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EVALUATION OF THE RADIOLOGICAL QUALITY OF THE WATER ON BIKINI AND ENEU ISLANDS IN 1975: DOSE ASSESSMENT BASED ON INITIAL SAMPLING

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EVALUATION OF THE RADIOLOGICAL QUALITY OF THE WATER ON BIKINI AND ENEU ISLANDS IN 1975: DOSE ASSESSMENT BASED ON INITIAL SAMPLING

Abstract

In June of 1975 we conducted a survey to determine the residual radioactivity in the terrestrial environment on the two main islands (Eneu and Bikini) of Bikini Atoll. Our objective was to evaluate the potential radiation doses that could be received by the Bikinians scheduled to return to their atoll. This report describes the radiological quality of the groundwater during June 1975 (from data obtained from water samples collected at old and new well sites on both islands) and the cistern water on Bikini Island. Based on analyses of these samples, we found that the cistern water from Bikini Island is both chemically and radiologically acceptable as drinking water in accordance with standard limits established by the U.S. Public Health Service. However, on both islands the quality of the groundwater varies from one site to another. At some wells both chemical and radiological quality are acceptable; at others one or both are unacceptable according to U.S. Public Health Standards. The doses we predict from consumption of both cistern and groundwater are acceptable under federal guidelines. However, doses predicted from consumption of groundwater are high enough to warrant careful evaluation of other potential exposure pathways.

Introduction

To evaluate the potential radiation doses that could be received by Bikinians returning to their atoll, we conducted a survey during June 1975 to determine the residual radioactivity in the terrestrial environment on Bikini and Eneu Islands of Bikini Atoll. The survey included measuring environmental gamma-ray exposure rates and collecting samples of soil, groundwater, cistern water, and vegetation to use in assessing the internal doses from pertinent food chains.[1-4]

This report describes the radiological quality of the groundwater during June 1975, based on data obtained from water samples collected at old and new well sites on the islands. We also include results on the radionuclide levels in three rainwater cisterns on Bikini Island. Doses are calculated assuming water consumption from both cistern and groundwater sources.

The chemical and radiological quality of the water is compared to standards established by the U.S. Public Health Service and to the recommended maximum permissible water concentrations from Federal Radiation Council (FRC) part 20 standards for protection against radiation.[5]

We are presently evaluating the radionuclide and elemental content of groundwater samples collected from these wells in January of 1977. This will allow us to assess the temporal changes which may have resulted from disturbance of normal groundwater concentrations following the initial drilling of the wells.

Field Operations, Observations, and Procedures

Between June 16 and June 24, 1975, five new wells for surface groundwater were established on the island of Bikini and two were established on Eneu Island. The locations of the new Bikini wells (HFH 1 through HFH 5) and the previously established open well (HFH 7) are shown in Fig. 1 along with the locations of the three rainwater cisterns sampled. Figure 1 also shows the locations of the new wells (FWR 1 and FWR 2) on Eneu and the previously established wells (FWR 3 and FWR 4) along with pertinent landmarks for reference. The new wells were located to give the best possible definition of the surface groundwater quality over as large an area as possible. We had planned to establish additional wells in the southern parts of Bikini and Eneu but were unable to do so because of time restrictions.

The wells were started by excavating a pit with a backhoe to the depth of the groundwater surface. Hard beach-rock layers were encountered at HFH 2 (2.7 m below ground surface) and at HFH 5 (at 1.4 m); rock layers were not encountered at any other locations. Then, a gas-powered hand-held auger was used to loosen the coral aggregate below the water surface to as great a depth as physically possible, and slotted

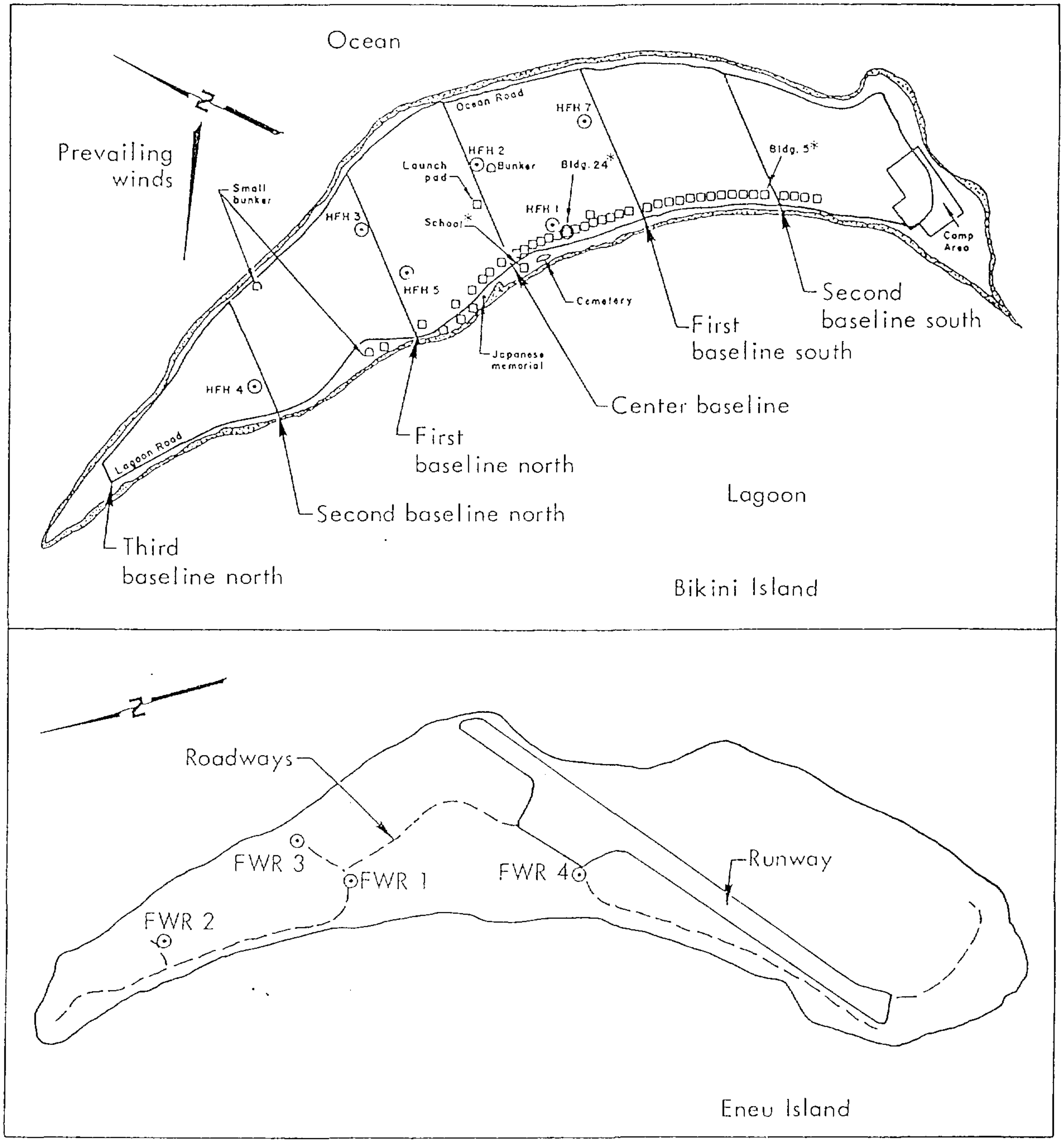

Fig. 1. Locations of wells on Bikini (upper) and Eneu (lower) Islands. An asterisk indicates that the building had an associated rainwater cistern that was sampled.

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2-in.-diam PVC pipe was forced into the hole. The pipe was capped at the bottom to prevent soil from filling the interior of the pipe. The slots above the waterline were taped over to prevent surface debris from entering the casing from above. The hole was backfilled with the excavated soil, with the removed bottom soil being returned to the pit first.

Table 1 gives the depth to which the slotted casing extends below the surface of the water table and the depth of the water table below ground surface. Most of these water depths were measured during periods of lowest tide. We detected no differences in conductivity throughout the accessible length of each water column. The thickness of the freshest water layer at each location is at least equivalent to the water depths in Table 1.

Before the water in the wells was sampled, it was allowed to stabilize for one to two days. The entire pumping system was purged with at least 100 litres of water from any respective well, and all collection containers were thoroughly rinsed to minimize cross-contamination of samples. Samples were withdrawn by a battery-operated pump (Fig. 2) through a section of flexible plastic tubing lowered into the pipe below the water surface. The pumping rate could be regulated by a variable-speed control over the range from a few millilitres per minute to 8 litres per minute. Conductivity was

Table 1. Depths of wells at Bikini and Eneu Islands.

Island	Well	Depth of well casing below water table (m)	Depth of water table below ground surface (m)
Bikini	HFH 1	1.21	2.48
	HFH 2	0.73	2.72
	HFH 3	0.87	2.33
	HFH 4	0.82	2.80
	HFH 5	0.73	2.67
	HFH 7[a]	0.6[b]	
Eneu	FWR 1	0.54	2.43
	FWR 2	0.81	1.92
	FWR 3[a]	9.0	4.0
	FWR 4[a]	--[c]	--[c]

[a]Old well. [b]Open well under block casing. [c]Not measured.

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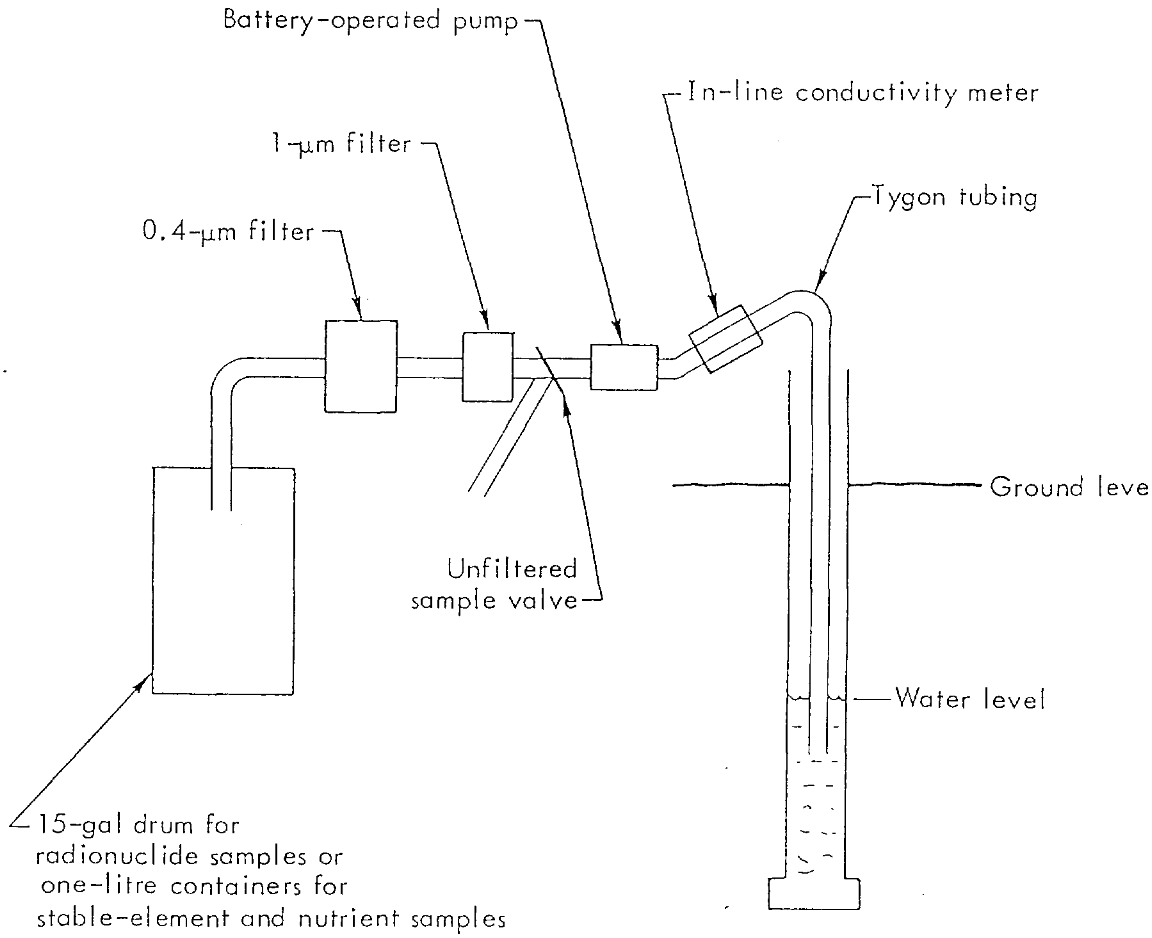

Fig. 2. Diagram of the pump arrangement for collection of groundwater samples.

monitored during pumping by channeling the water through an inline conductivity meter. The water then passed through two filters (1-μm and 0.4-μm) to remove suspended particulate material; these filters were subsequently analyzed for radionuclide content. The filtrate was collected for radionuclide analysis in 15-gal black "Deldrum" containers; smaller volumes were collected for analysis of chlorinity and other constituents.

In an experiment we designed to follow the chemical and radiological changes in the water resulting from continuous pumping at a constant rate, groundwater at HFH 1 was pumped out continuously over an 8-hr period; a total of 3200 litres was removed from the reservoir. Conductivity was monitored throughout

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the entire test, and samples were collected for analysis at the start, midpoint, and end of the test. If the mean daily water consumption rate by humans is assumed to be 2 litres per day, the total volume removed was equivalent to what could have been used by 100 people in 16 days. The usable groundwater is therefore a valuable resource to the people of the atoll.

A similar test was conducted at FWR 1 on Eneu, but only 2400 litres were removed during a half-day pumping period. Samples were taken at the beginning and end of this test. The conductivity of the water during the pumping operations at these two wells is shown in Fig. 3, which also relates conductivity to the time of sampling.

We also obtained a 15-gal filtered water sample from the old Bikini well (HFH 7). From our discussions with the Bikini people as well as from our own observations, we learned that large quantities of the groundwater from this well are being withdrawn almost daily for crop irrigation. This water has also been used for drinking during periods of drought. Large-volume samples were also pumped from the two old wells on Eneu (FWR 3 and 4) and from three rainwater cisterns sampled on Bikini Island (see Fig. 1).

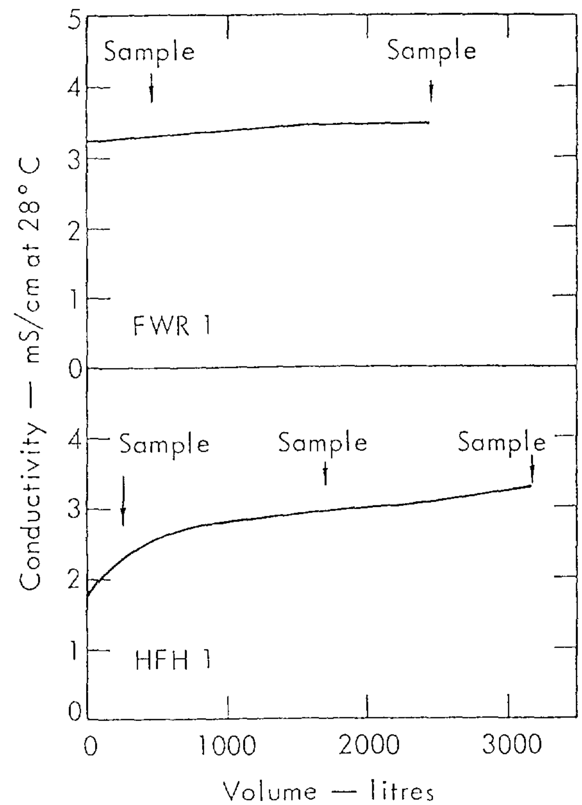

Fig. 3. Inline conductivity vs volume pumped for wells HFH 1 and FWR 1.

Well FWR 3 had been drilled and cased to a depth of 13 m below ground level. No record can be found to indicate why or when this well was established. A salinity profile of the water column (Fig. 4) showed the upper, fresher layer to be approximately 2 m thick. Below it the salinity rapidly increased in almost linear fashion to the bottom. A total of 64 litres was pumped from the surface layer; no change in water conductivity occurred. This well casing must be slotted in some manner

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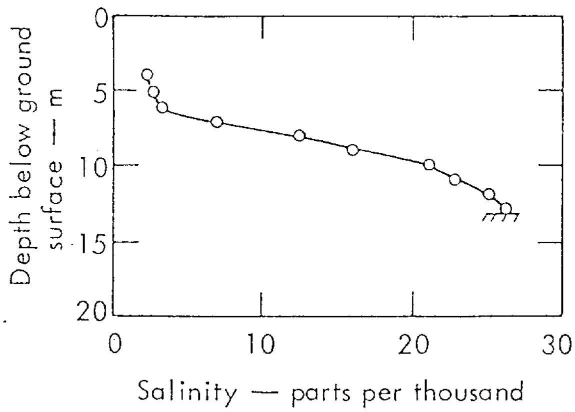

Fig. 4. Salinity profiles of groundwater column at FWR 3.

to permit rapid horizontal recharge. The bottom water, of course, was brackish and smelled very strongly of hydrogen sulfide; it contained a considerable amount of black suspended material of unknown composition.

All of the 15-gal water samples were returned to the Lawrence Livermore Laboratory for processing. (The samples for chemical analysis were sent to Dr. R. Buddemeier at the University of Hawaii.) One separation technique was used to isolate ^{90}Sr, ^{137}Cs, Pu, and other radionuclides from all samples regardless of water salinity. Standardized mixed carrier solutions (containing stable carriers of Cs, Sr, Co, Bi, Sb, rare earths, and either ^{242}Pu or ^{236}Pu and ^{243}Am) were added to the acidified samples. The radionuclides were separated from the water and the suspended samples using a published procedure[6] with some modifications. A complete description of these modifications and our newer separation technique is in press.[7] Precipitation from the water samples with ferric hydroxide or manganese dioxide scavenged any plutonium radionuclides, ^{241}Am, ^{60}Co, ^{207}Bi, ^{125}Sb, or rare-earth radionuclides. This precipitate was then counted on low-level gamma spectrometers for quantitative assay of the latter gamma-emitting radionuclides in the sample.

In 55-litre samples, ^{60}Co, ^{207}Bi, ^{155}Eu, ^{125}Sb, or ^{241}Am were not detected at levels above our lowest detection limits: 0.12, 0.10, 0.15, 0.12, and 0.10 pCi/litre, respectively, for those radionuclides.

The filter samples were dry-ashed and counted on gamma spectrometers; only ^{137}Cs was detected. The other gamma-emitting radionuclides in the particulate phase were below the limits listed above.

The ashed filters were then processed to separate and analyze Pu and ^{90}Sr.

No attempt was made to separate or determine ^{55}Fe or any beta-emitting radionuclides such as ^{147}Pm or ^{151}Sm, which are known to be present in environmental samples from Bikini[8] and Enewetak[9] Atoll.

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Water Quality Standards

The sections that follow give general descriptions of our chemical and radiological results. Before our results could be compared, we needed to define a standard for the freshness of the water. We use, but only as a guide and reference for the reader, the recommended limits of U.S. Public Health Service. The following two paragraphs are quoted from Public Health Service Publication 956.

> (a) The following chemical substance should not be present in a water supply in excess of the listed concentrations when other more suitable supplies are or can be made available:

Chloride	250 mg/l
Nitrate	45 mg/l
Sulfate	250 mg/l
Total dissolved solids	500 mg/l

> (b) The Advisory Committee, in considering limits which should be established for drinking water, recommended limits for only two of the above Ra^{226}, I^{131}, Sr^{90}, Sr^{89} nuclides, Radium-226 (3μμc/l) and Strontium-90 (10μμc/l). Water supplies shall be approved without further consideration of other sources of radioactivity intake of Radium-226 and Strontium-90 when the water contains these substances in amounts not exceeding 3 and 10μμc/l, respectively.[10]

Bikini Island Cistern Water

Unfiltered water samples were collected on June 21, 1975, from the rainwater cisterns connected to Bldgs. 5 and 24 and the school on Bikini Island. The available chemical and radiological data from these samples are given in Table 2.

The data summarized in the table indicate that the water appears to be chemically adequate for drinking purposes, as was anticipated, as well as suitable for any household or agricultural use. Chloride and sulfate concentrations are well below the limits established for drinking water by the U.S. Public Health Service. The total coliform content of the water was not determined.

The measured radionuclides were also low in concentration in these samples. The measured ^{90}Sr concentrations are roughly two to three times the 1974 average concentration of 0.5 pCi/litre in New York City tap water[11] but are equivalent to the average New York City tap water concentrations measured during the peak fallout years of 1963-1966. The

Table 2. Analytical data from cistern water sampled on June 21, 1975, on Bikini Island (Bikini Atoll).

	Chemicals (ppm)							Radionuclides (pCi/litre)[a]		
Bldg.	Cl^-	SO_4	Sr	K	Ca	Na	Mg	^{137}Cs	^{90}Sr	$^{239,240}Pu$
5	35.6	6.4	0.1	8.4	8.5	26.7	2.2	2.5(1)	1.1(11)	7.9×10^{-3} (5)
24	23.1	3.8	0.1	9.1	10.5	19.8	1.3	1.8(2)	1.9(2)	13.7×10^{-3} (4)
School	21.5	0	0.2	6.0	18	16	0.7	1.7(2)	1.42(7)	29.0×10^{-3} (2)

[a] The values in parentheses are the 1-σ counting errors expressed as percentages of the listed values.

present levels are also similar to the 1971-1973 water concentrations in Lake Ontario.[12] These present levels of ^{90}Sr in the Bikini wells are less than 20% of the drinking-water limit of 10 pCi/litre established by the U.S. Public Health Service for domestic supplies and are 0.4% of the FRC limit of 300 pCi/litre. The ^{137}Cs levels are higher than the 1974 tap water concentrations for New York City but are only 0.01% of the maximum permissible concentration of 20 nCi/litre based on FRC guidelines. The average concentration of $^{239,240}Pu$ in the cistern water is less than 0.0003% of the FRC concentration guideline. Interestingly, the average $^{239,240}Pu$ concentration of 17 fCi/litre in the cistern water is greater than the average surface groundwater concentrations at Eneu (9 fCi/litre) but much lower than the average concentration (44 fCi/litre) in Bikini surface groundwater.

Examination of the radionuclide concentrations in the cistern water and comparisons with other data reveal that the largest percentage of the radioactivity in the water must originate, surprisingly, from sources other than worldwide fallout. Consider first that the $^{137}Cs/^{90}Sr$ ratio varies between 0.93 and 2.27 in the three samples. One would expect that fallout depositions of these two radionuclides would be much more uniform over the small areas encompassing the three buildings attached to the cisterns. Shown in Table 3 are the ^{90}Sr concentrations in rainfall at several Pacific islands between 1968 and 1974. When the six-year mean values are plotted as a function of latitude, the interpolated mean quantity of fallout ^{90}Sr expected in rainwater at the latitude of Bikini Atoll is only 0.1 pCi/litre. The cisterns have, on the average, 15 times this concentration. Since the cisterns were constructed after 1969, we can only conclude that fallout ^{90}Sr, and by analogy ^{137}Cs and ^{239,240}Pu, contribute only a small percentage to the levels of those radionuclides found in the cistern samples.

As additional support for this argument, water samples from the drinking water tanks of the L.C.U. support boat R. V. Liktanur used during this expedition to Bikini have been analyzed for ^{137}Cs and ^{239,240}Pu. This drinking water is derived from rainwater catchment systems at Kwajalein Atoll. During October 1975 this fresh water contained 0.6 ± 0.2 fCi/litre ^{239,240}Pu and 90 ± 40 fCi/litre ^{137}Cs. These values are thus representative of the fallout levels in rainfall in the Marshall Islands. The ^{239,240}Pu and ^{137}Cs levels in this water are

Table 3. ^{90}Sr in yearly rainfall (pCi/litre).[a]

Island	1968	1969	1970	1971	1972	1973	1974	Six-year mean
Wake	0.35	0.47	0.44	0.35	0.28	0.07	0.25	0.32
Johnston	.36	.51	.26	.54	.14	.05	.68	.36
Guam	.20	.11	.13	.13	.10	.02	.10	.11
Yap	.12	.07	.11	.07	.05	.008	.07	.071
Truk	.08	.08	.10	.08	.03	.003	.06	.061
Koror	.095	.04	.07	.07	.05	.003	.06	.055
Majuro	.11	.09	.14	.09	.03	.006	.06	.075
Ponape	0.08	0.07	0.09	0.10	0.03	0.008	0.05	0.061

[a]Data from Ref. 11.

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approximately a factor of 20 less than the concentrations in the Bikini cistern water.

This assessment suggests that either the radionuclides are being leached from the concrete of the cisterns (which was locally derived and locally mixed) at some small but finite rate, or that resuspended, airborne, labeled soil particulates which accumulated on the roof drainage surface between rains are subsequently washed into the cisterns.

Eneu and Bikini Groundwater

The available chemical and radiological data for groundwater samples from Eneu and Bikini islands, respectively, are shown in Tables 4 and 5. All groundwater was filtered through a 0.4-μm filter. Thus, the table entry, for example, for ^{137}Cs (Part.), refers to the quantity of ^{137}Cs associated with the particulate material held on a 0.4-μm filter normalized to a litre volume; the ^{137}Cs (Sol.) refers to the quantity that passed through the filter with the water.

It is not the purpose of this study to assess the chemical quality of the groundwater for human consumption but to make our chemical data available to the agency or group responsible for such assessments. We can state, however, that by U.S. Public Health Standards,[10] the groundwater at FWR 2 and FWR 3 on Eneu and at HFH 3 on Bikini would be considered brackish; the water at FWR 4 on Eneu and at HFH 2 and HFH 4 on Bikini appears to be definitely potable; and at FWR 1 on Eneu and HFH 1, HFH 5, and HFH 7, the water is chemically acceptable for household and agricultural purposes, and for drinking if the taste can be tolerated. Recall that the water from HFH 7, considered somewhat brackish by some western standards, has been used for drinking in the past.

The U.S. Public Health Service recommends that drinking water containing Cl, SO_4, and dissolved solids exceeding, respectively, 250, 250, and 500 mg/litre not be used if other less mineralized supplies are available. (However, it should also be emphasized that, according to U.S. Public Health Service data, more than 100 public supplies in the U.S. provide water with more than 2000 mg/litre of dissolved solids.) Newcomers and casual visitors would certainly find these waters almost intolerable, but many of the residents

Table 4. Groundwater data from Eneu Island.

Well	Date drilled	Date sampled	Hour sampled	Concentration (ppm)						
				Cl	SO_4	Sr	K	Ca	Na	Mg
FWR 1	6/23	6/24	0835	553	121	1.6	11.8	66.5	337	64.5
			1250	565	128	1.5	11.3	63.5	339	67.8
FWR 2	6/23	6/24	1430	1820	299	2.2	36	122	995	132
FWR 3S[a]	?	6/22	1330	1420	374	1.4	31	56	325	123
3B[a]				13610	1870	415	263	216	7760	854
FWR 4	?	6/22	1510	30.9	4	0.7	0.2	41.8	14.3	17.1

Well	Hour sampled	Concentration[b]					
		^{137}Cs (pCi/litre)		^{90}Sr (pCi/litre)		^{239}Pu (fCi/litre)	
		Sol.	Part.	Sol.	Part.	Sol.	Part.
FWR 1	0835	35.3(1)	1.17(2)	71 (1)	0.81	3.5(6)	9.5 (10)
	1250	30 (1)	0.73(3)	45.6(1)	0.56	3.3(8)	1.6 (22)
FWR 2		69.1(1)	0.95(3)	66 (2)		23.5(4)	8.4 (17)
FWR 3S[a]		32 (2)	0.59(2)	1.3(13)	0.03	0.72(22)	1.42(16)
3B[a]		20 (3)	0.49(5)	1.0(9)		0.32(30)	1.1 (15)
FWR 4		1.1(5)	0.57(2)	3.4(5)	0.11	0.85(18)	0.67(27)

[a] S = surface; B = bottom.

[b] Sol. = soluble fraction; Part. = particulate fraction. The values in parentheses are the 1-σ counting errors expressed as percentages of the listed values.

Table 5. Groundwater data from Bikini Island.

Well	Date drilled	Date sampled	Hour sampled	Concentration (ppm) Cl	SO$_4$	Sr	K	Ca	Na	Mg
HFH 1	6/17/75	6/21/75	0840	381	109	2.0	23.1	55.5	255	62.5
			1145	489	124	2.0	23.1	63.5	318	74.0
			1545	555	134	2.0	27.0	65.0	357	81.8
HFH 2	6/17/75	6/19/75	1100	6.1	20	1.7	2.5	61.8	42.5	25.8
HFH 3	6/18/75	6/20/75	0850	1390	303	2.2	37.9	84.0	805	124
HFH 4	6/19/75	6/20/75	1100	53.3	60	1.3	9.5	64.8	57.5	79.5
HFH 5	6/18/75	6/19/75	1600	344	124	1.2	18.2	36.7	221	52.3
HFH 7	?	6/20/75	1330	315	77	1.7	12.1	46.0	193	50.8

Well	Hour sampled	Concentration[a] ^{137}Cs (pCi/litre) Sol.	^{137}Cs Part.	^{90}Sr (pCi/litre) Sol.	^{90}Sr Part.	^{239,240}Pu (fCi/litre) Sol.	^{239,240}Pu Part.	Ratio $^{238/239,240}$Pu Sol.
HFH 1	0840	480	9.9	87(1)	1.31	40.0	3.3(13)	0.026(9)
	1145	629	10.9	46(1)	0.57	5.9	1.3(32)	<0.004
	1545	695	15.6	38(1)	0.48	4.7	1.9(21)	<0.004
HFH 2		294	12.0	77	1.37	7.5	71.3(4)	0.04 (35)
HFH 3		335	8.3	227		38.2	8.4(10)	<0.008
HFH 4		226	6.5	260		89	33.6(4)	<0.001
HFH 5		530	8.5	180		25.6	13.4(12)	0.004(60)
HFH 7		250	5.8	1.0		9.8	2.0(22)	0.022(30)

[a] Sol. = soluble fraction; Part. = particulate fraction. The values in parentheses are the 1-σ counting errors expressed as percentages of the listed values.

are able to tolerate if not to enjoy these highly mineralized waters with no ill effects. Hence, if the taste can be tolerated, the water from the chemically acceptable wells could be used for drinking by the Bikinians. However, a recent study[13] has shown that the concentrations of some water components such as SO_4 Na, Ca, and Cl in some U.S. water supplies are close to or within chronic toxicity limits that could lead to weight loss, diarrhea in infants, urinary disease, strong physiological effects, and arthritic conditions in humans. Many of the same chemical constituents measured in the brackish and chemically acceptable wells on Bikini and Eneu are close to the limits defined in Ref. 13.

ENEU ISLAND: RADIONUCLIDES

The radionuclide concentrations vary among the groundwater samples collected from the Eneu locations. The ^{137}Cs, ^{90}Sr, and ^{239,240}Pu concentrations show no obvious correlations with water freshness, and the ^{137}Cs/^{90}Sr ratios in the water show no apparent geographical patterns. At FWR 1, for example, the ^{90}Sr is higher in concentration than ^{137}Cs but is significantly lower than ^{137}Cs in both the surface and bottom water from FWR 3. At FWR 2 the concentrations of the two radionuclides were comparable. Although the levels of both ^{137}Cs and ^{90}Sr are low at FWR 4, the ^{90}Sr concentration exceeded the ^{137}Cs level. In contrast, comparison of the radionuclides in Bikini groundwater shows that the ^{90}Sr was either comparable to the ^{137}Cs or much lower. The two islands differ either with respect to the mechanisms regulating the cycling of these two radionuclides or with respect to the relative inventories of ^{137}Cs and ^{90}Sr in the sources supplying the water reservoirs.

On the average, 2.4% of the total ^{137}Cs was found associated with the particulate material in the Bikini groundwater samples. Except for FWR 4, the fraction is similar to the average fraction at Eneu. At FWR 4, 34% of the ^{137}Cs in the water is associated with particulate material. This unusually high percentage indicates that this water contains unique particulates having a high affinity for ^{137}Cs.

The water at FWR 4 is of high quality, however, and has low levels of radionuclides. The levels of ^{90}Sr and ^{137}Cs are comparable to those in the Bikini cisterns and in U.S. freshwater supplies. The ^{90}Sr level is 34% of the U.S. Public Health Service limit of 10 pCi/litre.

FWR 1 has the next freshest groundwater, but the ^{90}Sr concentrations in the two samples taken at the beginning and end of the continuous pumping experiment exceed the USPHS limit of 10 pCi/litre. The USPHS recommends that

> when the concentration of 10 pCi/l is exceeded, a water supply shall be approved by the certifying authority if surveillance of total intake of radioactivity from all sources indicates that such intakes are within the limits recommended by the Federal Radiation Council for control action.[10]

Therefore before this water is recommended as usable, a complete dose assessment of all pathways must first be completed. Also, because the concentrations in the water may either increase or decrease with time, it must be remembered that regardless of the total assessment, if the water levels are critical to the total dose, the dynamics of the radionuclides in the groundwater must be understood before any realistic long-term dose prediction can be made. The concentrations in the groundwater will depend on the soil burdens, the rates of leaching and groundwater recharge, the groundwater residence time, and other physical, biological, and chemical factors.

The freshness of the water at FWR 4 apparently relates to the geography of the area. The runway probably acts as a large catchment system for rainfall, draining large quantities of fresh water that recharge the groundwater reservoirs around the perimeter. It is quite possible that exploration of the area between FWR 4 and FWR 1 and the area south of FWR 4 along the runway perimeter both to the east and west will uncover quantities of usable groundwater. In a northerly direction from FWR 1, the water tends to be more brackish (see FWR 2 data in Table 4). The only hope of uncovering drinkable groundwater in the northern area would be to chance upon a perched lens.

BIKINI ISLAND: RADIONUCLIDES

The average concentrations of ^{137}Cs, ^{90}Sr, and $^{239,240}Pu$ in the groundwater from the newly established wells on Bikini were much higher than those at Eneu. Interestingly, although the ^{137}Cs and $^{239,240}Pu$ concentrations in the groundwater at the old Bikini well site (HFH 7) were higher than the respective levels at the old Eneu well (FWR 4), the concentration of ^{90}Sr in the soluble fraction from HFH 7 is lower than the level at FWR 4 on Eneu by a factor of 3. Except for HFH 7, the ^{90}Sr groundwater concentrations at the other Bikini locations exceeded the U.S. Public Health Service recommended limit of 10 pCi/litre.

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As at Eneu, the radionuclide concentrations in Bikini surface groundwater samples are variable. Both the ^{90}Sr and $^{239,240}Pu$ are in higher concentration in the groundwater from locations north of the center baseline (HFH 3, HFH 4, HFH 5) than in the waters south of this road. The ^{137}Cs concentrations show no apparent geographical correlation, and none of the radionuclide concentrations appear related to water freshness. Of the newly established wells, we found HFH 4 to have the lowest ^{137}Cs concentration and the highest ^{90}Sr concentration in its water. The last two samples pumped from HFH 1 had the lowest ^{90}Sr concentrations and the highest ^{137}Cs concentrations among the newly established wells. These data might suggest that the concentration of ^{137}Cs is inversely related to the concentration of ^{90}Sr.

During the pumping experiment at HFH 1, the ^{137}Cs groundwater concentrations increased over the day, but both the ^{90}Sr and $^{239,240}Pu$ concentrations were lower in the final samples than in the first sample. These data demonstrate that a single radionuclide should not be used as a universal indicator to describe the temporal variations of other radionuclides in the groundwater reservoirs. Coincident with the radionuclide changes during pumping at HFH 1, the chemical quality of the water also changed slowly over the day. Therefore, we recommend that to assure the best-quality water for any use, withdrawal rates should not exceed 8 litres/min.

The mean ^{137}Cs concentration in the surface groundwaters at Bikini was 430 ± 179 pCi/litre. An additional 2.4% is associated with the particulate phase. The present total ^{137}Cs concentration is, on the average, 2.5% of the recommended FRC concentration guideline for drinking water. In a recent report, Conard[14] shows ^{137}Cs and ^{90}Sr concentrations in well water samples from several Bikini locations for the years 1971, 1972, and 1973. Since no locations or identifications were given with Conard's data, we have averaged both the ^{137}Cs and ^{90}Sr concentrations for each year and have plotted the values, together with our 1975 mean concentrations, as a function of time in Fig. 5. Although the standard deviations during any single year are large, the data strongly indicate that the mean ^{137}Cs groundwater concentrations have declined over the last four years, while the ^{90}Sr concentrations appear to have increased over this same interval. These data demonstrate again the great need for detailed assessment of the mechanisms controlling the cycling of individual radionuclides

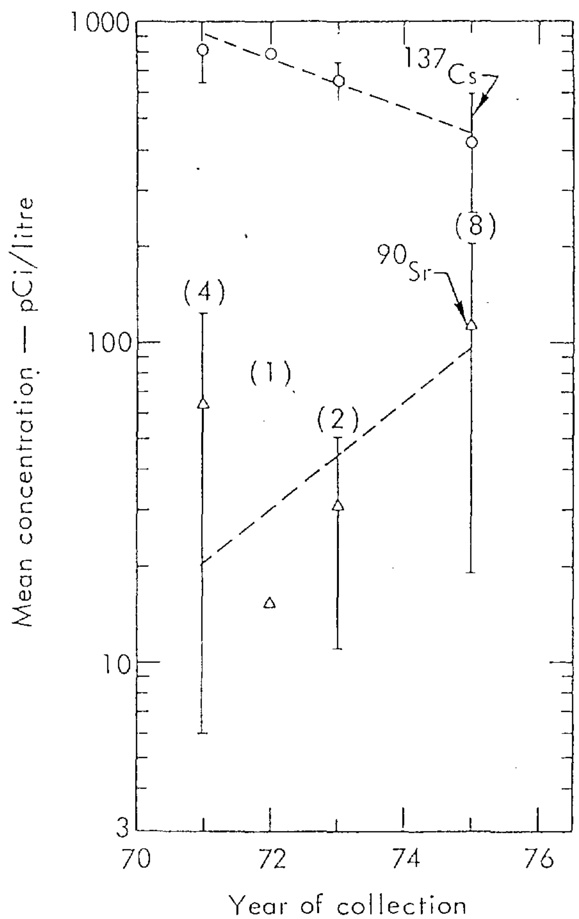

Fig. 5. Changes in groundwater concentrations of ^{137}Cs and ^{90}Sr with time at Bikini Island. Numbers in parentheses are the number of samples analyzed.

in the groundwater reservoirs if the long-term radiological doses to populations using this water are to be properly assessed.

Although there are significant errors associated with the measurement of ^{238}Pu in the water samples, the concentrations of ^{238}Pu are low. The ^{238}Pu concentrations in the soluble fractions average about 1.3% of the ^{239,240}Pu levels. In general, the lowest ^{238}Pu/^{239,240}Pu ratios (averaging 0.004) are found in the groundwater at wells HFH 3, HFH 4, and HFH 5, north of the center baseline road.

From our groundwater studies at Enewetak, we developed a relationship between the mean ^{239,240}Pu concentrations in the surface groundwaters of any island and its median soil inventory. The relationship is

^{239,240}Pu (fCi/litre) in filtered surface groundwater = $(8 \pm 4.9 \times 10^{-3}) \times$ ^{239,240}Pu (mCi/km^2) in the respective island soil column to a depth of 125 cm.

If this relationship is applicable to any Pacific atoll where similar mechanisms are moving plutonium to the groundwater reservoirs, it can be used to predict soil inventories from groundwater data. The mean concentration of ^{239,240}Pu in the soluble fraction in the Bikini groundwater is 27.6 fCi/litre. Using this value and the above relationship, we estimate that the median soil inventory on Bikini Island is $3.5 \pm 1.3 \times 10^3$ mCi/km^2. The mean concentration in the groundwaters at Eneu is 6.4 fCi/litre which, with the above relationship, indicates that the median soil burden on Eneu will be

$0.8 \pm 0.5 \times 10^3$ mCi/km^2. We eagerly await completion of the soil analyses to adequately test the applicability of this model in its present form.

Dose Assessment

The 10-, 30-, 50-, and 70-year integral doses are listed in Table 6 for consumption of Bikini cistern water and in Tables 7 and 8 for consumption of Bikini and Eneu groundwater, respectively. The doses are calculated using an average daily intake of 2 litres of water and using a sum of the average radionuclide concentrations for the soluble and particulate phases listed in Tables 2, 4, and 5. We have further assumed that the only loss of radionuclides from the water is due to radioactive decay. If the water concentrations increase with time relative to the 1975 concentrations or if they decrease more rapidly than assumed from radioactive decay because of more rapid environmental turnover, then the long-term integrated doses would be affected accordingly. Therefore, the dynamics of radionuclide transport in the groundwater reservoirs and the mechanism of nuclide contamination in the cistern water must be understood before final long-term dose evaluations can be made.

As was previously mentioned, we are continuing groundwater studies at Bikini Atoll. Samples collected during January 1977 will indicate whether the present dose assessment based upon observed concentrations in June 1975 is acceptable or whether the 1975 concentrations might have been higher than normal due to possible contamination resulting from the initial drilling operations.

The results for the 30-year integral dose in the tables can be used for comparison and discussion. The whole-body dose for all three water sources is contributed almost entirely by ^{137}Cs. For both cistern and groundwater ^{90}Sr contributes approximately 4 to 5 times more of the bone-marrow dose than ^{137}Cs and both ^{90}Sr and ^{137}Cs are approximately two orders of magnitude more significant than ^{239,240}Pu.

The 30-year integral doses predicted from consumption of Bikini cistern water are 1.7 mrem for the whole body and 11 mrem for the bone marrow. The annual federal guide is 0.5 rem for a member of the population, or 15 rem in 30 years. Therefore, the whole-body and bone-marrow doses resulting from consumption

Table 6. Bikini cistern water integral dose (rem).

Radionuclide	10-yr dose: Whole body	10-yr dose: Bone marrow	10-yr dose: Liver	30-yr dose: Whole body	30-yr dose: Bone marrow	30-yr dose: Liver
^{137}Cs	7.46(-4)[a]	7.46(-4)	7.46(-4)	1.85(-3)	1.85(-3)	1.85(-3)
^{90}Sr	-	3.08(-3)	-	-	9.11(-3)	-
$^{230,240}Pu$	-	6.9 (-6)	5.4 (-6)	-	5.9 (-5)	4.4 (-5)
Total	7.46(-4)	3.83(-3)	7.51(-4)	1.85(-3)	1.10(-2)	1.89(-3)
	50-yr dose			**70-yr dose**		
^{137}Cs	2.55(-3)	2.55(-3)	2.55(-3)	2.98(-3)	2.98(-3)	2.98(-3)
^{90}Sr	-	1.29(-2)	-	-	1.52(-2)	-
$^{230,240}Pu$	-	1.6 (-4)	1.1 (-4)	-	2.97(-4)	1.94(-4)
Total	2.55(-3)	1.56(-2)	2.66(-3)	2.98(-3)	1.85(-2)	3.17(-3)

[a] Numbers in parentheses refer to exponents, e.g., 7.46×10^{-4}.

of Bikini cistern water are 0.012% and 0.073% of the equivalent 30-year federal guide (see Table 9).

The doses resulting from consumption of groundwater at Bikini and Eneu are significantly higher than those from consumption of cistern water (see Table 9). The 30-year doses resulting from consumption of Eneu groundwaters are 29 mrem and 220 mrem for the whole body and the bone marrow, respectively. The bone-marrow dose is about 1.5% of the 30-year federal guide. Consumption of Bikini groundwater, however, leads to predicted 30-year doses of 0.41 rem and 1.1 rem for the whole body and bone marrow. A percentage this high resulting from one pathway is sufficient to warrant a careful assessment of the potential exposure through other pathways.

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Table 7. Bikini groundwater integral dose (rem).

	10-yr dose			30-yr dose		
Radionuclide	Whole body	Bone marrow	Liver	Whole body	Bone marrow	Liver
^{137}Cs	0.164	0.164	0.164	0.407	0.407	0.407
^{90}Sr	–	0.241	–	–	0.73	–
$^{239,240}Pu$	–	1.13(-5)[a]	8.82(-6)	–	9.71(-5)	7.12(-5)
Total	0.164	0.405	0.164	0.407	1.12	0.407
	50-yr dose			70-yr dose		
^{137}Cs	0.560	0.560	0.560	0.656	0.656	0.656
^{90}Sr	0	1.01	–	–	1.19	–
$^{239,240}Pu$	–	2.58(-4)	1.78(-4)	–	4.84(-4)	3.17(-4)
Total	0.560	1.57	0.560	0.656	1.85	0.656

[a] Numbers in parentheses refer to exponents, e.g., 1.13×10^{-5}.

Table 8. Eneu groundwater integral dose (rem).

Radionuclide	10-yr dose			30-yr dose		
	Whole body	Bone marrow	Liver	Whole body	Bone marrow	Liver
^{137}Cs	1.17(-2)[a]	1.17(-2)	1.17(-2)	2.90(-2)	2.90(-2)	2.90(-2)
^{90}Sr	-	6.57(-2)	-	-	0.195	-
$^{239,240}Pu$	-	2.20(-6)	1.72(-6)	-	1.89(-5)	1.38(-5)
Total	1.17(-2)	7.74(-2)	1.17(-2)	2.90(-2)	0.224	2.90(-2)
	50-yr dose			70-yr dose		
^{137}Cs	3.98(-2)	3.98(-2)	3.98(-2)	4.67(-2)	4.67(-2)	4.67(-2)
^{90}Sr	-	0.276	-	-	0.325	-
$^{239,240}Pu$	-	5.02(-5)	3.47(-5)	-	9.43(-5)	6.17(-5)
Total	3.98(-2)	0.316	3.99(-2)	4.67(-2)	0.372	4.68(-2)

[a] Numbers in parentheses refer to exponents, e.g., 1.17×10^{-2}.

Table 9. Comparison of doses from cistern and groundwater sources to federal guides.

Water source	Integral 30-yr dose (rem)		Annual federal guide[a] times 30-yr dose for whole body and bone marrow	Percent of 30-yr guide	
	Whole body	Bone marrow		Whole body	Bone marrow
Bikini cistern	1.9 (-3)[b]	1.1 (-2)	15 rem	0.12	0.73
Bikini ground	0.41	1.1	15 rem	2.7	7.3
Eneu ground	2.9 (-2)	0.22	15 rem	0.19	1.5

[a] Annual federal guide for a member of the population is 0.5 rem for whole body and bone marrow.

[b] Numbers in parentheses refer to exponents, e.g., 1.9×10^{-3}.

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