 (0.21)	0.11 (0.14)
Village area				
0–5	1.2 (2.0)	1.0 (2.0)	0.20 (0.40)	0.11 (0.22)
5–10	1.0 (1.6)	1.2 (2.0)	0.30 (0.40)	0.13 (0.20)
10–15	0.81 (1.2)	1.5 (1.7)	0.22 (0.28)	0.12 (0.19)
15–25	0.53 (1.0)	0.90 (1.6)	0.14 (0.25)	0.064 (0.15)
25–40	0.18 (0.80)	0.62 (1.7)	0.064 (0.25)	0.059 (0.13)
40–60	0.028 (0.23)	0.32 (1.2)	0.0058 (0.11)	0.012 (0.11)
0–40	0.67 (1.1)	1.6 (1.5)	0.24 (0.29)	0.13 (0.17)

[a] Decay corrected to 1999. The numbers in parentheses are the arithmetic mean.

that the ^{137}Cs concentration data in the tables were recorded over different periods of time by different researchers, and this explains some of the variability in the data, mainly of a statistical nature. All surveys have undergone quality control programmes and inter-laboratory comparisons, and therefore the ^{137}Cs data are reasonably consistent.

Activities per unit mass of foodstuff for ^{90}Sr, $^{239+240}$Pu and ^{241}Am are provided in Tables VIII, IX and X. The ^{90}Sr activities are less than 10% of the respective ^{137}Cs activities in the relevant foodstuffs. The $^{239+240}$Pu and ^{241}Am activities are even lower than the ^{90}Sr activities in the relevant foodstuffs.

6.3. ACTIVITY IN AIR (RESUSPENSION)

Of the residual radionuclides present in soil, those of greatest potential significance for the inhalation exposure pathway are $^{239+240}$Pu and ^{241}Am incorporated into surface soil particles which can be resuspended by wind action. A detailed resuspension study was made at Bikini Atoll in 1978 [34, 35]. Additional work on resuspension has subsequently been completed at Rongelap and Enewetak Atolls. The results are similar at all the atolls: the average resuspension of the surface soil is very low, with resuspension factors (i.e. the relation between the activity per unit volume of air and the activity per unit area of surface soil giving rise to it) ranging from 10^{-10} to 10^{-11} m^{-1}. A mass loading model has been developed from the data generated in these studies and used in conjunction with the $^{239+240}$Pu and ^{241}Am concentrations in the surface soil (0–5 cm) to estimate the daily inhalation of the two radionuclides [35]. On the basis of the measured activities of these radionuclides in the soil and the resuspension factors mentioned above, the air concentrations of these radionuclides are expected to be very low, and consequently the expected contribution to doses from radiation exposure via inhalation pathways is judged to be insignificant.

6.4. ACTIVITY IN THE LAGOON

The residual radionuclides ^{137}Cs, ^{90}Sr, $^{239+240}$Pu and ^{241}Am are present in the atoll's lagoon, mainly in sediments, but also in water and in biota. In general, radionuclide concentrations in the lagoon sediments are about one order of magnitude higher in the northeastern, northern and northwestern parts of the atoll than in sediments in the southern half of the atoll. Additional information on levels and distribution of activity in Bikini lagoon sediment can be found in Refs [36, 37].

TABLE VII. ACTIVITY[a] OF ^{137}Cs PER UNIT WET WEIGHT OF LOCAL (BIKINIAN) FOOD (Bq/g)

Food type	Mean	Median	SD	Minimum	Maximum	Ref. [20] except where stated
Reef fish	2.9×10^{-3}	1.4×10^{-3}	3.1×10^{-3}	4.4×10^{-5}	1.2×10^{-2}	
Tuna (pelagic fish)	4.5×10^{-3}	4.6×10^{-3}	2.9×10^{-3}	1.2×10^{-3}	9.6×10^{-3}	
Mahi mahi	4.5×10^{-3}	4.6×10^{-3}				
Marine crabs (shellfish)	1.4×10^{-3}	9.4×10^{-4}	1.3×10^{-3}	3.2×10^{-4}	4.0×10^{-3}	
Lobster	1.4×10^{-3}	9.4×10^{-4}				
Clams	$<4.6 \times 10^{-4}$	$<2.1 \times 10^{-4}$	$<4.0 \times 10^{-4}$	$<8.3 \times 10^{-5}$	$<1.1 \times 10^{-3}$	
Trochus	$<4.6 \times 10^{-4}$	$<2.1 \times 10^{-4}$				
Tridacna muscle	$<4.6 \times 10^{-4}$	$<2.1 \times 10^{-4}$				
Jedrul	$<4.6 \times 10^{-4}$	$<2.1 \times 10^{-4}$				
Coconut crabs	3.7×10^{-1}	3.2×10^{-1}	2.2×10^{-1}	1.4×10^{-1}	6.7×10^{-1}	
Land crabs	3.7×10^{-1}	3.2×10^{-1}				
Octopus	1.8×10^{-3}	1.8×10^{-3}	3.8×10^{-4}	1.6×10^{-3}	2.1×10^{-3}	
Turtle	$<2.8 \times 10^{-4}$	$<2.8 \times 10^{-4}$	$<2.7 \times 10^{-4}$	$<8.9 \times 10^{-5}$	$<4.7 \times 10^{-4}$	
Chicken muscle	1.5×10^{-1}	1.5×10^{-1}	0.0×10^{0}	1.5×10^{-1}	1.5×10^{-1}	
Chicken liver		1.5×10^{-1}	1.5×10^{-1}			
Chicken gizzard	1.5×10^{-1}	1.5×10^{-1}				
Pork muscle	7.0×10^{0}	7.4×10^{0}	4.4×10^{0}	2.2×10^{0}	$1.3 \times 10^{+1}$	
Pork kidney	6.5×10^{0}	5.0×10^{0}	4.4×10^{0}	1.8×10^{0}	$1.3 \times 10^{+1}$	
Pork liver	3.6×10^{0}	3.1×10^{0}	3.3×10^{0}	1.0×10^{0}	9.2×10^{0}	
Pork heart	4.2×10^{0}	2.7×10^{0}	4.6×10^{0}	2.3×10^{-1}	$1.2 \times 10^{+1}$	
Bird muscle	$<2.5 \times 10^{-3}$	$<1.4 \times 10^{-3}$	$<3.5 \times 10^{-3}$	$<3.0 \times 10^{-4}$	$<1.2 \times 10^{-2}$	
Birds' eggs	6.7×10^{-4}	6.7×10^{-4}	0.0×10^{0}	6.7×10^{-4}	6.7×10^{-4}	
Chicken eggs		1.5×10^{-1}	1.5×10^{-1}			
Turtle eggs	$<2.8 \times 10^{-4}$	$<2.8 \times 10^{-4}$				
Pandanus fruit	3.9×10^{0}	3.2×10^{0}	3.3×10^{0}	1.1×10^{-1}	$1.9 \times 10^{+1}$	
Pandanus nuts	3.9×10^{0}	3.2×10^{0}				
Pandanus[b]	7.4×10^{0}	7.4×10^{0}				*[1]*
Breadfruit	3.8×10^{-1}	3.1×10^{-1}	2.2×10^{-1}	9.0×10^{-2}	1.1×10^{0}	
Breadfruit[b]	4.7×10^{0}	7.1×10^{-1}				*[1]*
Coconut fluid	1.2×10^{0}	9.6×10^{-1}	8.9×10^{-1}	2.8×10^{-2}	6.1×10^{0}	
Coconut fluid[b]	6.2×10^{-1}	4.6×10^{-1}				*[1]*
Coconut milk	5.4×10^{0}	5.4×10^{0}				
Tuba/jekero	5.4×10^{0}	5.4×10^{0}				
Drinking coconut meat	2.9×10^{0}	2.6×10^{0}	2.2×10^{0}	1.4×10^{-1}	$1.6 \times 10^{+1}$	
Drinking coconut meat[b]	4.1×10^{0}	2.4×10^{0}				*[1]*
Copra meat	5.4×10^{0}	5.4×10^{0}	3.5×10^{0}	7.2×10^{-2}	$2.2 \times 10^{+1}$	
Sprouting coconut	5.4×10^{0}	5.4×10^{0}				
Marshallese cake	5.4×10^{0}	5.4×10^{0}				
Papaya	2.2×10^{0}	8.2×10^{-1}	2.9×10^{0}	8.1×10^{-2}	$1.4 \times 10^{+1}$	
Squash	1.2×10^{0}	5.9×10^{-1}	1.4×10^{0}	6.3×10^{-2}	5.9×10^{0}	
Pumpkin	1.2×10^{0}	5.9×10^{-1}				
Banana	1.8×10^{-1}	1.5×10^{-1}	1.1×10^{-1}	3.3×10^{-2}	4.7×10^{-1}	
Arrowroot (cooked)	5.4×10^{-2}	6.7×10^{-2}	2.2×10^{-2}	2.8×10^{-2}	6.7×10^{-2}	
Citrus	1.2×10^{-1}	1.2×10^{-1}	0.0×10^{0}	1.2×10^{-1}	1.2×10^{-1}	
Rainwater	4.3×10^{-5}	3.3×10^{-5}	4.7×10^{-5}	6.8×10^{-6}	2.0×10^{-4}	
Groundwater[b]	1.1×10^{-3}	1.1×10^{-3}				*[1]*
Well water	4.5×10^{-3}	3.1×10^{-3}	3.4×10^{-3}	9.1×10^{-4}	1.5×10^{-2}	
Malolo	4.3×10^{-5}	3.3×10^{-5}				
Coffee/tea	4.3×10^{-5}	3.3×10^{-5}				

[a] Decay corrected to 1999.

[b] Data in italics are from Ref. [1].

SD: standard deviation.

TABLE VIII. ACTIVITY[a] OF ^{90}Sr PER UNIT WET WEIGHT OF LOCAL (BIKINIAN) FOOD (Bq/g) [20]

Food type	Mean	Median	SD	Minimum	Maximum
Reef fish	4.5×10^{-5}	2.2×10^{-5}	4.5×10^{-5}	9.7×10^{-6}	1.3×10^{-4}
Tuna (pelagic fish)	5.3×10^{-6}	5.3×10^{-6}	0.0×10^{0}	5.3×10^{-6}	5.3×10^{-6}
Mahi mahi	5.3×10^{-6}	5.3×10^{-6}			
Marine crabs (shellfish)	$<8.9 \times 10^{-5}$	$<8.9 \times 10^{-5}$	0.0×10^{0}	$<8.9 \times 10^{-5}$	$<8.9 \times 10^{-5}$
Lobster	$<8.9 \times 10^{-5}$	$<8.9 \times 10^{-5}$			
Clams	$<8.7 \times 10^{-5}$	$<8.7 \times 10^{-5}$	$<6.2 \times 10^{-5}$	$<4.3 \times 10^{-5}$	$<1.3 \times 10^{-4}$
Trochus	$<8.7 \times 10^{-5}$	$<8.7 \times 10^{-5}$			
Tridacna muscle	$<8.7 \times 10^{-5}$	$<8.7 \times 10^{-5}$			
Jedrul	$<8.7 \times 10^{-5}$	$<8.7 \times 10^{-5}$			
Octopus	4.5×10^{-5}	2.2×10^{-5}			
Turtle	4.5×10^{-5}	2.2×10^{-5}			
Chicken muscle	1.5×10^{-3}	1.4×10^{-3}			
Chicken liver	1.5×10^{-3}	1.4×10^{-3}			
Chicken gizzard	1.5×10^{-3}	1.4×10^{-3}			
Pork muscle	1.5×10^{-3}	1.4×10^{-3}	7.6×10^{-4}	8.2×10^{-4}	2.3×10^{-3}
Pork kidney	6.2×10^{-3}	7.3×10^{-3}	2.6×10^{-3}	3.2×10^{-3}	8.1×10^{-3}
Pork liver	2.9×10^{-3}	1.6×10^{-3}	3.1×10^{-3}	7.0×10^{-4}	6.4×10^{-3}
Pork heart	1.5×10^{-3}	1.2×10^{-3}	7.7×10^{-4}	9.1×10^{-4}	2.4×10^{-3}
Bird muscle	2.3×10^{-4}	2.3×10^{-4}	0.0×10^{0}	2.3×10^{-4}	2.3×10^{-4}
Birds' eggs	3.6×10^{-4}	3.6×10^{-4}	0.0×10^{0}	3.6×10^{-4}	3.6×10^{-4}
Chicken eggs	1.5×10^{-3}	1.4×10^{-3}			
Turtle eggs	4.5×10^{-5}	2.2×10^{-5}			
Pandanus fruit	1.2×10^{-1}	5.6×10^{-2}	1.3×10^{-1}	8.6×10^{-3}	3.6×10^{-1}
Pandanus nuts	1.2×10^{-1}	5.6×10^{-2}			
Breadfruit	6.9×10^{-2}	5.1×10^{-2}	6.2×10^{-2}	6.0×10^{-3}	2.0×10^{-1}
Coconut fluid	4.5×10^{-4}	4.8×10^{-4}	3.1×10^{-4}	7.1×10^{-5}	8.8×10^{-4}
Coconut milk	3.2×10^{-3}	2.5×10^{-3}			
Drinking coconut meat	5.9×10^{-3}	5.1×10^{-3}	3.6×10^{-3}	6.3×10^{-4}	2.9×10^{-2}
Copra meat	3.2×10^{-3}	2.5×10^{-3}	2.9×10^{-3}	3.7×10^{-4}	1.6×10^{-2}
Sprouting coconut	3.2×10^{-3}	2.5×10^{-3}			
Marshallese cake	3.2×10^{-3}	2.5×10^{-3}			
Papaya	4.9×10^{-2}	4.8×10^{-2}	2.8×10^{-2}	9.4×10^{-3}	8.1×10^{-2}
Squash	6.8×10^{-2}	5.3×10^{-2}	3.8×10^{-2}	2.6×10^{-2}	1.7×10^{-1}
Pumpkin	6.8×10^{-2}	5.3×10^{-2}			
Banana	4.9×10^{-2}	4.8×10^{-2}			
Arrowroot (cooked)	6.8×10^{-2}	5.3×10^{-2}			
Citrus	4.9×10^{-2}	4.8×10^{-2}			
Rain water	1.4×10^{-5}	8.6×10^{-6}	1.5×10^{-5}	3.4×10^{-6}	5.9×10^{-5}
Well water	1.2×10^{-3}	6.5×10^{-4}	1.5×10^{-3}	2.1×10^{-5}	5.5×10^{-3}
Malolo	1.4×10^{-5}	8.6×10^{-6}			
Coffee/tea	1.4×10^{-5}	8.6×10^{-6}			

[a] Decay corrected to 1999.
SD: standard deviation.

TABLE IX. ACTIVITY[a] OF $^{239+240}Pu$ PER UNIT WET WEIGHT OF LOCAL (BIKINIAN) FOOD (Bq/g) [20]

Local food	Mean	Median	SD	Minimum	Maximum
Reef fish	1.3×10^{-5}	8.6×10^{-6}	1.2×10^{-5}	1.1×10^{-6}	4.1×10^{-5}
Tuna (pelagic fish)	1.9×10^{-6}	2.1×10^{-6}	1.3×10^{-6}	5.6×10^{-7}	4.0×10^{-6}
Mahi mahi	1.9×10^{-6}	2.1×10^{-6}			
Marine crabs (shellfish)	3.6×10^{-5}	3.6×10^{-5}	0.0×10^{0}	3.6×10^{-5}	3.6×10^{-5}
Lobster	3.6×10^{-5}	3.6×10^{-5}			
Clams	8.3×10^{-4}	8.1×10^{-4}	6.9×10^{-4}	8.2×10^{-6}	1.9×10^{-3}
Trochus	8.3×10^{-4}	8.1×10^{-4}			
Tridacna muscle	8.3×10^{-4}	8.1×10^{-4}			
Jedrul	8.3×10^{-4}	8.1×10^{-4}			
Octopus	1.3×10^{-5}	8.6×10^{-6}			
Turtle	1.3×10^{-5}	8.6×10^{-6}			
Chicken muscle	7.7×10^{-6}	6.6×10^{-6}			
Chicken liver	7.7×10^{-6}	6.6×10^{-6}			
Chicken gizzard	7.7×10^{-6}	6.6×10^{-6}			
Pork muscle	7.7×10^{-6}	6.6×10^{-6}	5.6×10^{-6}	2.7×10^{-6}	1.4×10^{-5}
Pork kidney	3.5×10^{-5}	2.8×10^{-5}	3.3×10^{-5}	6.4×10^{-6}	7.0×10^{-5}
Pork liver	1.2×10^{-4}	1.2×10^{-4}	8.2×10^{-5}	3.6×10^{-5}	2.0×10^{-4}
Pork heart	5.9×10^{-6}	3.6×10^{-6}	4.1×10^{-6}	3.4×10^{-6}	1.1×10^{-5}
Bird muscle	1.3×10^{-5}	8.6×10^{-6}			
Birds' eggs	1.3×10^{-5}	8.6×10^{-6}			
Chicken eggs	7.7×10^{-6}	6.6×10^{-6}			
Turtle eggs	1.3×10^{-5}	8.6×10^{-6}			
Pandanus fruit	3.2×10^{-6}	1.8×10^{-6}	3.1×10^{-6}	3.4×10^{-7}	1.1×10^{-5}
Pandanus nuts	3.2×10^{-6}	1.8×10^{-6}			
Breadfruit	1.8×10^{-6}	9.6×10^{-7}	2.8×10^{-6}	1.4×10^{-7}	9.8×10^{-6}
Coconut juice	1.0×10^{-6}	6.0×10^{-7}	1.0×10^{-6}	3.3×10^{-7}	2.2×10^{-6}
Coconut milk	1.9×10^{-6}	7.7×10^{-7}			
Tuba/jekero	1.9×10^{-6}	7.7×10^{-7}			
Drinking coconut meat	2.7×10^{-6}	1.5×10^{-6}	3.5×10^{-6}	1.7×10^{-7}	1.4×10^{-5}
Copra meat	1.9×10^{-6}	7.7×10^{-7}	2.7×10^{-6}	1.4×10^{-7}	1.0×10^{-5}
Sprouting coconut	1.9×10^{-6}	7.7×10^{-7}			
Marshallese cake	1.9×10^{-6}	7.7×10^{-7}			
Papaya	2.5×10^{-6}	1.0×10^{-7}	4.2×10^{-6}	6.2×10^{-8}	7.3×10^{-6}
Squash	2.2×10^{-5}	5.0×10^{-6}	3.8×10^{-5}	5.0×10^{-7}	1.3×10^{-4}
Pumpkin	2.2×10^{-5}	5.0×10^{-6}			
Banana	2.5×10^{-6}	1.0×10^{-7}			
Arrowroot	2.2×10^{-5}	5.0×10^{-6}			
Citrus	2.5×10^{-6}	1.0×10^{-7}			
Rain water	3.3×10^{-7}	1.6×10^{-7}	4.8×10^{-7}	7.0×10^{-8}	1.9×10^{-6}
Well water	6.1×10^{-7}	3.9×10^{-7}	6.2×10^{-7}	1.1×10^{-7}	3.3×10^{-6}
Malolo	3.3×10^{-7}	1.6×10^{-7}			
Coffee/tea	3.3×10^{-7}	1.6×10^{-7}			

[a] Decay corrected to 1999.

SD: standard deviation.

TABLE X. ACTIVITY[a] OF ^{241}Am PER UNIT WET WEIGHT OF LOCAL (BIKINIAN) FOOD (Bq/g) [20]

Local food	Mean	Median	SD	Minimum	Maximum
Reef fish	6.5×10^{-6}	3.1×10^{-6}	1.0×10^{-5}	4.1×10^{-8}	4.0×10^{-5}
Tuna (pelagic fish)	1.3×10^{-6}	1.3×10^{-6}	0.0×10^{0}	1.3×10^{-6}	1.3×10^{-6}
Mahi mahi	1.3×10^{-6}	1.3×10^{-6}			
Clams	4.6×10^{-4}	3.7×10^{-4}	4.2×10^{-4}	1.8×10^{-5}	1.2×10^{-3}
Trochus	4.6×10^{-4}	3.7×10^{-4}			
Tridacna muscle	4.6×10^{-4}	3.7×10^{-4}			
Jedrul	4.6×10^{-4}	3.7×10^{-4}			
Octopus	6.5×10^{-6}	3.1×10^{-6}			
Turtle	6.5×10^{-6}	3.1×10^{-6}			
Chicken muscle	6.0×10^{-6}	7.6×10^{-6}			
Chicken liver	6.0×10^{-6}	7.6×10^{-6}			
Chicken gizzard	6.0×10^{-6}	7.6×10^{-6}			
Pork muscle	6.0×10^{-6}	7.6×10^{-6}	4.4×10^{-6}	9.5×10^{-7}	9.4×10^{-6}
Pork kidney	1.2×10^{-5}	5.1×10^{-6}	1.4×10^{-5}	3.1×10^{-6}	2.8×10^{-5}
Pork liver	5.2×10^{-5}	4.4×10^{-5}	2.5×10^{-5}	3.2×10^{-5}	8.1×10^{-5}
Pork heart	1.8×10^{-5}	1.8×10^{-5}	0.0×10^{0}	1.8×10^{-5}	1.8×10^{-5}
Bird muscle	6.5×10^{-6}	3.1×10^{-6}			
Birds' eggs	6.5×10^{-6}	3.1×10^{-6}			
Chicken eggs	6.0×10^{-6}	7.6×10^{-6}			
Turtle eggs	6.5×10^{-6}	3.1×10^{-6}			
Pandanus fruit	3.8×10^{-6}	2.7×10^{-6}	4.8×10^{-6}	2.8×10^{-7}	1.5×10^{-5}
Pandanus nuts	3.8×10^{-6}	2.7×10^{-6}			
Breadfruit	1.2×10^{-6}	2.9×10^{-7}	1.9×10^{-6}	1.5×10^{-7}	5.3×10^{-6}
Coconut juice	8.5×10^{-6}	8.5×10^{-6}	0.0×10^{0}	8.5×10^{-6}	8.5×10^{-6}
Coconut milk	1.1×10^{-6}	6.8×10^{-7}			
Tuba/jekero	1.1×10^{-6}	6.8×10^{-7}			
Drinking coconut meat	3.6×10^{-6}	1.9×10^{-6}	5.1×10^{-6}	5.0×10^{-7}	1.6×10^{-5}
Sprouting coconut	1.1×10^{-6}	6.8×10^{-7}			
Marshallese cake	1.1×10^{-6}	6.8×10^{-7}			
Copra meat	1.1×10^{-6}	6.8×10^{-7}	1.1×10^{-6}	2.3×10^{-7}	3.9×10^{-6}
Papaya	3.6×10^{-7}	3.6×10^{-7}	2.8×10^{-7}	1.6×10^{-7}	5.6×10^{-7}
Squash	3.0×10^{-6}	3.0×10^{-6}	0.0×10^{0}	3.0×10^{-6}	3.0×10^{-6}
Pumpkin	3.0×10^{-6}	3.0×10^{-6}			
Banana	3.6×10^{-7}	3.6×10^{-7}			
Arrowroot	3.0×10^{-6}	3.0×10^{-6}			
Citrus	3.6×10^{-7}	3.6×10^{-7}			
Rain water	3.7×10^{-8}	3.7×10^{-8}	5.4×10^{-9}	3.3×10^{-8}	4.1×10^{-8}
Malolo	3.7×10^{-8}	3.7×10^{-8}			
Coffee/tea	3.7×10^{-8}	3.7×10^{-8}			

[a] Decay corrected to 1999.

SD: standard deviation.

TABLE XI. ISOLINES (IN FIG. 3) *OF ABSORBED DOSE RATE IN AIR AT* BIKINI ISLAND (AUGUST 1978)

Contour area	Annual absorbed dose in air at 1 m above surface (mGy)
A	<0.011
B	0.011–0.031
C	0.031–0.066
D	0.066–0.123
E	0.123–0.202
F	0.202–0.351
G	0.351–0.526
H	0.526–0.789
I	0.789–1.23
J	1.23–1.75
K	1.75–2.63
L	2.63–3.51
M	3.51–5.26

Caesium-137 is found in very low concentrations in lagoon sediment, lagoon water and fish. Compounds of caesium are generally highly soluble and the majority of the original inventory of ^{137}Cs in the lagoon has long since dissolved and become mixed with the world's oceans.

Strontium-90, which is chemically similar to calcium, a major component of the coral soils (as $CaCO_3$), competes with the very large quantities of calcium available for uptake by and distribution in marine species. It is also chemically bound in the growing coral and in the coral sediment, and remains in the lagoon environment, primarily in the carbonate matrix. Consequently, ^{90}Sr is relatively unavailable to marine life [38, 39].

The occurrence and redistribution of the transuranic radionuclides $^{239+240}$Pu and ^{241}Am in the coral sediments and the mobilization and redistribution in the water column, both in solution and in association with resuspended particulate material, are discussed in the literature [40–48]. Published estimates of transuranic inventories are provided in Refs [43, 44, 47]. Distributions in surface sediment at Bikini Atoll were constructed and inventories were estimated from published and unpublished data. It should be noted that sediment inventories for Bikini Atoll were estimated from substantially fewer data than were available for Enewetak Atoll.

The initially estimated $^{239+240}$Pu inventory based on the analysis of sediment columns of 16 cm depth taken from Bikini Atoll was 55.5 TBq. However, in a few deeper cores, which are difficult to obtain from carbonate deposits, $^{239+240}$Pu and ^{241}Am were detected at depths below 20 cm. The inventories computed to a depth of 16 cm can therefore be assumed only to represent lower limits. From recent results [48], the best estimate for the total inventory of $^{239+240}$Pu in Bikini Atoll sediments is 103 ± 25 TBq. The best estimate of the total inventory for ^{241}Am is 93 ± 10 TBq.

6.5. RATES OF ABSORBED DOSE IN AIR

Measurements of absorbed dose rates in air due to gamma radiation were made at Bikini Atoll both as part of the NWRS [1] and as part of the LLNL survey [9, 16]. The measurements were made using high resolution solid state detectors 1 m above ground level to obtain an average of the radiation emissions over a circle about 10 m in radius. Earlier measurements had also been obtained by means of an aerial measurement technique [15].

Comparisons between the two approaches were made by locating the ground measurement points on the aerial photographs of the islands of the atoll onto which isodose contours were superimposed [1]. Some differences were found in the results, as expected, owing to the uneven patterns of ground activity, especially for the smallest islands of the atoll, and differences in resolution for the different methods. (The resolution was about 20 m for the in situ approach and about 100 m for the aerial approach.) However, the ratio between the mean value of the in situ measurements and the corresponding value of the aerial measurements is close to 1, showing good agreement between them.

On Bikini Island the annual absorbed dose in air measured at 1 m above the ground varied from about 0.01 to 5 mGy (see Fig. 3 and Table XI). These measurements were conducted in August 1978; the values, decay corrected to 1999, would be about 60% of those in 1978: from 0.006 to 3 mGy.

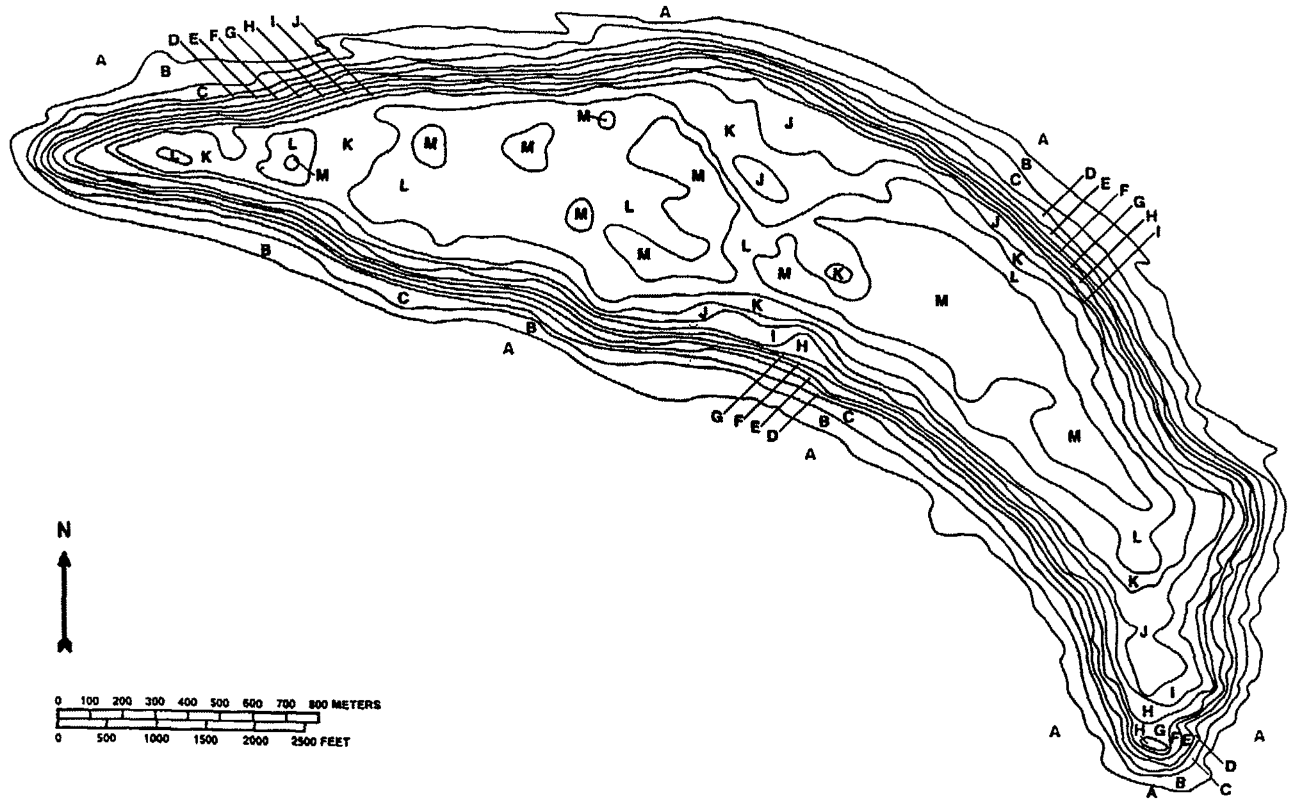

FIG. 3. Isolines of the absorbed dose rates in air for Bikini Island.

7. ESTIMATES OF POTENTIAL RADIATION DOSES TO PEOPLE RESETTLING BIKINI ISLAND UNDER PRESENT CONDITIONS

7.1. SOURCES AND PATHWAYS OF EXPOSURE

The radiation exposure of persons living at Bikini Island would result from two sources: (1) natural sources of radiation; and (2) residues from nuclear weapon testing.

For natural sources of radiation, the main exposure pathways are external exposure to cosmic radiation and external and internal exposure to terrestrial radionuclides which — in the case of the Marshall Islands — is dominated by the intake of naturally occurring radionuclides in foodstuffs, mainly fish.

For residual activity, the main exposure pathways of relevance are external exposure due to radioactive materials on the ground and internal exposure arising from the ingestion of radioactive materials in foodstuffs produced on the island. The ingestion pathway includes the intake of terrestrial and marine foods, possibly small quantities of soil, stored rain water and groundwater. Inhalation of resuspended radioactive materials is also a plausible pathway of exposure.

There is evidence in some parts of the world of a condition called 'pica' in which people, mainly children, may deliberately ingest non-food items such as soil in substantial quantities. In the case of the Marshall Islands, such intakes could result in non-trivial radiation doses due mainly to actinides such as plutonium and americium. However, such intakes are considered to be unlikely and, even if they did occur, evidence suggests that pica cases are intermittent and would not extend for periods of a year at a sustained rate of intake. Furthermore, it has been pointed out that there was no indication from a urine analysis study undertaken on the populations of Rongelap, Enewetak and Bikini Atolls [49] and a bone autopsy study on the inhabitants of Rongelap Atoll [50] of a significant route of intake for actinide elements.

Other potential routes by which exposure could occur, such as exposure while swimming or diving in the lagoon, have been analysed, with account taken of the known radionuclide concentrations in water and sediments. The contribution to dose via these pathways was found to be so small that they could be neglected in the general dose assessment.

As the reviewed assessments focused on doses to adults, an independent analysis was carried out of the potential significance of doses to children [51]. This study concluded that, on the basis of the information available, the estimated doses for adults serve as conservative estimates of doses for children.

7.2. DOSES DUE TO NATURAL SOURCES

The worldwide exposure to natural background radiation has been estimated by UNSCEAR. The average annual effective dose is 2.4 mSv [52], apportioned as shown in Table XII, which also provides the estimated average dose in the Marshall Islands [53]. In the case of the northern atolls of the islands, the annual external effective dose due to cosmic radiation is significantly lower than the global average: 0.22 mSv. The annual external effective dose due to naturally occurring terrestrial radionuclides on the atolls is insignificant, but the annual committed effective dose from the intake of naturally occurring radionuclides such as ^{210}Po and ^{210}Pb in food is about 2.2 mSv/a. The source of ^{210}Po and ^{210}Pb in the diet is fish, which constitutes a major component of the diet of the atoll dwellers. In total, therefore, the natural background doses at Bikini Atoll can be assumed to be comparable with the global average [54].

7.3. DOSES DUE TO RESIDUES FROM NUCLEAR WEAPON TESTING

Two independent assessments were reviewed (the NWRS [1] and the LLNL [20] study). These had been performed in order to evaluate the potential committed doses to the population who in the future might live on Bikini Island.

TABLE XII. AVERAGE ANNUAL EFFECTIVE DOSES DUE TO NATURAL SOURCES OF RADIATION (mSv)

Source	Global average annual effective dose in areas of normal background radiation		Average annual effective dose in the Marshall Islands
Cosmic rays		0.38	0.22
Cosmogenic radionuclides		0.01	0.01
Terrestrial radionuclides:			
^{40}K		0.3	0.18
^{238}U series:			
$^{238}U \rightarrow ^{234}U \rightarrow ^{230}Th$	0.014		Nil
^{226}Ra	0.004		Nil
$^{222}Rn \rightarrow ^{214}Po$	1.2		Nil
$^{210}Pb \rightarrow ^{210}Po$	0.05		^{210}Po diet 1.8 ^{210}Pb diet 0.20
Total ^{238}U series		1.4	
^{232}Th series		0.27	Nil
Total (rounded)		2.4	2.4

For external irradiation, the average effective dose contribution due to external gamma radiation was estimated by means of direct measurements inside and outside houses, measurements in the village area and aerial survey measurements. The dose estimate is based on the following occupancy assumptions, made on the basis of discussions with the Marshallese people and observations: ten hours per day spent inside the houses, nine hours per day outside in the village area, three hours per day in the interior region of the island and two hours per day on the beach or lagoon. The average annual effective dose based on this occupancy model, and decay corrected to 1999, is 0.4 mSv.

For internal doses, both assessments used conversion factors from activity intake into effective dose which are compatible with those established in the Basic Safety Standards [25].

The NWRS [1] presumed a low but still reasonable caloric value in the diet model. The diet included a 25% contribution from rice, which all Marshallese have as a common dietary component. The dose assessment was a probabilistic (Monte Carlo) calculation and used probability distributions for all parameters. The model was not described in the NWRS report because the report was not intended to include technical details, but there is a description of the probabilistic dose calculation in Ref. [55]. The median doses are presented in the NWRS report with estimated uncertainties as a robust description of the best estimate of dose for skewed probability distributions. The study predicted an annual individual dose of 8.0 mSv (if the dose due to natural background radiation were added, this would result in an annual effective dose of about 10.4 mSv).

The second study, by LLNL [20], assumed a high calorie diet model, as listed in Table XIII. The information on diets was obtained from a limited study carried out in the Marshall Islands. The US National Academy of Sciences reviewed the diet assumptions [56]. The overall dose, i.e. the sum of the annual effective dose due to external radiation and the committed effective dose due to intakes in the year being considered, on the assumption of a diet consisting of both imported and locally derived foods, is 4.0 mSv (if the dose due to natural background radiation were added, this would result in an annual effective dose of 6.4 mSv). For a diet consisting of only locally derived foodstuffs, the annual overall dose is 15 mSv (if the dose due to natural background radiation were added, this would result in an annual effective dose of about 17.4 mSv).

If the NWRS estimate was adjusted to account for the LLNL's assumption of a high calorie intake,

TABLE XIII. SOME DIET MODELS FOR ADULTS LIVING ON BIKINI ISLAND [1, 20]

Local food	Local component of an 'imported foods' diet		'Local foods only' diet	
	g/d	kcal/d	g/d	kcal/d
Reef fish	24.2	33.8	86.8	121
Tuna	13.9	19.4	72.0	101
Mahi mahi	3.56	3.92	21.4	23.5
Marine crabs	1.68	1.51	19.5	17.6
Lobster	3.88	3.49	35.2	31.7
Clams	4.56	3.65	58.1	46.5
Trochus	0.10	0.080	0.24	0.19
Tridacna muscle	1.67	2.14	11.4	14.6
Jedrul	3.08	2.46	19.4	17.4
Coconut crabs	3.13	2.19	24.9	17.5
Octopus	4.51	4.51	49.0	49.0
Turtle	4.34	3.86	17.8	15.8
Chicken muscle	8.36	14.2	31.2	53.0
Chicken liver	4.50	7.38	17.7	29.0
Chicken gizzard	1.66	2.46	3.32	4.91
Pork muscle	5.67	25.5	13.9	62.6
Pork liver	2.60	6.27	6.70	16.1
Pork heart	0.31	0.60	0.62	1.21
Bird muscle	2.71	4.61	26.4	44.8
Birds' eggs	1.54	2.31	22.8	34.1
Chicken eggs	7.25	11.8	41.2	67.2
Turtle eggs	9.36	14.0	235	352
Pandanus fruit	8.66	5.20	63.0	37.8
Pandanus nuts	0.50	1.33	2.00	5.32
Breadfruit	27.2	35.3	186	242
Coconut juice	99.1	10.9	333	36.6
Coconut milk	51.9	179	122	421
Drinking coconut meat	31.7	32.3	181	18
Copra meat	12.2	50.3	71.3	295
Sprouting coconut	7.79	6.23	122	97.8
Marshallese cake	11.7	39.2	0.00	0.00
Papaya	6.59	2.57	27.0	10.5
Pumpkin	1.24	0.37	5.44	1.63
Banana	0.020	0.018	0.58	0.51
Arrowroot	3.93	13.6	94.9	328
Citrus	0.10	0.049	0.20	0.10
Rain water	313	0.00	629	0.00
Well water	207	0.00	430	0.00
Malolo	199	0.00	0.00	0.00
Coffee/tea	228	0.00	0.00	0.00
Total	1322	547	3083	2783

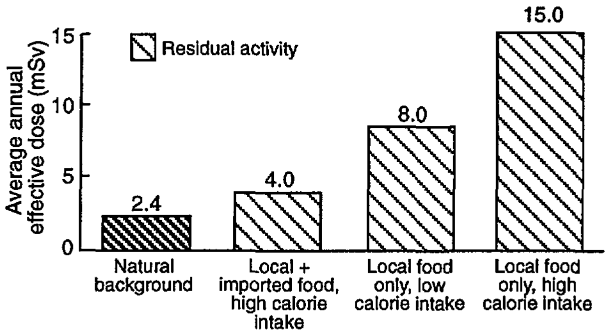

FIG. 4. Comparison of natural background and predicted average annual effective doses for residents of Bikini Island for different types of diet.

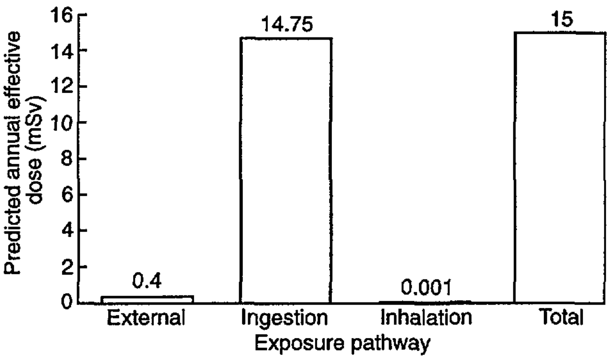

FIG. 5. Contribution by pathway to the predicted annual effective dose for a local high calorie intake diet [8].

the adjusted annual effective dose would become about 14 mSv. The two assessments are therefore comparable in their results.

The review of the information presented in the two dose assessments showed that the assumed dietary models are appropriate, and that the approaches used are satisfactory. The similar results obtained in the two independent assessments provide a good degree of assurance of the reliability of the estimated doses.

For the purposes of this review, it was considered prudent to take the upper estimates of annual dose, based on a 'local food only, high calorie intake diet', and thus the annual effective dose under current conditions for persons living on an entirely locally derived diet is taken to be about 15 mSv. Figure 4 presents the results of the various assessments graphically.

The contributions to annual effective dose by radionuclide and by pathway (local diet assumptions) are presented in Table XIV and Fig. 5 [8]. It can be seen that uptake of ^{137}Cs into terrestrial foodstuffs accounts for the largest fraction of the total estimated

TABLE XIV. PREDICTED ANNUAL EFFECTIVE DOSES BY PATHWAY AND RADIONUCLIDE FOR A LOCAL DIET [8]

Exposure pathway	Annual dose (mSv)
External gamma	0.40
Ingestion	
^{137}Cs	14.6
^{90}Sr	0.15
$^{239+240}Pu$	0.0019
^{241}Am	0.0010
Inhalation	
$^{239+240}Pu$	0.00074
^{241}Am	0.00049
Total (rounded)	15

TABLE XV. THIRTY YEAR PREDICTED COMMITTED EFFECTIVE DOSES BY PATHWAY AND RADIONUCLIDE FOR A LOCAL DIET [20]

Exposure pathway	Integral dose (mSv)
External gamma	9.1
Ingestion	
^{137}Cs	330
^{90}Sr	5.9
$^{239+240}Pu$	0.098
^{241}Am	0.062
Inhalation	
$^{239+240}Pu$	0.069
^{241}Am	0.050
Total (rounded)	345

dose and that the external gamma exposure pathway accounts for most of the remainder. The contribution of ^{90}Sr to the total dose is minor and the contributions from $^{239+240}Pu$ and ^{241}Am are insignificant.[8] Marine foods, stored rain water and groundwater, and inhalation of resuspended soil as pathways together account for less than 1% of the dose.

Since the dominant contribution to dose comes from ^{137}Cs, the annual doses from living on Bikini Atoll will decline approximately according to the radioactive decay of this radionuclide. In the period from now to 30 years in the future, the total dose received — on the assumption of a locally derived diet and with natural background contributions added — is estimated to be about 350 mSv [20] (Table XV and Fig. 6).

The inventory of transuranic radionuclides in the lagoon is an important potential source of radiation exposure and is associated with the many components (forams, Halimeda (cactus algae) remains, unidentifiable fine and coarse carbonate materials, corals, shells, etc.) making up the lagoon sediments. The source term for the radionuclides in solution and in the organisms is the inventory associated with the different components that make up the sedimentary reservoir. Radionuclides are found accumulated by zooplankton and there are also many reports of radionuclides accumulated by fish species, benthic invertebrates and algae in the Bikini Atoll lagoon. Therefore, there is evidence that plutonium is indeed transferred into the aquatic ecosystem in small but measurable concentrations through the action of (perhaps many) biogeochemical processes acting on contaminated components of the sedimentary reservoir at the atoll.

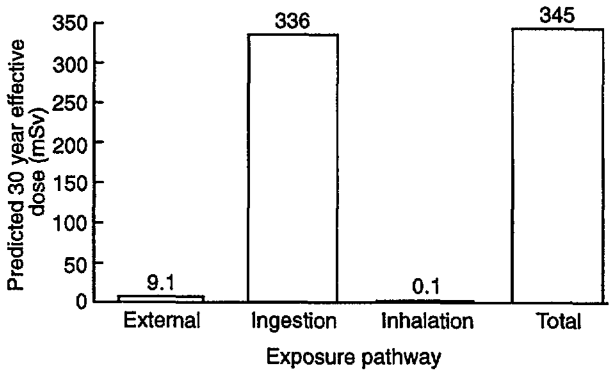

FIG. 6. Contribution by pathway to the predicted 30 year effective dose for a local high calorie intake diet [20].

However, it is noted that the observed transfer of these radionuclides through the marine food chain to human foodstuffs is very low, such that any associated radiological impact would be expected to be negligible. It is nevertheless necessary also to review other mechanisms or pathways by which there could be a significant transfer of radionuclides to people living on the atoll. In this context, the available information indicates that the actions of severe storms and hurricanes in the area over the past 40 years do not appear to have mobilized or transported the transuranic radionuclides to any significant extent [8].

It is concluded that on the evidence presented it seems unlikely that the plutonium in the lagoon sediment could constitute a significant source of radiation doses to a population resettling Bikini Island.

[8]The minor contribution of the transuranic radionuclides predicted from the environmental data and models has been corroborated in the study of $^{239+240}Pu$ in autopsy bone samples from people who had lived on Rongelap Atoll for their entire lives [50.]

8. RADIATION PROTECTION CRITERIA

8.1. PROTECTION AGAINST RADIATION

As indicated in Section 5, exposure to radiation may have detrimental effects on the health of people, and it is for this reason that standards of safety for protection against radiation are established. It should be emphasized that radiation and radioactive substances are a natural, permanent and inherent feature of the human environment, both in the Marshall Islands and elsewhere: people are unavoidably and permanently exposed to radiation from natural sources, such as that from the cosmos and naturally occurring radioactive materials in the geosphere. In addition, they are subject to exposure to many artificial sources of radiation nowadays used widely for human welfare. The background exposure caused by these natural and artificial sources is incurred to different extents by everyone and, therefore, radiation exposure can only be controlled and restricted, and not eliminated entirely, by radiation safety standards.

International radiation safety standards, such as the Basic Safety Standards, are intended to provide guidance on safety for national regulation of the peaceful, beneficial uses of radiation and nuclear energy. The practice of nuclear weapon testing was therefore not considered in the establishment of the Basic Safety Standards. This section is intended to describe the protection policy and main requirements of these Standards with the aim of deriving ad hoc guidance for dealing with the particular case of the radiological conditions caused by nuclear weapon testing at Bikini Atoll.

8.2. INTERNATIONAL RADIATION SAFETY STANDARDS

The Basic Safety Standards are the worldwide agreed radiation safety standards set out by the specialized sponsoring international organizations. They rely on the scientific information on radiation levels and health effects compiled globally by UNSCEAR, a body set up by the United Nations General Assembly in 1955; the latest report of UNSCEAR to the General Assembly was issued in 1993 [30]. The safety criteria in the Basic Safety Standards are based primarily on the recommendations of the ICRP, a non-governmental scientific organization founded in 1928 to establish basic principles and recommendations for radiation protection. The most recent recommendations of the ICRP were issued in 1991 [57].

8.3. ACTIVITIES INVOLVING RADIATION EXPOSURE

The Basic Safety Standards apply to two classes of activity involving radiation exposure. These activities are termed *practices* and *interventions*. Practices are those activities which make deliberate use of radiation sources for a beneficial purpose — such as the use of X rays in medical diagnosis — where their use may lead to adventitious radiation doses which add to the doses that people normally incur due to background radiation. Interventions are activities to reduce the doses caused by existing de facto situations — such as situations involving exposure to elevated background radiation levels due to natural sources or exposure to residues from past events and activities — where the doses incurred are sufficiently high and it is feasible and reasonable to take remedial measures to reduce them to some extent.

8.4. PRACTICES

For practices, the Basic Safety Standards require, among other things, that:

"No practice or source within a practice should be authorized unless the practice produces sufficient benefit to the exposed individuals or to society to offset the radiation harm that it might cause... The normal exposure of individuals shall be restricted so that neither the total effective dose nor the total equivalent dose to relevant organs or tissues, caused by the possible combination of exposures from authorized practices, exceeds any relevant dose limit... In relation to exposures from any particular source within a practice...protection and safety shall be optimized in order that the magnitude of individual doses, the number of people exposed and the likelihood of incurring exposures all be kept as low as reasonably achievable, economic and social factors being taken into account, within the restriction that the doses to individuals delivered by the source be subject to dose constraints."

These radiation protection requirements for practices are referred to as *justification of practices, optimization of protection* and *limitations of individual doses.*

In summary, therefore, the Basic Safety Standards require that *additional* doses above background levels expected to be delivered by the *introduction* or *proposed continuation* of a *practice* be restricted. The restriction is intended to be applied *prospectively* to control and constrain the extra doses forecast and seeks to ensure that:

— The practice is justified, taking into account the doses it will deliver to people;
— The protection against the radiation exposure caused by the sources involved in the practice has been optimized in order to keep all doses as low as reasonably achievable under the prevailing circumstances;
— The additional doses (above the background dose) expected to be incurred by any individual do not exceed prescribed dose limits (the currently established limit of additional doses above background doses — excluding medical exposures — for members of the public being 1 mSv in a year under normal circumstances and up to 5 mSv in a year in special circumstances).

8.5. INTERVENTIONS

For interventions, the Basic Safety Standards state that:

"Intervention is justified only if it is expected to achieve more good than harm, with due regard to health, social and economic factors. If the dose levels approach or are expected to approach [specified] levels, protective actions or remedial actions will be justified under almost any circumstances... Optimized intervention levels and action levels shall be specified in plans for intervention situations, on the basis of the guidelines given [in the Basic Safety Standards], modified to take account of local and national conditions, such as: (a) the individual and collective exposures to be averted by the intervention; and (b) the radiological and non-radiological health risks and the financial and social costs and benefits associated with intervention."

The radiation protection requirements for interventions are referred to as *justification of interventions*, and *optimization of the protective measures.*

In summary, therefore, the Basic Safety Standards require that:

— Existing radiation exposure situations shall be assessed in order to determine whether an intervention is justified to *reduce* the doses being delivered because of the situation;
— Should the intervention be justified and therefore undertaken, the form, nature and scale of the protective measures should be optimized in order to ensure that they are not disproportionate to the benefit gained from the reduction in radiation doses.

Importantly, as dose limits are applicable to the increases to the background radiation dose expected to arise from a practice, they are not applicable to interventions, which by definition are intended to reduce (rather than increase) doses.

8.6. THE SITUATION AT BIKINI ATOLL

The situation at Bikini Atoll does not fit the concept of a *practice.* The practices identified for the application of the Basic Safety Standards include the use of radiation or radioactive substances for medical, industrial, veterinary, agricultural and educational purposes, as well as for the generation of nuclear electricity. The practice of nuclear weapon testing is not contemplated in these international standards intended to regulate the peaceful, beneficial uses of radiation and nuclear energy. In any case, in the Marshall Islands the practice of nuclear weapon testing was terminated long ago. The additional doses caused by such a practice can no longer be controlled prospectively and what remains is an exposure situation only amenable to intervention, i.e. to the introduction of remedial protective measures aimed at reducing the radiation doses caused by the existing situation.

8.7. INTERVENTION SITUATIONS

Two types of intervention situations are recognized in the Basic Safety Standards. The first relates to emergency exposure situations, such as in the immediate aftermath of a radiological accident, requiring protective actions to reduce or avert the temporary (short term) doses caused by the situation. The second relates to *chronic exposure situations* where long term environmental radiation levels exist leading to continuing exposure of a resident population, usually at a relatively low dose rate, requiring remedial actions to reduce the exposure rate.

The intervention situation in Bikini Atoll, where a returning population would commence receiving continued radiation exposures, for instance from locally grown foods, represents an unusual example of intervention in chronic exposure situations. In this case, an a priori intervention took place when the Bikinians were first evacuated from Bikini Island and then a new intervention was undertaken when those who had returned to their island in 1970 were re-evacuated in 1978. The current intervention issues are whether that specific protective measure — evacuation — can be terminated and whether any other protective measure should be instituted to permit the safe resettlement of Bikini Island.

8.8. GENERIC INTERVENTION LEVEL

The underlying policy on intervention set in the Basic Safety Standards is that the decision on whether or not intervention should be contemplated and how much the existing dose levels should be reduced *depends on the circumstances of each individual case*. In order to determine whether and when an intervention should be undertaken, *intervention levels* are established. Intervention levels should be determined in terms of the doses expected to be averted by a specific *remedial action* intended to protect people from exposure. The intervention levels are usually expressed in quantities derived from the avertable dose. In the case of chronic exposure situations these derived levels are usually referred to as *action levels*. They are always expressed in terms of dose rate or activity concentration above which *remedial actions* to reduce exposure levels should be carried out. *Remedial action* — or *remediation* — is therefore the term used in this report to refer to a protective action taken when a specified *action level* is exceeded in a chronic exposure situation in order to reduce radiation doses that might otherwise be received.

Intervention action levels, therefore, are expected to be determined on an ad hoc basis, i.e. case by case, and tailored to the specific circumstance of the intervention situation. However, there has been a recognized need for simple and internationally agreed guidance on *generic levels* applicable to any intervention situation, particularly in chronic exposure situations.

The Basic Safety Standards establish some generic levels for interventions as follows:

(a) For the justification of the intervention:
   - Dose levels at which intervention is expected to be undertaken under any circumstances.

(b) For the optimization of protective measures in emergency exposure situations:
   - Optimized avertable dose levels for sheltering, evacuation and iodine prophylaxis.
   - Optimized dose levels for initiating and terminating temporary relocation and for permanent resettlement.

(c) For the optimization of action levels in the quasi-chronic exposure situation caused by the presence of radioactive materials in foodstuffs:
   - Generic action levels of activity per unit mass of foodstuff.

(d) For the optimization of action levels in the particular case of chronic exposure to radon:
   - Optimized action level for activity concentration of radon in the air for dwellings.
   - Optimized action level for activity concentration of radon in the air for workplaces.

Although there is no explicit international guidance for generic action levels for chronic exposure due to radioactive residues from previous activities and events, in particular from events such as nuclear weapon testing, ad hoc generic guidance can be derived implicitly from the guidance established in the Basic Safety Standards for other situations. Moreover, the typical levels of doses caused by chronic exposure to the unavoidable natural background radiation could also be used as a reference for purposes of comparison.

8.8.1. Guidelines for justifying interventions

The Basic Safety Standards establish that if doses approach levels at which the likelihood of deleterious health effects is very high, intervention would

TABLE XVI. LEVELS OF EQUIVALENT DOSE RATE AT WHICH INTERVENTION IS EXPECTED TO BE UNDERTAKEN UNDER ANY CIRCUMSTANCES

Organ or tissue	Equivalent dose rate (mSv/a)
Gonads	200
Lens of the eye	100
Bone marrow	400

TABLE XVII. GENERIC LEVELS FOR TEMPORARY RELOCATION AND PERMANENT RESETTLEMENT

Intervention	Initiate	Terminate
Temporary relocation	30 mSv/month	10 mSv/month
Permanent resettlement	Lifetime dose > 1 Sv	

be expected to be undertaken under almost any circumstances. These quasi-mandatory levels, which are established in the Basic Safety Standards, depend on the organ exposed, and for chronic exposure situations vary from a level of equivalent dose of 100 mSv per year for the lens of the eye to 400 mSv per year for the bone marrow (see Table XVI).

From the established levels of equivalent doses and on the basis of recommended weighting factors to take account of the radiosensitivity of the relevant organs, it could be construed that intervention would not be 'expected to be undertaken under any circumstances' unless the annual effective dose exceeds several tens of millisieverts. At lower doses, proposed interventions need to be justified on a case by case basis. The following subsections develop some generic guidance for such cases.

8.8.2. Guidelines for emergency exposure situations that may be applicable to chronic exposure situations

8.8.2.1. *Intervention levels for relocation and resettlement*

Temporary relocation and *permanent resettlement* are among the more extreme protective measures available to control exposures to the public in the event of a radiological emergency. Table XVII shows the generic levels established in the Basic Safety Standards for temporary relocation and permanent resettlement.

Temporary relocation is used to mean the organized and deliberate removal of people from the area affected during an extended but limited period of time (typically several months) to avert exposures, principally from radioactive material deposited on the ground and from inhalation of any resuspended radioactive particulate material. During this period, people would typically be housed in temporary accommodation. As the radiological situation is temporary, the generic guidelines to initiate and terminate relocation refer to relatively high levels of dose: 30 mSv and 10 mSv per month, respectively.

Permanent resettlement is the term used for the deliberate removal of people from the area with no expectation of return. Permanent resettlement should, according to the Basic Safety Standards, be considered if the lifetime dose over 70 years cannot be reduced by other means and is projected to exceed 1 Sv. This lifetime dose corresponds to an average annual dose of about 14 mSv. When doses are below this level, permanent resettlement is unlikely to be necessary. It can thus be construed that if doses fall below an average annual effective dose of about 10 mSv, it would not indicate a requirement for permanent resettlement, but rather for the termination of relocation if it has been instituted.

8.8.3. Guidelines for a quasi-chronic exposure situation

8.8.3.1. *Activity in foodstuffs*

The Basic Safety Standards establish that if there is no shortage of food and there are no other compelling social or economic factors, action levels for the withdrawal and substitution of specific supplies of food and drinking water which have been contaminated with radioactive substances should be based on the guidelines for foodstuffs in international trade established by the Codex Alimentarius Commission (CAC) [58]. These are included in the Basic Safety Standards as recommended generic action levels for activity in foodstuffs. The levels are limited to radionuclides usually considered relevant to emergency exposure situations. They include, however, all the relevant radionuclides for the situation prevailing in Bikini Atoll (see Table XVIII).

TABLE XVIII. GENERIC ACTION LEVELS FOR FOODSTUFFS[a]

Radionuclide	Foods destined for general consumption (kBq/kg)	Radionuclide	Milk, infant food and drinking water (kBq/kg)
^{134}Cs, ^{137}Cs, ^{103}Ru, ^{106}Ru, ^{89}Sr, ^{131}I	1	^{134}Cs, ^{137}Cs, ^{103}Ru, ^{106}Ru, ^{89}Sr	1
^{90}Sr	0.1	^{131}I, ^{90}Sr	0.1
^{241}Am, ^{238}Pu, ^{239}Pu	0.01	^{241}Am, ^{238}Pu, ^{239}Pu	0.001

[a] For practical reasons, the criteria for separate radionuclide groups will be applied independently to the sum of the activities of the radionuclides in each group.

The levels are recommended for use by national authorities as the generic action levels in their emergency plans unless there are strong reasons for adopting substantially different values. Use of these internationally recognized levels by national authorities would have the considerable advantage of helping to retain public confidence and trust. Moreover, the use of such values helps to prevent anomalies that otherwise might occur between neighbouring countries. When a foodstuff is exported from a country, it must meet certain standards in order that it may be exempted from any further monitoring or control by the receiving country and any subsequent receiving countries. Thus, the internationally agreed standards established by the CAC are essential in order that international trading in food is not severely disrupted by excessive monitoring, administrative and legal requirements.

The CAC's action levels for activity concentration in foodstuffs are conceptually 'non-action' levels. This means that the residual individual doses from the consumption of foodstuffs showing such levels are considered acceptable without any actions to be taken to reduce the levels.

Depending on the annual 'food basket' [59] of the population, the doses resulting from the CAC's levels will vary, but — with the FAO figure for total food consumption of 550 kg per year (not including drinking water) — the consumption of food of which every component had activity concentrations at the CAC action levels would result in a *maximum annual committed effective dose of up to about 10 mSv.* This figure assumes that the food basket is contaminated to the full CAC values for the whole year.

8.8.4. Guidelines for a chronic exposure situation

The Basic Safety Standards establish that, in the case of a chronic exposure situation, remedial actions are not normally likely to be necessary unless relevant (generic) action levels are exceeded. As stated earlier, an action level is a level of dose rate or activity concentration above which remedial or protective actions should be undertaken to protect people; generally, they are specified separately for different remedial actions. The Basic Safety Standards establish action levels only for the case of exposure to radon in air for both dwellings and workplaces. As the former involves members of the public, it could be used as a sound reference for other generic chronic exposure situations involving the public.

8.8.4.1. Radon in dwellings

The Basic Safety Standards establish that the optimized action levels for remedial action relating to chronic exposure situations involving radon in dwellings should, in most situations, fall within a yearly average concentration of 200–600 Bq·m^{-3} of ^{222}Rn in air. The conversion coefficient established in the Basic Safety Standards for the annual exposure to the progeny of ^{222}Rn per unit ^{222}Rn concentration is 1.56×10^{-2} mJ·h·m^{-3} per Bq·m^{-3}, and the coefficient for the dose conversion for exposure in dwellings is 1.1 mSv per mJ·h·m^{-3}. Thus, the optimized action level for radon in dwellings can be translated approximately to an *annual effective dose of about 3 to 10 mSv.*

TABLE XIX. ANNUAL EFFECTIVE DOSES TO ADULTS FROM NATURAL SOURCES

Source of exposure	Global average exposure (mSv)	Typical elevated exposure (mSv)
Cosmic rays	0.39	2.0
Terrestrial gamma rays	0.46	4.3
Radionuclides in the body (except radon)	0.23	0.6
Radon and its decay products	1.3	10
Total (rounded)	2.4	—

8.8.5. Reference for comparison: Doses due to natural background radiation

As stated earlier, the worldwide average annual dose incurred by the global population as a result of radiation from natural sources is estimated to be 2.4 mSv [30, 52], of which about half is mainly due to cosmic and terrestrial background radiation and half is due to exposure to ^{222}Rn. There is, however, a large variability in the annual effective doses caused by natural sources. It is common to find large regions with exposures elevated by up to an order of magnitude and smaller regions with even higher levels. Table XIX indicates, in addition to the global average exposures referred to in Table XII, typical elevated values of annual effective doses to adults from natural sources. The elevated values are representative of large regions, but much higher atypical values may occur locally.

The effective dose rate caused by cosmic radiation depends on the height above sea level and the latitude. The annual effective doses in areas of high exposure (locations at higher elevations) are about five times the average. The terrestrial effective dose rate depends on local geology, with a high level typically being about ten times the average; the effective dose to communities living near some types of mineral sand may be up to about 100 times the average. The effective dose from radon decay products depends on the local geology and housing construction and use, with the dose in some regions being about ten times the average. Local geology and the type and ventilation of some houses may combine to give effective dose rates from radon decay products of several hundred times the average. A range of the worldwide annual effective dose from natural sources would be 1–20 mSv, with values in some regions of the order of 30–50 mSv and high levels of above 100 mSv.

In summary, although the global average annual effective dose due to natural background radiation is of the order of a few millisieverts, annual effective doses of about 10 mSv are not unusual and very high annual effective doses of up to about 100 mSv are found in some places. As national authorities have considered these situations and decided not to take protective actions against typical elevated background levels, it appears that doses caused by these levels can be used as another reference for deciding on interventions under chronic exposure situations.

8.9. GENERIC GUIDANCE FOR REHABILITATION OF AREAS OF CHRONIC EXPOSURE

From the earlier discussion it appears that an *annual effective dose of up to about 10 mSv* can be used as a generic guideline for action levels aimed at considering protective remedial actions for rehabilitating areas subject to chronic exposure, such as the areas with residual radionuclides from nuclear weapon testing in Bikini Island. For doses below the guidance action levels, the situation could, after consideration, be taken as being generally safe for the population.

It is emphasized, however, that this generically acceptable action level of annual dose *does not imply that below such a level it is never worthwhile to reduce the radiation exposure.* If it is justified on radiological grounds, intervention for the purposes of radiological protection should always be undertaken, and the form, scale and duration of the intervention would be determined by a process of optimization of protection.

In addition, it is essential to keep in mind that there are levels of equivalent dose and of effective dose at which intervention would almost always be justified on radiological grounds. As indicated before, the Basic Safety Standards implicitly indicate that an annual effective dose of several tens of millisieverts would almost always justify some kind of intervention.

A generic action level of up to about 10 mSv per annum is therefore applicable to the chronic exposure situation on Bikini Island and has been used in the review as the basis for judging the prospects for resettlement and — should resettlement be decided on by the population concerned — the required remedial actions.[9]

One problem is whether it is the doses caused by the residual radionuclides or the total dose (including natural background doses) that should be compared with the action level. In theory only the avertable dose must be considered. In the situation at Bikini Atoll by far the largest doses (doses due to residual activity and those due to natural radionuclides) are incurred through the ingestion pathway. Therefore, any planned remedial action should be expected to affect the diet — or more precisely the activity in the diet — and thus change the contribution of both residual and natural radionuclides. However, the remediation strategies considered in this review only assess the decrease of doses due to the residual radionuclides and this will be used as the main reference for judgement. The natural background doses will be assumed to remain constant at the current level of about 2.4 mSv and the total dose (i.e. the dose from residual radionuclides plus the natural background dose) is also presented (in parentheses) for reference purposes.

[9] This discussion is further elaborated in recent interim guidance on the subject published by the IAEA [60].

9. HABITABILITY OF BIKINI ISLAND

9.1. RADIOLOGICAL ASSUMPTIONS

9.1.1. Critical group

Should the people of Bikini Atoll decide to resettle Bikini Island, it was judged that it would be desirable to base intervention decisions on the likely exposure of a hypothetical critical group living on the island and consuming a high calorie diet derived entirely from foods produced locally on the island. This assumption is conservative and probably unrealistic in the sense that it is more likely that, should resettlement come about, future diets would include imported foodstuffs. In fact, diets throughout the Marshall Islands nowadays have a large component of imported foodstuffs, and it seems unlikely that the trend in this direction will be reversed in the near future. However, it is possible that the consumption of locally derived foodstuffs could increase again were the financial conditions that presently permit the import of many foodstuffs to change in the future, and it is conceivable that some of the Bikinian community might be obliged to readopt an exclusively traditional locally derived diet.

Evidence of the conservative nature of the current diet assumption comes from studies on Rongelap and Utirik Atolls, where ^{137}Cs body burden estimates based on the mixed diet and local food only diet were compared with actual whole body measurements of ^{137}Cs in the two populations. The study showed that a mixed diet of local plus imported food comes much closer to predicting the current body content of ^{137}Cs than the local food only diet models (see Figs 7 and 8) [61].

9.1.2. Radiation doses

On the assumption that the critical group consumes a high calorie diet of only locally produced foodstuffs, the annual effective dose to the critical group has been assessed (see Section 7) to be about 15 mSv (or 17.4 mSv if natural background doses were to be included) — higher than the generic action level of an annual effective dose of up to about 10 mSv. There is, therefore, strong justification for exploring possible remediation strategies for reducing the potential radiation exposure of a population resettling Bikini Atoll under the presumed diet conditions.

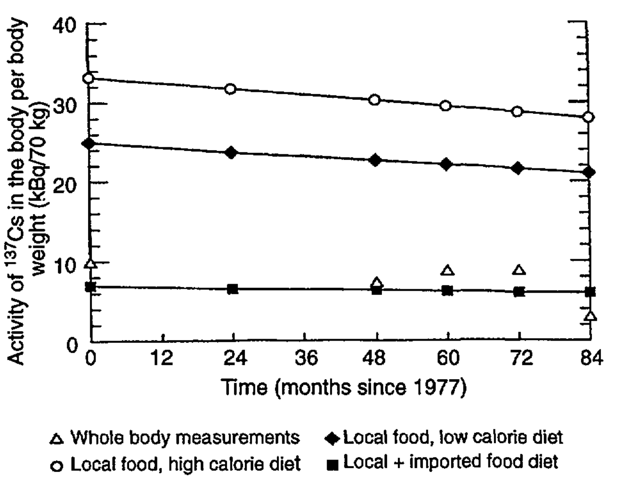

FIG. 7. Comparison of the estimated activity of ^{137}Cs in the body from different environmental models with data from whole body measurements of ^{137}Cs for residents of Rongelap Island.

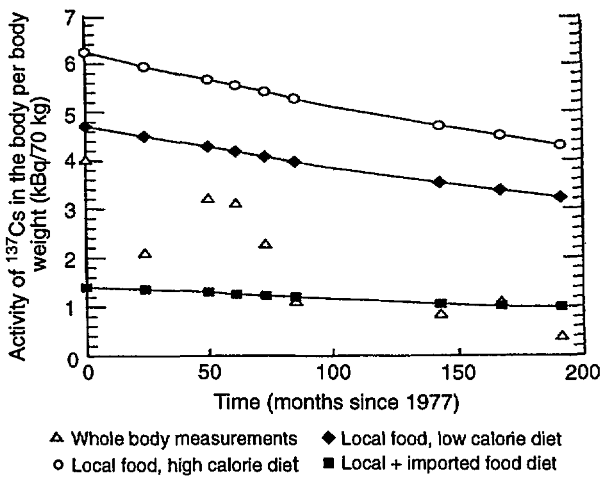

FIG. 8. Comparison of the estimated activity of ^{137}Cs in the body from different environmental models with data from whole body measurements of ^{137}Cs for residents of Utirik Island.

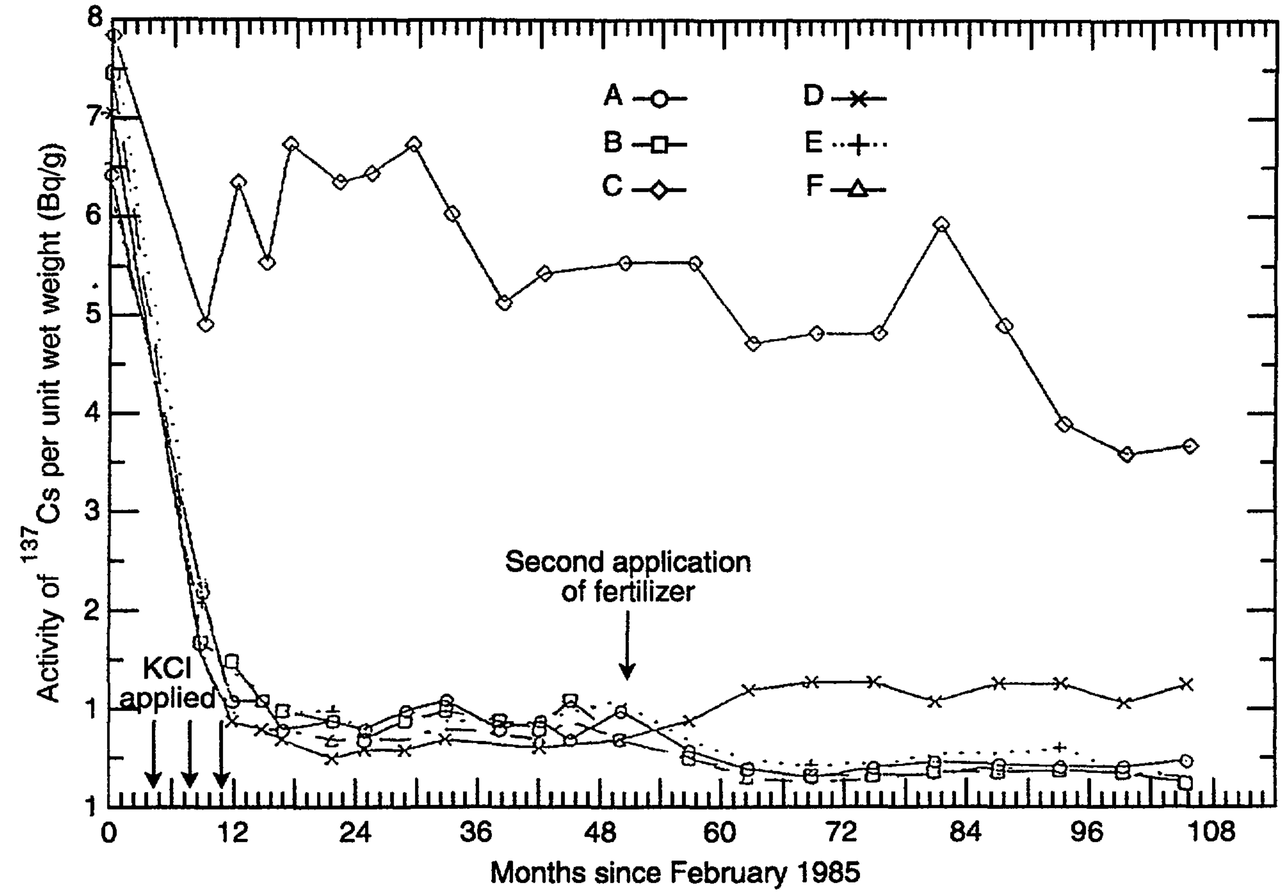

FIG. 9. Reduction of ^{137}Cs levels in drinking coconuts at Bikini Island after initial and second applications of potassium fertilizer [62]. (A: KCl application — 1000 kg/ha, two treatments; B: KCl + NP fertilizer application — 1000 kg/ha, two treatments; C: no application of K; D: KCl application — 2000 kg/ha, one treatment; E: KCl application — 2000 kg/ha, two treatments; F: KCl + NP fertilizer application — 2000 kg/ha, two treatments.)

It should be noted, however, that on the same presumption the total lifetime dose to be received by people returning has been estimated to be about 350 mSv (see Section 7), i.e. lower than the generic guidance level for permanent resettlement given in the Basic Safety Standards.

9.2. POSSIBLE REMEDIAL MEASURES

Several remedial methods to reduce the dose from ^{137}Cs at Bikini Island have been evaluated over the years. These include:

- Irrigation of the soil with large quantities of salt water for the purpose of leaching the ^{137}Cs from the soil,
- Addition of binding agents such as illite and zeolites to trap the ^{137}Cs and make it unavailable for plant uptake,
- .Cropping and disposal of vegetation to remove ^{137}Cs accumulated in plants,
- Excavation and disposal of the top 40 cm of the soil column that generates most of the activity on the island,
- Treatment of the soil with high potassium fertilizers.

Of these methods, the latter two, soil removal and treatment with potassium, have been found to be the most effective and attention has subsequently been focused on these two alternative remedial strategies.

9.2.1. Soil removal

The removal of the top 40 cm of soil from Bikini Island would be effective in reducing radiation exposure due to ^{137}Cs and other residual radionuclides in the terrestrial environment. It is estimated to reduce the projected annual effective dose due to weapon test residues to below 0.1 mSv (to which the annual effective dose of 2.4 mSv due to natural background radiation must be added). It is noted, however, that natural activity levels of the local topsoil are very low in comparison with those of soil generally, particularly of continental soil. If the topsoil on Bikini Island were to be replaced by soil brought in from outside the Marshall Islands, the annual effective dose due to natural background radiation would consequently be expected to increase.

Soil removal is stated to be the option favoured by the Bikinians. However, the removal of hundreds of thousands of tonnes of soil could have adverse environmental and social consequences, especially because the tree crops that constitute the natural food supply require the fertile topsoil. Removal of the topsoil would necessitate removing some 30 000 mature coconut trees and breadfruit, pandanus and papaya trees. It would be an enormous — and probably prohibitively expensive — undertaking to replenish this resource, either by restoring the topsoil over time or by replacing it with fresh soil from elsewhere.

The detailed assessment of the environmental and social consequences of this particular remediation strategy is beyond the scope of the present review.

9.2.2. Soil treatment with potassium fertilizer

The treatment of local soil with potassium fertilizer has been shown in experiments to be very effective in reducing the uptake of ^{137}Cs into edible foods [62]. Results from one of several field trials at Bikini Island are shown in Fig. 9 [62]. A reduction of ^{137}Cs concentrations in coconut milk (and many other food items) to 5% of their original values has been achieved in several experiments. The reduced concentration of ^{137}Cs persists for nearly five years after the application of potassium fertilizer is terminated and the subsequent increase in uptake of ^{137}Cs is very slow (see Fig. 9). Subsequently, application of potassium fertilizer is likely to be needed every four or five years to maintain the ^{137}Cs activity levels in local foods and until radioactive decay reduces the activity to insignificant levels.

Two other potentially significant exposure pathways under present conditions are external exposure to the gamma radiation emitted by ^{137}Cs and possible ingestion or inhalation of plutonium and americium in the soil in dwelling areas. Thus, a further component of the remediation strategy could be the removal of surface soil to a depth of 30 cm where the village will be established and from around each housing site, and its replacement with a layer

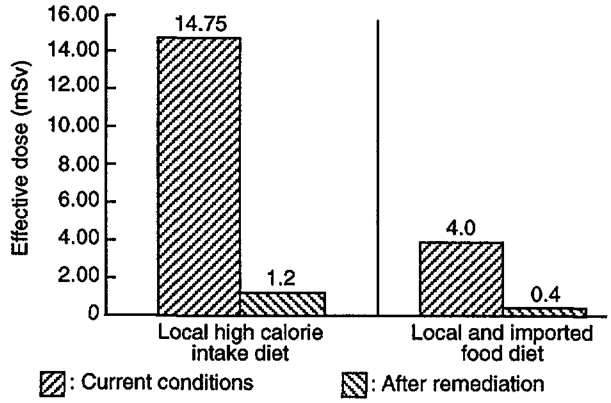

FIG. 10. Predicted radiation doses before and after remediation.

of crushed coral to minimize external exposure and possible ingestion from the remaining soil.

An alternative to the removal of soil from the living areas is a process employed successfully in the aftermath of the Chernobyl accident, whereby the uppermost 30–50 cm of soil is turned over so that it is buried and replaced by deeper soil, which is much less contaminated. This would avoid the problem of soil disposal, but would require that, should crops be raised in the living areas, the same potassium fertilizer treatment be applied as for the rest of the land where domestic crops are grown.

Treating the soil over most of the island where food crops are grown with fertilizer (either as a mixed fertilizer or as potassium chloride, KCl) would reduce the ^{137}Cs concentration in foods and thereby reduce the internal dose via the ingestion pathway. Additionally, the removal of the surface soil in the area of housing and villages, where people spend most of their time, would reduce the external gamma whole body exposure from ^{137}Cs, the skin dose from beta and alpha emitters and the potential dose from the ingestion of soil. This combination of remedial actions is estimated to reduce doses by a factor of nearly 10 from pretreatment levels [20].

Consideration has been given to the potential ecological effects of the proposed potassium fertilizer treatment on Bikini Island. At the planned levels of potassium treatment there seems to be no possibility of altering significantly the soil chemistry and, furthermore, the transfer of potassium to groundwater has been found to be very low [8].

After potassium treatment of the soil in areas where food crops are grown, together with replacement of soil from around the living areas, the estimated dose rate from the consumption of an entirely

TABLE XX. RADIONUCLIDE ACTIVITIES[a] PER UNIT WET WEIGHT (Bq/g) FOR LOCAL FOODSTUFFS ON BIKINI ISLAND AFTER REMEDIATION [20]

Local foodstuffs	^{137}Cs	^{90}Sr	$^{239+240}Pu$	^{241}Am
Reef fish	2.9×10^{-3}	4.5×10^{-5}	1.3×10^{-5}	6.5×10^{-6}
Tuna	4.5×10^{-3}	5.3×10^{-6}	1.9×10^{-6}	1.3×10^{-6}
Mahi mahi	4.5×10^{-3}	5.3×10^{-6}	1.9×10^{-6}	1.3×10^{-6}
Marine crabs	1.4×10^{-3}	8.9×10^{-5}	3.6×10^{-5}	2.6×10^{-5}
Lobster	1.4×10^{-3}	8.9×10^{-5}	3.6×10^{-5}	2.6×10^{-5}
Clams	4.6×10^{-4}	8.7×10^{-5}	8.3×10^{-4}	4.6×10^{-4}
Trochus	4.6×10^{-4}	8.7×10^{-5}	8.3×10^{-4}	4.6×10^{-4}
Tridacna muscle	4.6×10^{-4}	8.7×10^{-5}	8.3×10^{-4}	4.6×10^{-4}
Jedrul	4.6×10^{-4}	8.7×10^{-5}	8.3×10^{-4}	4.6×10^{-4}
Coconut crabs	3.7×10^{-1}	5.2×10^{-2}	3.8×10^{-5}	2.8×10^{-5}
Land crabs	3.7×10^{-1}	5.2×10^{-2}	3.8×10^{-5}	2.8×10^{-5}
Octopus	1.8×10^{-3}	4.5×10^{-5}	1.3×10^{-5}	6.5×10^{-6}
Turtle	2.8×10^{-4}	4.5×10^{-5}	1.3×10^{-5}	6.5×10^{-6}
Chicken muscle	2.1×10^{-2}	1.5×10^{-3}	7.7×10^{-6}	6.0×10^{-6}
Chicken liver	2.1×10^{-2}	1.5×10^{-3}	7.7×10^{-6}	6.0×10^{-6}
Chicken gizzard	2.1×10^{-2}	1.5×10^{-3}	7.7×10^{-6}	6.0×10^{-6}
Pork muscle	1.6×10^{0}	1.5×10^{-3}	7.7×10^{-6}	6.0×10^{-6}
Pork kidney	1.4×10^{0}	6.2×10^{-3}	3.5×10^{-5}	1.2×10^{-5}
Pork liver	8.1×10^{-1}	2.9×10^{-3}	1.2×10^{-4}	5.2×10^{-5}
Pork heart	9.8×10^{-1}	1.5×10^{-3}	5.9×10^{-6}	1.8×10^{-5}
Bird muscle	2.5×10^{-3}	2.3×10^{-4}	1.3×10^{-5}	6.5×10^{-6}
Birds' eggs	6.7×10^{-4}	3.6×10^{-4}	1.3×10^{-5}	6.5×10^{-6}
Chicken eggs	2.1×10^{-2}	1.5×10^{-3}	7.7×10^{-6}	6.0×10^{-6}
Turtle eggs	2.8×10^{-4}	4.5×10^{-5}	1.3×10^{-5}	6.5×10^{-6}
Pandanus fruit	1.9×10^{-1}	1.2×10^{-1}	3.2×10^{-6}	3.8×10^{-6}
Pandanus nuts	1.9×10^{-1}	1.2×10^{-1}	3.2×10^{-6}	3.8×10^{-6}
Breadfruit	1.9×10^{-2}	6.9×10^{-2}	1.8×10^{-6}	1.2×10^{-6}
Coconut juice	5.8×10^{-2}	4.5×10^{-4}	1.0×10^{-6}	8.5×10^{-6}
Coconut milk	2.7×10^{-1}	3.2×10^{-3}	1.9×10^{-6}	1.1×10^{-6}
Tuba/jekero	2.7×10^{-1}	3.2×10^{-3}	1.9×10^{-6}	1.1×10^{-6}
Drinking coconut	1.5×10^{-1}	5.9×10^{-3}	2.7×10^{-6}	3.6×10^{-6}
Copra meat	2.7×10^{-1}	3.2×10^{-3}	1.9×10^{-6}	1.1×10^{-6}
Sprouting coconut	2.7×10^{-1}	3.2×10^{-3}	1.9×10^{-6}	1.1×10^{-6}
Marshallese cake	2.7×10^{-1}	3.2×10^{-3}	1.9×10^{-6}	1.1×10^{-6}
Papaya	1.1×10^{-1}	4.9×10^{-2}	2.5×10^{-6}	3.6×10^{-7}
Squash	5.9×10^{-2}	6.8×10^{-2}	2.2×10^{-5}	3.0×10^{-6}
Pumpkin	5.9×10^{-2}	6.8×10^{-2}	2.2×10^{-5}	3.0×10^{-6}
Banana	8.9×10^{-3}	4.9×10^{-2}	2.5×10^{-6}	3.6×10^{-7}
Arrowroot	5.4×10^{-2}	6.8×10^{-2}	2.2×10^{-5}	3.0×10^{-6}
Citrus	6.0×10^{-3}	4.9×10^{-2}	2.5×10^{-6}	3.6×10^{-7}
Rain water	4.3×10^{-5}	1.4×10^{-5}	3.3×10^{-7}	3.7×10^{-8}
Well water	4.5×10^{-3}	1.2×10^{-3}	6.1×10^{-7}	4.4×10^{-7}
Malolo	4.3×10^{-5}	1.4×10^{-5}	3.3×10^{-7}	3.7×10^{-8}
Coffee/tea	4.3×10^{-5}	1.4×10^{-5}	3.3×10^{-7}	3.7×10^{-8}
Soil[b]		9.9×10^{-1}	2.0×10^{-1}	1.2×10^{-1}
Soil[c]	3.9×10^{-1}	7.3×10^{-1}	5.5×10^{-2}	4.7×10^{-2}

[a] Decay corrected to 1999.

[b] Soil represents the current conditions on Bikini Island, Bq/g dry weight.

[c] Soil represents the option of soil removal and potassium fertilizer treatment for Bikini Island, Bq/g dry weight.

locally derived diet is significantly reduced: the annual effective dose estimate of 15 mSv (or 17.4 mSv if natural background doses are added; see Section 7) is, after remediation, estimated to be reduced to 1.2 mSv (or 3.6 mSv if natural background doses are added). The mixed diet of imported plus local foods, which resulted in an annual effective dose estimate of 4 mSv without remediation (or 6.4 mSv if doses due to the natural background radiation are added), would — after the same remediation — result in a dose of 0.4 mSv (or 2.8 mSv if natural background doses are added) (Fig. 10).

An uncertainty analysis of these dose predictions [63] indicates that the estimated maximum uncertainty is a factor of 2 in either direction, which is considered to be acceptable in the present context.

9.3. CONDITIONS FOR HABITABILITY

From the evidence presented it seems that either of the treatment strategies considered, i.e. total topsoil removal and potassium treatment plus localized soil removal, would be effective in reducing the annual doses to well below the generic action level of annual effective dose of up to about 10 mSv and, therefore, would establish appropriate radiation protection conditions for the resettlement of Bikini Island.

Because of the reservations expressed earlier concerning the total soil removal option, potassium treatment together with localized soil removal is the preferred strategy.

9.4. ACTIVITY LEVELS IN FOODSTUFFS

As discussed earlier, international guidelines for the specific activity of radionuclides in foodstuffs are established in the Basic Safety Standards. Predicted radionuclide activities for local foodstuffs on Bikini Island following the preferred remediation measures are shown in Table XX.

Several food products under current conditions at Bikini Island (with no potassium fertilizer treatment) do exceed the guideline for ^{137}Cs; for the other radionuclides (^{90}Sr, $^{239+240}$Pu and ^{241}Am) the foodstuffs are all already well below the guideline levels (see Tables VII–X). After treatment with potassium fertilizer, the ^{137}Cs concentration in these food groups would also be reduced to well below the guideline levels.

10. CONCLUSIONS AND RECOMMENDATIONS

1. On the basis of the amount and quality of the scientific information on the residual radionuclides from nuclear weapon testing at Bikini Atoll submitted for review, it is concluded that:

No further independent corroboration of the measurements and assessments of the radiological conditions at Bikini Atoll is necessary.

This conclusion is based on: the excellent quality control of those measurements and assessments; the regular participation in intercomparison programmes by the various scientific groups that carried out those measurements and assessments; and the good agreement among the data submitted. Nevertheless, it is acknowledged that the Bikinian people have concerns about the actual radiological conditions in their homeland, and it is therefore considered that:

The Bikinians might be reassured about the actual radiological conditions at Bikini Atoll by a limited programme of monitoring of radiation levels, which should involve some participation by members of the community.

2. In view of the information submitted and under the assumption that the Bikinian community decides to resettle Bikini Island (the main island of residence at Bikini Atoll), it is concluded that:

Permanent resettlement of Bikini Island under the present radiological conditions without remedial measures is not recommended in view of the radiation doses that could potentially be received by inhabitants with a diet of entirely locally produced foodstuffs.

This conclusion was reached on the basis that a diet made up entirely of locally produced food — which would contain some amount of residual radionuclides — could lead the hypothetical resettling population to be exposed to radiation from residual radionuclides in the island, mainly from ^{137}Cs, resulting in annual effective dose levels of about 15 mSv (if the dose due to natural background radiation were added, this would result in an annual effective dose of about 17.4 mSv). This level was judged to require intervention of some kind for radiation protection purposes.

3. However, it is considered that:

In practice, doses caused by a diet of locally derived foodstuffs are unlikely to be actually incurred under the current conditions, as the present Marshallese diet contains — and would in the near future presumably continue to contain — a substantial proportion of imported food which is assumed to be free of residual radionuclides.

Nevertheless, the hypothesis of a diet of solely locally produced food was adopted in the assessment for reasons of conservatism and simplicity, and also because the present level of imports of foodstuffs could decrease in the future.

4. A number of straightforward environmental remediation strategies at Bikini Island have been considered, which, if properly implemented, would achieve very satisfactory results from the point of view of radiation protection. It is therefore concluded that:

Provided that certain remedial measures are taken, Bikini Island could be permanently reinhabited.

5. Several possible remediation strategies were considered with the result that the following were selected as a basis for further assessment:

— The periodic application of potassium based fertilizer to all areas of Bikini Island where edible crops may be grown, supported by the removal of soil from around and beneath the dwelling areas and its replacement by crushed coral (known as the *potassium fertilizer remediation strategy*);

— The complete removal of the topsoil from Bikini Island (called the *soil scraping remediation strategy*).

While no definite recommendations are given on which strategy to follow, it is considered that the strategy using potassium fertilizer is the preferred approach.

In this connection, it was noted that the soils of Bikini Atoll are extremely deficient in potassium and extensive field trials have demonstrated that the application of potassium rapidly reduces the concentration of ^{137}Cs in food crops since potassium is taken up by the plants in preference to caesium. The reduction of ^{137}Cs in the food crops is sustained for about four to five years, after which the values slowly begin to increase again. However, repeated application of fertilizer forms an effective strategy in reducing the estimated doses to the potential inhabitants of Bikini Island. Furthermore, the supporting strategy of removing soil from dwelling areas would eliminate most of the external and internal exposures from direct soil ingestion or inhalation.

6. It is concluded that:

The results expected from the potassium fertilizer remediation strategy are consistent with international guidance on interventions to avoid dose in chronic exposure situations and, therefore, this strategy would provide a radiologically safe environment permitting early resettlement.

Depending on the assumptions made concerning diet, the annual calculated mean effective doses would be reduced as follows: from about 15 mSv (if the dose due to natural background radiation were added, this would result in an annual effective dose of about 17.4 mSv), for a high calorie diet of totally local foodstuffs, to about 1.2 mSv (if the dose due to natural background radiation were added, this would result in an annual effective dose of about 3.6 mSv); and from about 4 mSv (if the dose due to natural background radiation were added, this would result in an annual effective dose of about 6.4 mSv), for a high calorie diet of both local and imported foodstuffs, to about 0.4 mSv (if the dose due to natural background radiation were added, this would result in an annual effective dose of about 2.8 mSv). Even for the more conservative assumption of a high calorie diet of totally locally produced foodstuffs, the resulting doses will be far below acceptable generic action levels for intervention. The doses will be somewhat higher than those due to natural background radiation that were incurred by the inhabitants of Bikini Island before the evacuation and prior to when the nuclear weapon tests took place, and also somewhat higher than global average natural background doses, but lower than typical elevated levels of natural background doses around the world.

7. The conclusion is that:

The alternative strategy, i.e. the soil scraping remediation strategy — stated to be the alternative preferred by the Bikinians — would be very effective in avoiding doses caused by the residual radionuclides, but it could entail serious adverse environmental and social consequences.

The consequences may be serious because the fertile topsoil supports the tree crops, which are the major local food resource. The replacement of the soil with topsoil from elsewhere would be an enormous undertaking which is likely to be prohibitively expensive. The content of natural radionuclides in any continental soil used as replacement soil would most probably exceed that of the present soil.

8. It is concluded that:

No remedial actions should be proposed at this stage for the islands of Bikini Atoll other than Bikini Island.

The other islands have historically been non-residential and used only for occasional visits and for fishing.

9. On the assumption that the proposed remediation strategy is undertaken, it is further recommended that:

Regular measurements of activity in local foodstuffs should be made to assess the effectiveness of the measures taken. A simple, local whole body monitor and training in its use should be provided as a further means of enabling potential inhabitants to satisfy themselves that there is no significant uptake of caesium into their bodies.

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Addendum

IAEA CORROBORATORY MONITORING MISSION TO BIKINI ISLAND

A–1. INTRODUCTION

This report was presented to and discussed with the late President of the Republic of the Marshall Islands, His Excellency Amata Kabua, who was accompanied by the Honourable Thomas Kijiner, then the Republic's Minister of Health and Environment, during the President's official visit to Tokyo on 14 October 1996. Immediately after this, on 17 October 1996, the report was formally submitted to the Government of the Republic of the Marshall Islands in Majuro through the requesting office, the Ministry of Foreign Affairs. The report was also presented to the Bikinian community through the Office of the Local Government of Kili/Bikini/Ejit in Majuro on 18 October 1996. The report was finally officially accepted by the Government of the Republic of the Marshall Islands through a letter from its Ambassador to the United States of America on 18 September 1997.

At the meeting on 14 October 1996, President Kabua suggested that an independent corroboration by IAEA experts of the available environmental data relating to the residual radioactive materials on Bikini Island, which had served as the basis for the assessment contained in the main report, would be desirable. That report concluded that no further independent corroboration of the measurements and assessments of the radiological conditions on Bikini Atoll was necessary. However, taking into account the need for the Bikinians to be reassured about the situation, the IAEA agreed to carry out the requested corroboratory monitoring.

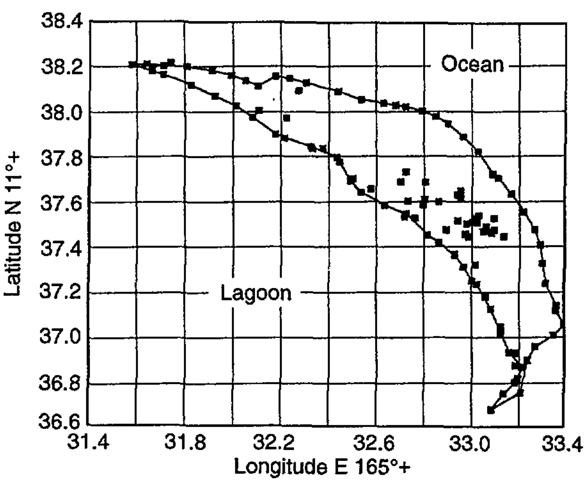

FIG. A–1. Measurement sites of absorbed dose rate in air on Bikini Island.

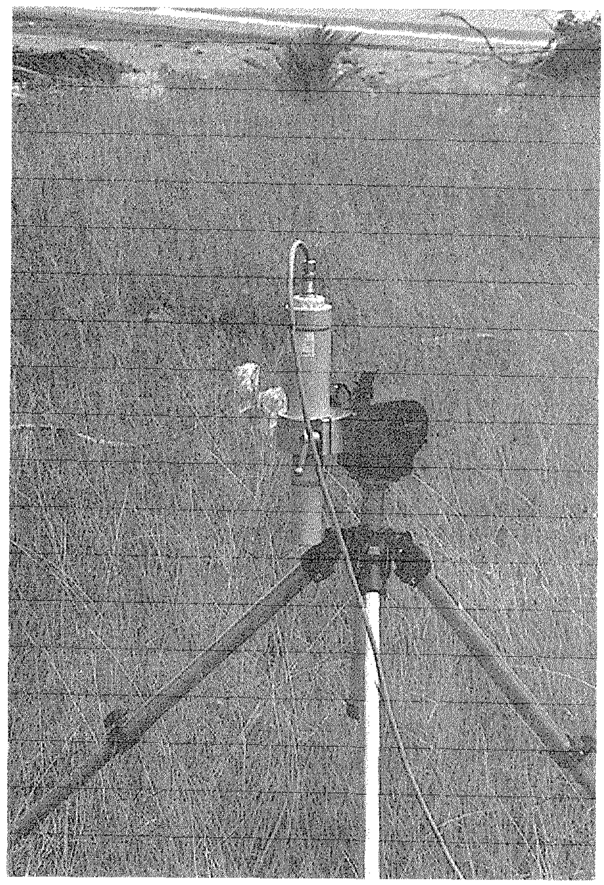

FIG. A–2. Measurement of the absorbed dose rate in air.

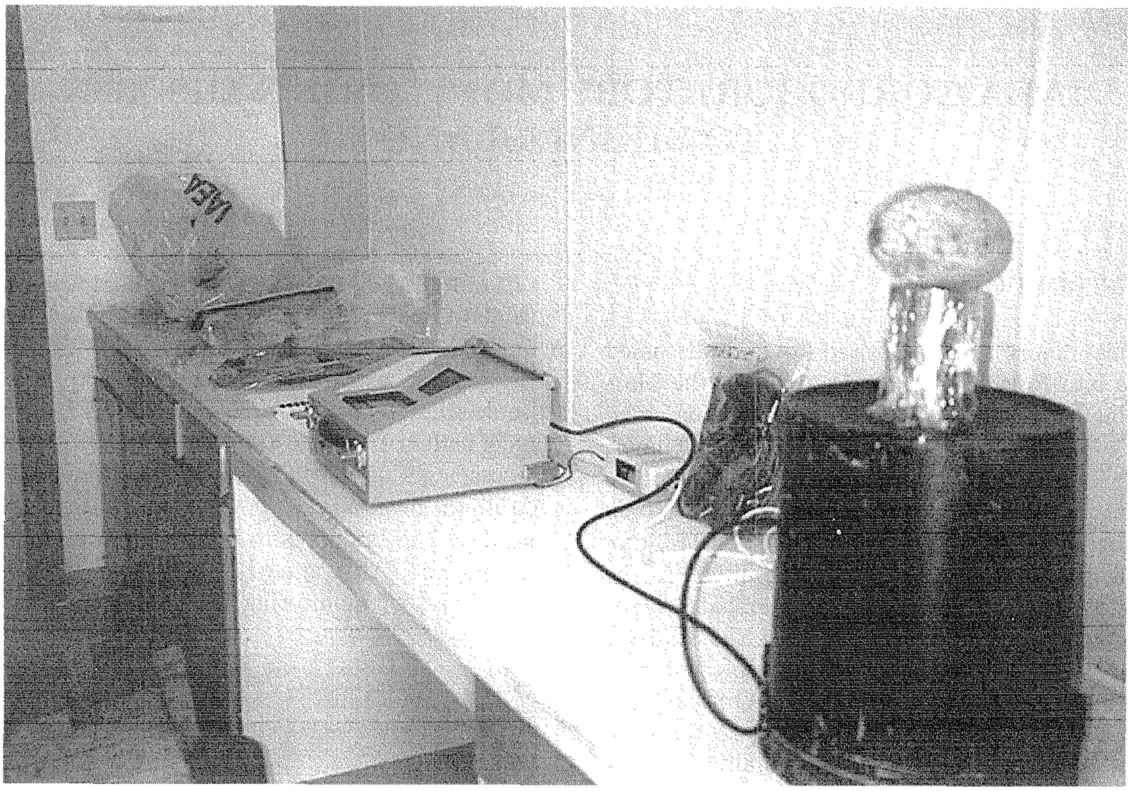

FIG. A-3. Gamma spectrometric system for ^{137}Cs measurements.

An IAEA environmental monitoring team carried out a limited programme of environmental measurements and sampling during the period 7–22 May 1997. Measurements were made of the absorbed dose rate in air and of the concentration of the most radiologically significant radionuclides in representative soil and foodstuff samples on Bikini Island. This addendum summarizes the results of the IAEA environmental monitoring mission.

A–2. MEASUREMENT PROGRAMME

A–2.1. Absorbed dose rate in air on Bikini Island

The team made 113 measurements of the absorbed dose rate in air (1 m above ground) at selected sites on Bikini Island (Fig. A–1). The measurements were made with an energy compensated, low dose rate Geiger–Müller (GM) detector (Fig. A–2) and with a radiometer with built-in GM detectors. The locations for the measurements were chosen to give an indication of the distribution of dose rates over the whole surface of Bikini Island. Account was also taken, in selecting measurement locations, of previous measurements on the island to ensure that appropriate comparisons could be made.

A–2.2. Preliminary determination of ^{137}Cs concentrations in selected foodstuffs and soil samples on Bikini Island

Selected food samples — coconut, pandanus and breadfruit, and soil samples (surface soil and vertical profiles) — from a number of locations on Bikini Island were used for a preliminary determination (screening of the samples) of ^{137}Cs concentrations by field gamma spectrometric equipment in the King Juda (provisional) laboratory on Bikini Island. Two independent gamma spectrometric systems, with sodium iodide scintillation detectors connected to computerized analysers, were used.

Both were found to be very efficient for the rapid checking of ^{137}Cs concentrations in the relevant environmental samples (Fig. A–3). The counting times ranged from a few minutes to one hour, depending on the activity concentrations of ^{137}Cs in the samples. The detectors were not shielded because of the very low background activity in the energy region of ^{137}Cs (fewer than 2 counts per second), and the results were corrected for interference from the environmental background radiation. On the basis of the preliminary field gamma spectrometric analysis (screening of samples for ^{137}Cs content), coconut, pandanus and breadfruit samples as well as soil samples were collected for subsequent, more accurate determination of radionuclide concentrations at the Agency's Laboratories in Seibersdorf, Austria.

FIG. A–4. Preparation of coconut fruit for measurement.

A–2.3. Collection and preparation of foodstuffs and soil samples for subsequent radionuclide analysis at the Agency's Laboratories

A representative number of coconut (Fig. A–4), pandanus and breadfruit samples (no papaya, pumpkin or squash samples were available on Bikini Island at the time of the mission), topsoil (Fig. A–5) and vertical profile soil samples from different locations on Bikini Island were collected, prepared for shipment and shipped to the Agency's Laboratories in Seibersdorf. Some of the coconuts (coded as COC01–COC06) and corresponding soil samples were collected from undisturbed locations. Other coconut samples (coded as COC08–15) and corresponding soil samples were collected from experimental fields where the soil had been treated with potassium chloride (KCl) to reduce ^{137}Cs uptake from soil to the coconut fruit. Coconut samples coded as COC16–20 were collected randomly from undisturbed areas. Four vertical soil profile samples and five topsoil samples (0–2 cm) were also collected at selected sites. The vertical profile samples comprised six layers, 0–2, 2–7, 7–12, 12–17, 17–27 and 27–37 cm, and were coded as, for instance, COR1–1 to COR1–6. The first layer of the vertical profile soil samples was always considered to be the topsoil layer. The sampling locations are shown in Fig. A–6.

A–2.4. Determination of radionuclide concentrations in foodstuffs and soil samples at the Agency's Laboratories

All foodstuffs and soil samples from Bikini Island were prepared for quantitative determination of radionuclides at the Agency's Laboratories in Seibersdorf. High resolution gamma spectrometry was used for the determination of gamma emitting radionuclides (mainly ^{137}Cs) in food and soil samples after applying appropriate preparation techniques, such as freeze drying and ashing for the food samples, and drying, grinding and sieving for the soil samples. The alpha emitting radionuclides ($^{239+240}Pu$ and ^{241}Am) were determined by alpha spectrometry following specific radiochemical procedures, and ^{90}Sr was determined by liquid scintillation counting after chemical separation from other radionuclides in the samples. For the determination of $^{239+240}Pu$, ^{241}Am and ^{90}Sr, six soil samples were selected, four from the vertical profiles and two from the topsoil samples. For

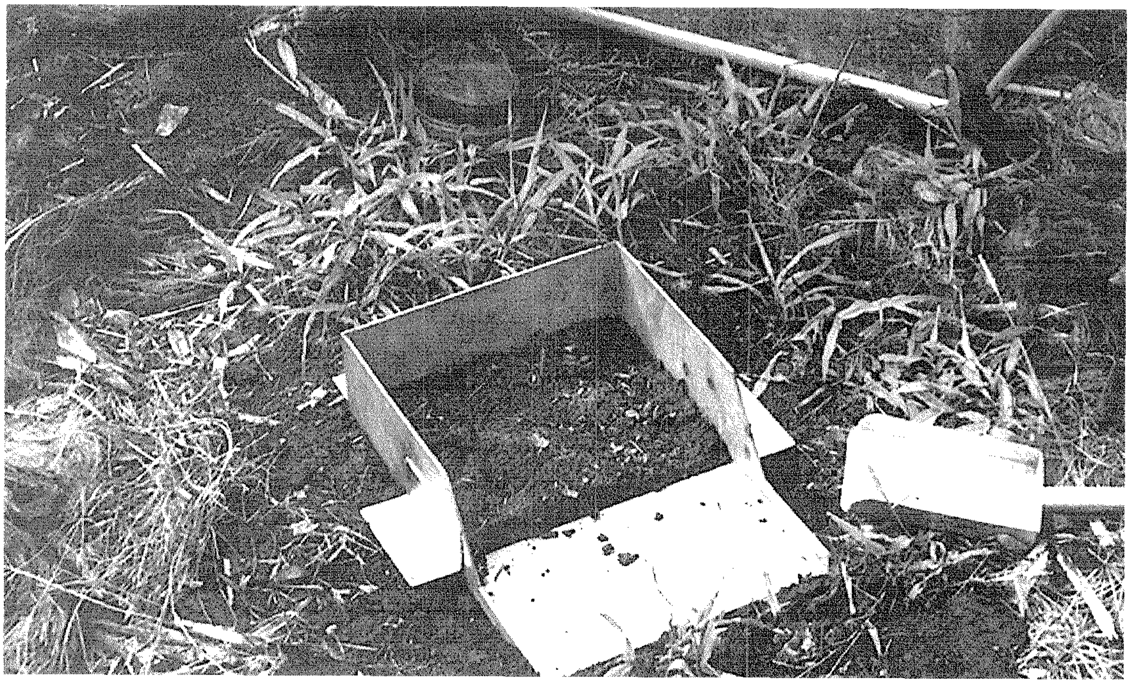

FIG. A–5. Collection of topsoil samples.

quality control (QC) purposes, the reference materials IAEA-367 and IAEA-368 — marine sediments — were used.

For the analysis of alpha emitting radionuclides and ^{90}Sr in food samples, two composite samples consisting of coconut meat and the corresponding coconut fluid were prepared from three coconuts (COC01, 02, 03) obtained from a sampling location of elevated soil activity concentration. Similarly, the coconut meat and corresponding fluid from four coconuts (COC17, 18, 19, 20) from randomly selected locations were combined into two other composite samples (one meat and one fluid). Only edible parts of pandanus and breadfruit were analysed. For QC purposes, the reference material IAEA-307 (marine plant *Posidonia oceanica*) was used.

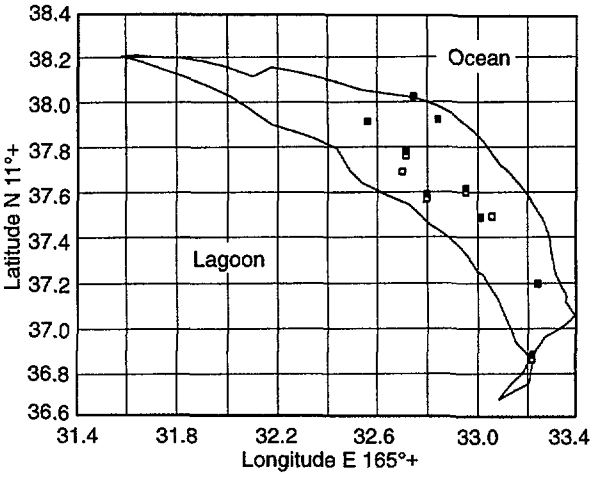

FIG. A–6. Sample collection sites on Bikini Island (□ : fruits; ■ : soil).

A–3. RESULTS AND DISCUSSION

A–3.1. Measurements of the absorbed dose rate in air

The measurements of the absorbed dose rate in air at selected locations on Bikini Island are shown in Table A–I. The results range from 0.06 to 0.50 $\mu Gy \cdot h^{-1}$ (0.5–4.4 mGy per year) and are in good agreement with the information presented earlier to the Advisory Group, as given in Table XI and Fig. 3 of the main report.

A–3.2. Preliminary determination of ^{137}Cs concentrations in selected foodstuffs and soil samples on Bikini Island

The results obtained show the expected higher concentrations of ^{137}Cs in coconuts and pandanus fruits from the locations where soil was not treated with KCl, and considerably lower ^{137}Cs levels in the same fruits from locations where the soil had been treated with KCl, shown in Table XX of the main report.

A–3.3. Activity concentrations of radionuclides in soil

The concentrations of ^{137}Cs, ^{241}Am, ^{90}Sr and $^{239+240}Pu$ in topsoil and vertical profile soil samples from non-disturbed locations are given in Tables A–II and A–III. The activity concentrations of each nuclide in topsoil (0–2 cm) at different locations show a wide variation — by more than an order of magnitude for ^{137}Cs. This is consistent with previously reported data given in Table VI of the main report. The concentrations of ^{137}Cs decrease with depth at all locations sampled (Table A–III), but at two of the locations sampled, ^{241}Am concentrations were almost constant throughout the top 17 cm of soil.

The mean activity concentrations of ^{137}Cs, ^{90}Sr, $^{239+240}Pu$ and ^{241}Am in soil measured by the IAEA were compared with those reported earlier to the Advisory Group (Table A–IV). Overall there is good agreement between the values reported to the Advisory Group in December 1995 and those obtained later by the IAEA team. Any differences can probably be ascribed to the necessarily limited nature of the soil sampling by the IAEA team.

A–3.4. Activity concentrations in foodstuffs

Table A–V presents the activity concentrations of ^{137}Cs and ^{40}K in the edible parts of breadfruit, pandanus and coconuts. The breadfruit samples originate from the only place on Bikini Island where breadfruit is available, and the ^{137}Cs concentrations in the breadfruits sampled are very similar. The ^{137}Cs activity concentration was markedly lower in the pandanus and coconut samples collected at locations where the soil had been treated with KCl.

Activity concentrations per unit mass of selected breadfruit, pandanus and coconut (composite fluid and meat samples) for ^{90}Sr and transuranic radionuclides $^{239+240}Pu$ and ^{241}Am are shown in Table A–VI. The ^{90}Sr activities are about one order of magnitude lower than the respective ^{137}Cs activities in the relevant foodstuffs, and the activities of $^{239+240}Pu$ and ^{241}Am are much lower than the ^{90}Sr values.

A comparison of ^{137}Cs, ^{90}Sr, $^{239+240}Pu$ and ^{241}Am activity concentrations in selected foodstuffs with those reported to the Advisory Group is made in Tables A–VII to A–X. Samples obtained from soil locations treated with KCl are excluded from this comparison. Both the mean values and the ranges of activity concentrations for ^{137}Cs, ^{90}Sr, $^{239+240}Pu$ and ^{241}Am in selected foodstuffs measured by the IAEA team are in good agreement with previously reported data.

A–4. CONCLUSIONS

The IAEA monitoring mission to Bikini Island was of limited duration and scope but it was sufficient for the IAEA experts to corroborate the environmental radiation data presented to the Advisory Group meeting in December 1995 and to concur with the account of the radiological conditions on Bikini Island contained in the main report. The measurements are generally in good agreement with the previously reported values contained in the main report. The minor differences are not radiologically significant and can be ascribed to the limited amount of sampling that was possible by the IAEA team.

TABLE A–I. ABSORBED DOSE RATE IN AIR AT SELECTED LOCATIONS ON BIKINI ISLAND

Site No.	Location	Geographical description		Instrument reading		Absorbed dose rate		Samples taken
		Latitude	Longitude	counts/s	SD	μGy/h	SD	
1	Exploration plot, code KNPK L13-L14 mark C	N 11°37.508′	E 165°33.022′	1.30	2.9%	0.243	0.008	
2	Exploration plot, code KNPK L21-L22 mark D	N 11°37.461′	E 165°33.081′	1.36	4.7%	0.255	0.013	
3	Exploration plot, code CLC K27-K28 mark H	N 11°37.445′	E 165°33.134′	1.8	4.3%	0.343	0.015	
4	Exploration plot, code KNPK S21-S22 mark E	N 11°37.468′	E 165°33.047′	1.45	4.5%	0.273	0.013	
5	Exploration plot, code KNPK C16-C17 mark F	N 11°37.525′	E 165°33.094′	1.43	4.1%	0.269	0.012	
6	Exploration plot, code KNPK F9-F10 mark B	N 11°37.539′	E 165°33.029′	1.5	4.9%	0.283	0.015	
7	Exploration plot, code KNPK F1-F2 mark A	N 11°37.526′	E 165°33.012′	1.5	4.7%	0.283	0.014	
8	Exploration plot, code KNPK M6-M7 mark G	N 11°37.508′	E 165°33.001′	1.01	6.7%	0.185	0.014	
8	Exploration plot, code KNPK M6-M7 mark G	N 11°37.508′	E 165°33.001′	1.05	4.8%	0.193	0.010	
9	Exploration plot, code WLR C8-C9 mark K	N 11°37.454′	E 165°32.972′	1.4	4.9%	0.263	0.014	
10	Exploration plot, code WLR E10-E11 mark J	N 11°37.444′	E 165°32.986′	0.99	4.8%	0.181	0.010	
11	Exploration plot, code CLC H29-H30 mark I	N 11°37.473′	E 165°33.094′	1.56	4.4%	0.295	0.014	
12	Exploration plot, code Exc. Control K3-J3 mark L	N 11°37.628′	E 165°32.941′	2.1	4.4%	0.403	0.018	
13	Exploration plot, code Exc. Control I3-J5 mark M	N 11°37.615′	E 165°32.953′	2.6	3.1%	0.503	0.016	COR2, PAN1, PAN2
14	Exploration plot, code Exc. Control, at tower mark M	N 11°37.648′	E 165°32.953′	2.3	4.2%	0.443	0.019	
15	Exploration plot, code HEJ I14-I15 mark O	N 11°37.685′	E 165°32.805′	1.13	4.2%	0.209	0.009	
16	Exploration plot, code HEJ H40-H41 mark P	N 11°37.515′	E 165°32.941′	1.8	4.0%	0.343	0.014	
17	Exploration plot, code HEJ, random	N 11°37.598′	E 165°32.862′	1.79	3.6%	0.341	0.013	
18	Exploration plot, code HEJ, random	N 11°37.609′	E 165°32.802′	2.2	3.8%	0.423	0.017	

TABLE A–I. (cont.)

Site No.	Location	Geographical description		Instrument reading		Absorbed dose rate		Samples taken
		Latitude	Longitude	counts/s	SD	μGy/h	SD	
19	Exploration plot, code B1 WELL H2-H3 mark R	N 11°37.687′	E 165°32.701′	1.17	4.5%	0.217	0.011	COC07–COC15 (L,K,I)
20	Exploration plot, code B1 WELL F4-F5 mark Q	N 11°37.730′	E 165°32.724′	1.9	4.2%	0.363	0.016	
21	Exploration plot, code ACS VV11-VV12 mark S	N 11°37.500′	E 165°32.977′	1.4	3.6%	0.263	0.010	
22	Exploration plot, close to K16-K17	N 11°37.489′	E 165°33.059′	1.5	3.5%	0.283	0.011	COC01–COC06 (N,Q)
23	Exploration plot, random selection, close to 5D-5E-WR4/4E	N 11°37.475′	E 165°32.892′	1.5	4.7%	0.283	0.014	
24	East side of island, close to road and bunker	N 11°36.819′	E 165°33.192′	0.72	6.4%	0.127	0.009	
25	Along road, between bushes	N 11°36.876′	E 165°33.182′	0.82	6.2%	0.147	0.010	
26	Along road, behind ruins of a house	N 11°36.931′	E 165°33.186′	0.68	6.4%	0.119	0.009	
27	Along road	N 11°37.048′	E 165°33.121′	0.55	6.5%	0.093	0.007	
28	Along road	N 11°37.181′	E 165°33.059′	1.18	4.7%	0.219	0.011	
29	Along road	N 11°37.323′	E 165°33.012′	1.22	4.3%	0.227	0.010	
30	Along road	N 11°37.368′	E 165°32.927′	1.25	5.4%	0.233	0.014	
31	Village, between 4 breadfruit trees, tree 31	N 11°37.586′	E 165°32.797′	0.77	5.1%	0.137	0.008	TOP6, BRE1-BRE4
32	Along road, leaving village behind (E)	N 11°37.655′	E 165°32.578′	1.9	4.1%	0.363	0.016	
33	Along road, close to meteorological tower; at the road	N 11°37.701′	E 165°32.501′	2.0	4.0%	0.383	0.016	
34	Along road, old village	N 11°37.774′	E 165°32.447′	0.71	4.2%	0.125	0.006	
35	Along road, outside village, in bushes	N 11°37.836′	E 165°32.378′	1.2	5.5%	0.223	0.013	
36	Along road	N 11°37.833′	E 165°32.334′	0.78	5.2%	0.139	0.008	

TABLE A–I. (cont.)

Site No.	Location	Geographical description		Instrument reading		Absorbed dose rate		Samples taken
		Latitude	Longitude	counts/s	SD	μGy/h	SD	
37	Along road	N 11°37.882′	E 165°32.216′	1.25	5.1%	0.233	0.013	
38	Inside island, close to the middle of the island	N 11°37.973′	E 165°32.224′	1.14	5.1%	0.211	0.012	
39	Inside island, close to the ocean	N 11°38.092′	E 165°32.276′	1.14	5.1%	0.211	0.012	
40	Inside island, close to the main road	N 11°38.004′	E 165°32.109′	0.98	5.4%	0.179	0.011	
41	West end of the island	N 11°38.215′	E 165°31.742′	0.72	5.0%	0.127	0.007	
42	Village, cemetery, at lagoon	N 11°37.603′	E 165°32.733′	0.74	6.1%	0.131	0.009	
43	Village, at the lagoon beach, behind cemetery	N 11°37.531′	E 165°32.720′	0.55	5.6%	0.093	0.006	
44	Village, at the front of King Juda Lab.	N 11°37.526′	E 165°32.760′	0.60	4.9%	0.103	0.006	
45	Exploration plot, code KNPK, random selection for soil profile	N 11°37.485′	E 165°33.014′	1.65	3.9%	0.313	0.013	COR1
46	Random selection for soil core, close to ocean	N 11°37.196′	E 165°33.242′	0.72	5.7%	0.127	0.008	COR3
47	Random selection for topsoil and coconuts	N 11°37.777′	E 165°32.715′	1.68	3.5%	0.319	0.012	COC16-COC17, TOP1
48	Random selection for topsoil	N 11°37.921′	E 165°32.843′	0.93	6.6%	0.169	0.012	COR4 (2cm+5cm)
49	Random selection for topsoil, close to island centre	N 11°37.911′	E 165°32.561′	1.22	3.6%	0.227	0.009	TOP3
50	Random selection for topsoil, in the forest	N 11°38.021′	E 165°32.746′	0.91	5.2%	0.165	0.009	TOP4
51	Random selection for topsoil, at pandanus	N 11°36.882′	E 165°33.221′	0.61	6.3%	0.105	0.008	TOP5, PAN3
101	Trip around the island (Bikini contour)	N 11°37.544′	E 165°32.725′	Direct dose reading		0.10		
102	Trip around the island (Bikini contour)	N 11°37.451′	E 165°32.814′	Direct dose reading		0.16		
103	Trip around the island (Bikini contour)	N 11°37.418′	E 165°32.861′	Direct dose reading		0.07		

TABLE A–I. (cont.)

Site No.	Location	Geographical description		Instrument reading		Absorbed dose rate		Samples taken
		Latitude	Longitude	counts/s	SD	μGy/h	SD	
104	Trip around the island (Bikini contour)	N 11°37.363′	E 165°32.927′	Direct dose reading		0.13		
105	Trip around the island (Bikini contour)	N 11°37.311′	E 165°32.965′	Direct dose reading		0.12		
106	Trip around the island (Bikini contour)	N 11°37.250′	E 165°32.999′	Direct dose reading		0.08		
107	Trip around the island (Bikini contour)	N 11°37.237′	E 165°33.021′	Direct dose reading		0.18		
108	Trip around the island (Bikini contour)	N 11°37.126′	E 165°33.080′	Direct dose reading		0.17		
109	Trip around the island (Bikini contour)	N 11°37.018′	E 165°33.121′	Direct dose reading		0.11		
110	Trip around the island (Bikini contour)	N 11°36.934′	E 165°33.157′	Direct dose reading		0.17		
111	Trip around the island (Bikini contour)	N 11°36.870′	E 165°33.211′	Direct dose reading		0.15		
112	Trip around the island (Bikini contour)	N 11°36.801′	E 165°33.181′	Direct dose reading		0.14		
113	Trip around the island (Bikini contour)	N 11°36.753′	E 165°33.135′	Direct dose reading		0.12		
114	Trip around the island (Bikini contour)	N 11°36.684′	E 165°33.084′	Direct dose reading		0.12		
115	Trip around the island (Bikini contour)	N 11°36.756′	E 165°33.206′	Direct dose reading		0.11		
116	Trip around the island (Bikini contour)	N 11°36.900′	E 165°33.231′	Direct dose reading		0.14		
117	Trip around the island (Bikini contour)	N 11°36.959′	E 165°33.267′	Direct dose reading		0.13		
118	Trip around the island (Bikini contour)	N 11°37.009′	E 165°33.344′	Direct dose reading		0.14		
119	Trip around the island (Bikini contour)	N 11°37.054′	E 165°33.388′	Direct dose reading		0.12		
120	Trip around the island (Bikini contour)	N 11°37.118′	E 165°33.353′	Direct dose reading		0.18		
121	Trip around the island (Bikini contour)	N 11°37.141′	E 165°33.356′	Direct dose reading		0.10		

TABLE A–I. (cont.)

Site No.	Location	Geographical description		Instrument reading		Absorbed dose rate		Samples taken
		Latitude	Longitude	counts/s	SD	μGy/h	SD	
122	Trip around the island (Bikini contour)	N 11°37.239′	E 165°33.313′	Direct dose reading		0.16		
123	Trip around the island (Bikini contour)	N 11°37.327′	E 165°33.297′	Direct dose reading		0.10		
124	Trip around the island (Bikini contour)	N 11°37.406′	E 165°33.287′	Direct dose reading		0.07		
125	Trip around the island (Bikini contour)	N 11°37.474′	E 165°33.264′	Direct dose reading		0.20		
126	Trip around the island (Bikini contour)	N 11°37.553′	E 165°33.221′	Direct dose reading		0.15		
127	Trip around the island (Bikini contour)	N 11°37.633′	E 165°33.166′	Direct dose reading		0.12		
128	Trip around the island (Bikini contour)	N 11°37.703′	E 165°33.110′	Direct dose reading		0.10		
129	Trip around the island (Bikini contour)	N 11°37.720′	E 165°33.087′	Direct dose reading		0.14		
130	Trip around the island (Bikini contour)	N 11°37.821′	E 165°33.026′	Direct dose reading		0.11		
131	Trip around the island (Bikini contour)	N 11°37.888′	E 165°32.964′	Direct dose reading		0.12		
132	Trip around the island (Bikini contour)	N 11°37.946′	E 165°32.900′	Direct dose reading		0.11		
133	Trip around the island (Bikini contour)	N 11°37.977′	E 165°32.850′	Direct dose reading		0.10		
134	Trip around the island (Bikini contour)	N 11°38.002′	E 165°32.792′	Direct dose reading		0.11		
135	Trip around the island (Bikini contour)	N 11°38.021′	E 165°32.726′	Direct dose reading		0.07		
136	Trip around the island (Bikini contour)	N 11°38.029′	E 165°32.683′	Direct dose reading		0.12		
137	Trip around the island (Bikini contour)	N 11°38.037′	E 165°32.631′	Direct dose reading		0.10		
138	Trip around the island (Bikini contour)	N 11°38.053′	E 165°32.538′	Direct dose reading		0.11		
139	Trip around the island (Bikini contour)	N 11°38.089′	E 165°32.440′	Direct dose reading		0.10		

TABLE A–I. (cont.)

Site No.	Location	Geographical description		Instrument reading		Absorbed dose rate		Samples taken
		Latitude	Longitude	counts/s	SD	μGy/h	SD	
140	Trip around the island (Bikini contour)	N 11°38.127′	E 165°32.305′	Direct dose reading		0.16		
141	Trip around the island (Bikini contour)	N 11°38.146′	E 165°32.235′	Direct dose reading		0.13		
142	Trip around the island (Bikini contour)	N 11°38.155′	E 165°32.178′	Direct dose reading		0.14		
143	Trip around the island (Bikini contour)	N 11°38.113′	E 165°32.103′	Direct dose reading		0.12		
144	Trip around the island (Bikini contour)	N 11°38.136′	E 165°32.052′	Direct dose reading		0.14		
145	Trip around the island (Bikini contour)	N 11°38.160′	E 165°31.994′	Direct dose reading		0.09		
146	Trip around the island (Bikini contour)	N 11°38.182′	E 165°31.914′	Direct dose reading		0.06		
147	Trip around the island (Bikini contour)	N 11°38.199′	E 165°31.809′	Direct dose reading		0.16		
148	Trip around the island (Bikini contour)	N 11°38.201′	E 165°31.712′	Direct dose reading		0.14		
149	Trip around the island (Bikini contour)	N 11°38.210′	E 165°31.643′	Direct dose reading		0.12		
150	Trip around the island (Bikini contour)	N 11°38.206′	E 165°31.582′	Direct dose reading		0.11		
151	Trip around the island (Bikini contour)	N 11°38.181′	E 165°31.665′	Direct dose reading		0.14		
152	Trip around the island (Bikini contour)	N 11°38.162′	E 165°31.711′	Direct dose reading		0.12		
153	Trip around the island (Bikini contour)	N 11°38.117′	E 165°31.826′	Direct dose reading		0.10		
154	Trip around the island (Bikini contour)	N 11°38.070′	E 165°31.928′	Direct dose reading		0.16		
155	Trip around the island (Bikini contour)	N 11°38.026′	E 165°32.014′	Direct dose reading		0.14		
156	Trip around the island (Bikini contour)	N 11°37.976′	E 165°32.083′	Direct dose reading		0.13		
157	Trip around the island (Bikini contour)	N 11°37.899′	E 165°32.179′	Direct dose reading		0.20		
158	Trip around the island (Bikini contour)	N 11°37.844′	E 165°32.328′	Direct dose reading		0.12		

TABLE A–I. (cont.)

Site No.	Location	Geographical description		Instrument reading		Absorbed dose rate		Samples taken
		Latitude	Longitude	counts/s	SD	μGy/h	SD	
159	Trip around the island (Bikini contour)	N 11°37.795′	E 165°32.434′	Direct dose reading		0.14		
160	Trip around the island (Bikini contour)	N 11°37.691′	E 165°32.491′	Direct dose reading		0.12		
161	Trip around the island (Bikini contour)	N 11°37.641′	E 165°32.536′	Direct dose reading		0.19		
162	Trip around the island (Bikini contour)	N 11°37.584′	E 165°32.635′	Direct dose reading		0.14		

TABLE A–II. ACTIVITY CONCENTRATIONS IN TOPSOIL SAMPLES (0–2 cm) COLLECTED AT DIFFERENT LOCATIONS ON BIKINI ISLAND ($Bq \cdot g^{-1}$ DRY MASS); REFERENCE DATE: 20 MAY 1997

Sample code	^{137}Cs	^{241}Am	^{90}Sr	$^{239+240}Pu$
TOP1	4.50 ± 0.09	0.445 ± 0.010	2.6 ± 20%	0.58 ± 20%
TOP3	2.78 ± 0.08	0.143 ± 0.008		
TOP4	1.57 ± 0.04	0.191 ± 0.007		
TOP5	0.45 ± 0.01	0.084 ± 0.005		
TOP6	1.10 ± 0.03	0.069 ± 0.006	0.4 ± 20%	0.09 ± 20%

TABLE A–III. ACTIVITY CONCENTRATIONS IN SOIL CORE SAMPLES (0–2, 2–7, 7–12, 12–17, 17–27 AND 27–37 cm) COLLECTED AT DIFFERENT LOCATIONS ON BIKINI ISLAND ($Bq \cdot g^{-1}$ DRY MASS); REFERENCE DATE: 20 MAY 1997

Sample code	^{137}Cs	^{241}Am	^{90}Sr	$^{239+240}Pu$
COR1-1	5.20 ± 0.10	0.68 ± 0.01	2.3 ± 20%	0.89 ± 20%
COR1-2	2.80 ± 0.08	0.66 ± 0.02		
COR1-3	1.61 ± 0.04	0.44 ± 0.01		
COR1-4	2.07 ± 0.06	0.65 ± 0.02		
COR1-5	0.43 ± 0.01	0.06 ± 0.02	2.4 ± 20%	0.12 ± 20%
COR1-6	0.102 ± 0.004	< 0.006		
COR2-1	7.5 ± 0.2	0.65 ± 0.02	2.4 ± 20%	0.97 ± 20%
COR2-2	2.26 ± 0.06	0.63 ± 0.02		
COR2-3	1.45 ± 0.04	0.44 ± 0.01		
COR2-4	0.97 ± 0.03	0.183 ± 0.005		
COR2-5	0.76 ± 0.02	0.129 ± 0.005	1.8 ± 20%	0.20 ± 20%
COR2-6	0.179 ± 0.004	< 0.01		
COR3-1	0.386 ± 0.008	0.018 ± 0.002		
COR3-2	0.225 ± 0.007	0.0083 ± 0.0009		
COR3-3	0.0665 ± 0.0004	0.003 ± 0.002		
COR3-4	0.0336 ± 0.0006	< 0.009		
COR3-5	0.0155 ± 0.0007	< 0.006		
COR3-6	0.0120 ± 0.0004	< 0.006		
COR4-1	2.48 ± 0.05	0.285 ± 0.007		
COR4-2	1.31 ± 0.04	0.34 ± 0.01		

TABLE A–IV. COMPARISON OF MEAN ACTIVITY CONCENTRATIONS OF ^{137}Cs, ^{90}Sr, $^{239+240}Pu$ AND ^{241}Am ($Bq \cdot g^{-1}$ DRY MASS) IN SOIL ON BIKINI ISLAND

Soil depth (cm)	^{137}Cs	^{90}Sr	$^{239+240}Pu$	^{241}Am
Topsoil				
[a]Previous data (0–5 cm)	3.0	2.1	0.42	0.30
IAEA (0–2 cm)	*2.1*	*1.9*	*0.69*	*0.38*
5–10 cm				
[a]Previous data (5–10 cm)	1.8	2.4	0.44	0.27
IAEA (2–7 cm)	*1.6*	—	—	*0.41*
10–15 cm				
[a]Previous data (10–15 cm)	1.0	2.3	0.34	0.18
IAEA (7–12 cm)	*1.0*	—	—	*0.16*
15–25 cm				
[a]Previous data (15–25 cm)	0.48	1.4	0.16	0.11
IAEA (12–17 cm)	*1.0*	—	—	*0.36*
IAEA (17–27 cm)	*0.40*	*1.8–single value*	*0.14–single value*	*0.11*
25–40 cm				
[a]Previous data (25–40 cm)	0.19	0.77	0.061	0.051
IAEA (27-37 cm)	*0.09*	—	—	—

[a] Previous data are taken from Table VI of the main report.

TABLE A–V. ACTIVITY CONCENTRATIONS IN EDIBLE PARTS OF FRUITS COLLECTED AT DIFFERENT LOCATIONS ON BIKINI ISLAND ($Bq \cdot g^{-1}$ FRESH MASS); REFERENCE DATE: 20 MAY 1997

Sample code	^{137}Cs	^{40}K
Breadfruit		
BRE1	0.164 ± 0.005	0.09 ± 0.01
BRE2	0.115 ± 0.004	0.08 ± 0.01
BRE3	0.175 ± 0.005	0.10 ± 0.01
BRE4	0.154 ± 0.005	0.09 ± 0.01
Pandanus		
From non-treated sampling area		
PAN1	21.4 ± 0.6	< 0.3
From sampling area treated with KCl		
PAN2	1.91 ± 0.05	0.06 ± 0.01
Randomly selected/from non-treated sampling area		
PAN3	1.03 ± 0.03	0.07 ± 0.03
Coconut fluid		
From non-treated sampling area		
COC01	1.88 ± 0.05	0.03 ± 0.01
COC02	2.41 ± 0.07	0.03 ± 0.01
COC03	2.29 ± 0.06	0.03 ± 0.01
COC04	2.01 ± 0.06	0.04 ± 0.01
COC05	1.98 ± 0.05	0.03 ± 0.01
COC06	2.22 ± 0.06	0.04 ± 0.01
From sampling area treated with KCl		
COC08	0.087 ± 0.003	0.09 ± 0.01
COC09	0.084 ± 0.003	0.07 ± 0.01
COC10	0.170 ± 0.005	0.11 ± 0.01
COC11	0.116 ± 0.004	0.11 ± 0.01
COC12	0.146 ± 0.005	0.09 ± 0.01
COC14	0.197 ± 0.006	0.11 ± 0.01
COC15	0.192 ± 0.007	0.11 ± 0.02
Randomly selected/from non-treated sampling area		
COC16	0.43 ± 0.01	0.07 ± 0.01
COC17	0.40 ± 0.01	0.09 ± 0.01
COC18	0.40 ± 0.01	0.07 ± 0.01
COC19	0.45 ± 0.01	0.10 ± 0.01
COC20	0.41 ± 0.01	0.09 ± 0.01
Coconut meat		
From non-treated sampling area		
COC01	2.88 ± 0.08	< 0.09
COC02	3.60 ± 0.10	0.10 ± 0.02
COC03	3.20 ± 0.09	0.09 ± 0.02
COC04	2.88 ± 0.08	0.08 ± 0.01
COC05	3.80 ± 0.10	0.05 ± 0.01
COC06	3.02 ± 0.08	0.07 ± 0.01
From sampling area treated with KCl		
COC08	0.175 ± 0.006	0.15 ± 0.02
COC09	0.120 ± 0.004	0.15 ± 0.02
COC10	0.168 ± 0.005	0.14 ± 0.01
COC11	0.148 ± 0.005	0.14 ± 0.01
COC12	0.171 ± 0.006	0.17 ± 0.01
COC14	0.192 ± 0.006	0.12 ± 0.01
COC15	0.196 ± 0.006	0.13 ± 0.01
Randomly selected/from non-treated sampling area		
COC16	0.81 ± 0.02	0.13 ± 0.01
COC17	0.89 ± 0.02	0.15 ± 0.01
COC18	0.80 ± 0.02	0.13 ± 0.01
COC19	0.83 ± 0.02	0.13 ± 0.02
COC20	0.83 ± 0.02	0.12 ± 0.01

TABLE A–VI. ACTIVITY CONCENTRATIONS IN EDIBLE PARTS OF FRUITS COLLECTED AT DIFFERENT LOCATIONS ON BIKINI ISLAND ($Bq \cdot g^{-1}$ FRESH MASS); REFERENCE DATE: 20 MAY 1997

Sample code	$^{239+240}Pu$	^{241}Am	^{90}Sr
Breadfruit			
BRE3	1.1×10^{-7}	$<3.7 \times 10^{-7}$	2.7×10^{-2}
Pandanus			
PAN1	3.6×10^{-4}	1.7×10^{-5}	2.1×10^{-1}
PAN2	8.4×10^{-7}	5.0×10^{-7}	1.5×10^{-2}
Coconut fluid			
COC01–COC03	$<4.2 \times 10^{-7}$	$<3.4 \times 10^{-7}$	4.9×10^{-4}
COC17–COC20	$<2.0 \times 10^{-7}$	1.1×10^{-7}	6.3×10^{-3}
Coconut meat			
COC01–COC03	$<4.8 \times 10^{-7}$	$<4.0 \times 10^{-7}$	3.0×10^{-3}
COC17–COC20	2.7×10^{-7}	4.2×10^{-7}	1.5×10^{-2}

TABLE A–VII. COMPARISON OF ^{137}Cs ACTIVITIES IN FOOD ($Bq \cdot g^{-1}$ FRESH MASS)

Food type	Mean	Minimum	Maximum
Coconut fluid			
[a]Previous data	1.2×10^{0}	2.8×10^{-2}	6.1×10^{0}
IAEA	*0.8×10^{0}*	*8.4×10^{-2}*	*2.4×10^{0}*
Coconut meat			
[a]Previous data	2.9×10^{0}	1.4×10^{-1}	$1.6 \times 10^{+1}$
IAEA	*1.2×10^{0}*	*1.2×10^{-1}*	*3.8×10^{0}*
Pandanus fruit			
[a]Previous data	3.9×10^{0}	1.1×10^{-1}	$1.9 \times 10^{+1}$
IAEA	*8.1×10^{0}*	*1.0×10^{0}*	*$2.1 \times 10^{+1}$*
Breadfruit			
[a]Previous data	3.8×10^{-1}	9.0×10^{-2}	1.1×10^{0}
IAEA	*1.5×10^{-1}*	*1.2×10^{-1}*	*1.7×10^{-1}*

[a] Previous data are taken from Table VII of the main report.

TABLE A–VIII. COMPARISON OF ^{90}Sr ACTIVITIES IN FOOD ($Bq \cdot g^{-1}$ FRESH MASS)

Food type	Mean	Minimum	Maximum
Coconut fluid			
[a]Previous data	4.5×10^{-4}	7.1×10^{-5}	8.8×10^{-4}
IAEA		*4.9×10^{-4}*	*6.3×10^{-3}*
Coconut meat			
[a]Previous data	5.9×10^{-3}	6.3×10^{-4}	2.9×10^{-2}
IAEA		*3.0×10^{-3}*	*1.5×10^{-2}*
Pandanus fruit			
[a]Previous data	1.2×10^{-1}	8.6×10^{-3}	3.6×10^{-1}
IAEA		*1.5×10^{-2}*	*2.1×10^{-1}*
Breadfruit			
[a]Previous data	6.9×10^{-2}	6.0×10^{-3}	2.0×10^{-1}
IAEA	*2.7×10^{-2} single value*		

[a] Previous data are taken from Table VIII of the main report.

TABLE A–IX. COMPARISON OF $^{239+240}Pu$ ACTIVITIES IN FOOD ($Bq \cdot g^{-1}$ FRESH MASS)

Food type	Mean	Minimum	Maximum
Coconut fluid			
[a]Previous data	1.0×10^{-6}	3.3×10^{-7}	2.2×10^{-6}
IAEA		*2.0×10^{-7}*	*$<4.2 \times 10^{-7}$*
Coconut meat			
[a]Previous data	2.7×10^{-6}	1.7×10^{-7}	1.4×10^{-5}
IAEA		*$<2.7 \times 10^{-7}$*	*$<4.8 \times 10^{-7}$*
Pandanus fruit			
[a]Previous data	3.2×10^{-6}	3.4×10^{-7}	1.1×10^{-5}
IAEA		*8.4×10^{-7}*	*3.6×10^{-4}*
Breadfruit			
[a]Previous data	1.8×10^{-6}	1.4×10^{-7}	9.8×10^{-6}
IAEA	*1.1×10^{-7} single value*		

[a] Previous data are taken from Table IX of the main report.

TABLE A–X. COMPARISON OF ^{241}Am ACTIVITIES IN FOOD ($Bq \cdot g^{-1}$ FRESH MASS)

Food type	Mean	Minimum	Maximum
Coconut fluid			
[a]Previous data	8.5×10^{-6} single value		
IAEA		*1.1×10^{-7}*	$<3.4 \times$ *10^{-7}*
Coconut meat			
[a]Previous data	3.6×10^{-6}	5.0×10^{-7}	1.6×10^{-5}
IAEA		*$<4.0 \times 10^{-7}$*	*$<4.2 \times 10^{-7}$*
Pandanus fruit			
[a]Previous data	3.8×10^{-6}	2.8×10^{-7}	1.5×10^{-5}
IAEA		*5.0×10^{-7}*	*1.7×10^{-5}*
Breadfruit			
[a]Previous data	1.2×10^{-6}	1.5×10^{-7}	5.3×10^{-6}
IAEA	*$<3.7 \times 10^{-7}$* *single value*		

[a] Previous data are taken from Table X of the main report.

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