17 May 1973

SUGGESTIONS FOR INCLUSION IN THE ENVIRONMENTAL IMPACT STATEMENT FOR THE ENIWETOK ATOLL CLEANUP

R. B. Leachman

3.f. The U. S. Development of the Islands for Nuclear Testing

The testing of nuclear detonation requires testing grounds that, among other factors, are remote from populated areas. Previously, two tests had been conducted at Bikini Atoll in June and July 1946 under Operation Crossroads and, earlier, near Alamogordo, New Mexico on 16 July 1945 as Operation Trinity. However, for a continuing program of testing, Bikini suffered deficiencies in that the land areas were neither large enough nor properly oriented to the prevailing winds to permit construction of a major airstrip.[1] This led to the selection of Eniwetok Atoll for testing nuclear detonations, a selection administratively approved by President Truman on 2 December 1947.

The selection of Eniwetok Atoll was based on a study of possible ocean sites made by Captain J. S. Russell, USN, Deputy Director of the Division of Military Applications, and by Dr. Darol K. Froman of the Los Alamos Scientific Laboratory. In regard to possible fallout, Eniwetok Atoll was well located by having hundreds of miles of open sea lying from the Atoll in the westwardly direction of the prevailing winds.

1. N. O. Hines, Proving Ground (U. of Washington Press, Seattle, 1962) p 81.

The first of the groups assembled to conduct nuclear weapons tests on Eniwetok Atoll organizationally came into being on 18 October 1947. Called Joint Task Force Seven, the group was composed of personnel from many U.S. governmental Agencies.[2] Not having significant ground facilities on Eniwetok Atoll, the Task Force Seven operated from their many surface ships. Three nuclear detonations were made in this Operation Sandstone, which occurred during April and May in 1948.[3] The detonations were on 200 ft. towers in the lagoon; the first off Engebi, the second off Aemon, and the third off Runit. The largest yield was the second with a yield of 49 kilotons.[4,5] This kiloton terminology means that the explosive energy of the nuclear detonation equals 49 thousand tons of high explosive. (For these and following tests, table at the end of this section gives the test name, date, time, location, height of burst, position (airdrop, barge, ground surface, or underwater) of nuclear explosive and yield).

In preparation for the next series of nuclear tests, the Atomic Energy Commission in mid-1949 decided to facilitate further testing by improving ground-based structures and by providing more adequate technical facilities at Eniwetok Atoll.[5] This work was based on a survey submitted by Holmes and Narver, Inc., on 7 January 1949. The Commission approved the recommendation for construction in April 1949, and the contract was signed in June.[6]

2. Reference 1, p 85.
3. Reference 1, p 86.
4. Samuel Glasstone, The Effects of Nuclear Weapons, Department of the Army Pamphlet No. 39-3 (February 1964), and Mary A. Edwards, "Tabulation of Data on Announced Nuclear Detonations by All Nations through 1965," Report UCRL-14786, 17 March 1966 (Available from clearing house for Federal Scientific & Tech Info, Springfield, Va.)
5. Reference 1, p 87.
6. Reference 1, pp 113, 115

On 31 January 1950, President Truman made public the decision to develop a thermonuclear bomb, a decision which, of course, was to have great impact on Eniwetok Atoll. Tests of weapons with such large increases in yield and fallout radiation are not suitable for the continental United States, but are better suited for the remoteness of the Pacific Proving Ground. To facilitate tests of devices that at first were limited to the 20-kiloton nominal yield of the Hiroshima weapon, the Nevada Proving Ground, near Las Vegas, Nevada, was additionally established in the autumn of 1950. The first tests there were in a 1951 series starting on 27 January.

The Eniwetok Atoll test series also planned for 1951 was designated as Operation Greenhouse and included, among other tests, activities related to thermonuclear research, but not yet involving a full thermonuclear explosion. Between 7 April and 24 May 1951, four tests from towers were conducted at Eniwetok, with the second one called Easy announced as 47 kiloton yield.[4,7]

A full thermonuclear explosion was achieved the following year in the 1952 test series Operation Ivy at Eniwetok Atoll,[4,8] This involved only two tests, but the first had considerable significance and consequence. The first was Test Mike, the first thermonuclear detonation and a ground level explosion amounting to 10.4 megatons (equivalent of 10.4 million tons of high explosive) on 31 October 1952 on a small island, Elugelab (Eluklapin in Marshallese, and Flora by the U.S. code name), at the north end of the Atoll. Being a surface explosion and having this large yield, Test Mike actually removed this small island from the Atoll chain. A large reinforced concrete building built on the nearby large island of Engebi to test effects of pressure was partly damaged. The second test of

7. Reference 1, p 125.
8. Reference 1, p 135.

Operation Ivy was a "high yield" explosion, Test King from an air drop north of the northwest tip of Runit Island.

Associated with the greater yield of Mike, which was dozens of times greater than previously experienced yields, was a corresponding increase in the fallout radiation. Contrary to the usual direction and contrary to expectations, the winds prevailing at the time were from the south or southeast,[9] and so most of the radioactive debris fell on the open seas to the north and northwest. Nevertheless, local fallout did occur on the northern islands of the Atoll. Since these islands continued to be uninhabited, no harm resulted to humans from this local fallout.

U.S. tests were conducted only at the Nevada Proving Grounds in 1953, thereupon starting the pattern of tests entirely at the Nevada Proving Grounds or the Pacific Proving Grounds, each on alternate years. The next series of tests in the Pacific was in 1954 under the name Operation Castle.. It involved a task force, which retained the number Task Force Seven of the 1947 force. Five out of the six tests in this series were at Bikini Atoll, which had not been used for nuclear tests since 1946, and one of these had consequences affecting all testing in the Pacific. The 15-megaton thermonuclear tests Bravo in this series was conducted on the surface in Bikini Atoll on 28 February 1954.[4,10]

The radioactivity of this Bravo event was particularly troublesome by unexpectedly being carried to the east, rather than to the north as had been foreseen. Harmful amounts of radioactivity fell out on the inhabited atolls of Rongelap, Ailinginae, and Rongerik and on the Japanese fishing ship (Lucky Dragon). These events resulted in sharply renewed interest in radiological consequences, with principal focus on the Bikini series of tests. The Atomic Bomb Casualty Commission which had been established after the atomic bombing of Japan, became involved. The Shunkotsu Maru of the Japanese

9. Melvin P. Klein, "Fall-Out Gamma Ray Intensity" Lawrence Livermore Laboratory Report, UCRL-5125, (1958)
10. Reference 1, p 165.

Fisheries Training Institute cruised the Marshall Island area for survey purposes; this was followed by a U.S. cruise on the Coast Guard Cutter Roger B. Taney under the name Operation Troll.[11]

Operation Castle continued with other tests at Bikini Atoll, but with an enlarged exclusion of the oceanic areas of possible fallout. The only detonation of Operation Castle made in Eniwetok Atoll was the Nectar shot, detonated on 14 May 1954 on a barge in the lagoon over the Mike crater.

By 1954 the large island of Engebi (Janet in the U.S. code name) had become a barren, sandy island from which the coconut palms and other trees had long since disappeared. This major island of 291 acres had been subjected to World War II bombardment and, by 1954, to four series of nuclear weapons tests. The nuclear explosions produced blast and irradiated the island by initial radiation from nuclear detonations and by residual radiation of fallout. Nevertheless, colonies of rats continued to thrive on this isolated island in 1955[12] even though casualties resulted from the tests.

The 1956 series of tests in the Pacific Proving Ground was called Operation Redwing. These took place at both Bikini and Eniwetok Atolls, with eleven at Eniwetok Atoll. Part of Bokou Island (Irene in the U.S. code name) was removed on 6 June 1956 by test Seminole, which was positioned on the land surface. This Seminole crater is on the east side of the remainder of Bokou Island. The other surface test in Operation Redwing was Test Lacrosse, which formed a crater at the Northern tip of Runit Island (Yvonne is the U.S. code name) in the tide lands on the ocean side of the island.

11. John H. Harley, "Operation Troll," AEC report NYO-4656 (1956).
12. Reference 1, p 207.

Early in 1958 a moratorium against further testing of nuclear explosions was under consideration, partly in response to international awareness about the world-wide fallout of radioactivity from nuclear tests by the several nuclear nations. Before the moratorium, however, an intensive series of tests called Operation Hardtack was conducted. Operation Hardtack took place in 1958 both at Eniwetok Atoll as Phase I and at the Nevada Proving Grounds as Phase II, thereby breaking the pattern of alternate testing years at the sites.

Between 5 May and 26 July 1958, twenty-two tests were conducted at Eniwetok under Operation Hardtack, Phase I. This one intense period of testing thereby constituted over half of the 43 total tests conducted at the Atoll over the entire ten years of testing. Following Operation Hardtack, the U.S. moratorium on testing started on 31 October 1958 and was followed in a few days by a U.S.S.R. moratorium. This marked the end of all nuclear tests at Eniwetok. The intervening 15 years until the present time have allowed some natural restoration of vegetation on affected islands and have provided the time for a tremendous decrease in the residual radioactivity resulting from the tests.

Two islands were altered in this Operation Hardtack, Phase I. The test Koa was a surface explosion on the small island Dridrilbwij (Gene by the U.S. code name). This test removed the island from the Atoll. The other was Test Cactus at the northwest tip of Runit Island (Yvonne by the U.S. code name). This produced a crater nearby and to the Southwest of the La Crosse crater.

Further tests did occur in the Pacific, but they were in the vicinity of Johnston Island and Christmas Island,[4] so far to the east that there was no effect upon Eniwetok Atoll. These tests followed the 1 September 1961 announcement by the USSR of its intention to resume nuclear testing. The USSR tests occurred within days of this announcement. Many months later the United States started testing under a series called Operation Dominic, but, as just stated, not at Eniwetok Atoll. This test series was completed by the end of 1962 and was followed by the Limted Test Ban Treaty, which was signed in September 1963. This Treaty permitted only those tests that did not result in radiation going beyond the national boundaries, and so effectively limited tests to being underground. Although underground tests have been conducted in the continental United States and at Amchitka in Alaska, none have been conducted at Eniwetok Atoll.

In these test series, a total of 43 nuclear detonations or attempts at nuclear detonations have been made at Eniwetok Atoll. The number of tests either on individual islands or closest to these islands is as follows for the total of 43 tests at Eniwetok Atoll:

		Island Name		
Number of Tests	Board of Geo. Name	Marshallese	Other	US Code Name
18	Runit	Runit		Yvonne
10	Enjebi	Enjebi		Janet
4		Eluklap	Elugelab	Flora*
3	Aomon	Aomon	Aranit	Sally
2	Eberiru	Aleleron		Ruby
1**	Bogallua	Bokoluo		Alice
1		Dridrilbwiu		Gene***
1	Bogeirik	Bokaidrik		Helen
1	Rujiyoru	Lujor		Pearl
1	Buganegan	Mut	Miu	Henry
1	Bogan	Bokon	Pokon	Irwin

*This island no longer exists. It was removed by test Mike on 1 Nov 52.
**Actually located on the coral reef to the southwest of this island.
***This island no longer exists. It was removed by test Koa on 23 May 58. The underwater craters from Mike and Koa overlap each other.

The positioning of 35 of these nuclear explosives before detonation follows:

Positioning	Number of Tests
Barge	17
Tower	9
Land Surface	5
Air Drop	2
Underwater	2

Of course, land surface tests were the most destructive to the physical condition of the islands by producing still-existing craters or by removing an island entirely. All barge tests were offshore on the lagoon side, usually off the islands of Runit (Yvonne) and Enjebi (Janet). Being generally west of these islands, the tests produced radioactivity that the prevailing winds from the northeast generally carried away from the island and over the lagoon.

In either the case of a successful nuclear detonation or the case of an unsuccessful nuclear detonation, a spread of radioactivity results in addition to physical damage to the land, vegetation, and animals. In the case of a successful detonation, the following principal radioactive results are:

1. fission products resulting from the fission of the uranium or plutonium used for the nuclear explosive, with significant fission products being cesium-137 and strontiom-90. (Their 30- and 29-year half lives, respectively, roughly correspond to human lifetimes, so they do not decay appreciably in an acceptable waiting period, nor do they decay sufficiently slowly to result in a low amount of radioactivity.

2. cobolt-60, largely from activity induced in iron used for towers, etc., in the tests. (its 5-year lifetime makes waiting times for decay more acceptable).
3. various isotopes of plutonium produced from the capture of neutrons by uranium in the nuclear detonation.
4. The unconsumed plutonium and/or uranium used for the nuclear explosive but not having undergone fission. (When nuclear explosives misfire (or undergo "one-point" safety tests), the chemical-type high explosive used for assembling these nuclear components instead spreads them).
5. Tritium induced in water by neutrons and from thermonuclear reactions. (However, the mobility of the water in the ocean quickly dissipates this hazard.)

Misfires, near misfires (low yield), or "one-point" safety tests of nuclear explosives result in a spread of radioactivity, as mentioned in Item 4. In these misfire cases, the residual uranium or plutonium is deposited over a much smaller area than for the case of the spread from a nuclear explosive (perhaps square yards of spread in the former case, but worldwide or at least square miles in latter). A particular concern in these cases is the spread of plutonium-239; the lower radiological hazard of uranium-235 causes very much less of a radiological concern when used as the nuclear material. This plutonium concern is complicated by its long 24-thousand year half life for decay, which is far too long to enable nuclear decay over time to eliminate the hazard.

Just such difficulties of plutonium contamination have occurred around Runit Island. For example, the test Scaevola in Operation Hardtack I was a one-point safety test. Therefore, it was planned only to explode by high explosive but not by a nuclear explosion. Local spreads of plutonium exist near the middle of this long, narrow island.

NUCLEAR DETONATIONS AT ENIWETOK ATOLL

NAME	DATE (GCT)	TIME (GCT)	HEIGHT OF BURST (FEET)	TYPE OF BURST	GEOGRAPHICAL COORDINATES NORTH LAT	GEOGRAPHICAL COORDINATES EAST LONG	YIELD	REMARKS
SANDSTONE								
X-ray	14/4/48	1817	200	Tower	11°40'	162° 14'	37 kT	
Yoke	30/4/48	1809	200	Tower	11°37'	162° 19'	49 kT	
Zebra	14/5/48	1804	200	Tower	11°33'	162° 21'	18 kT	
GREENHOUSE								
Dog	7/4/51	1834	300	Tower	11°33'21"	162°21'16"		
Easy	20/4/51	1827	300	Tower	11°40'08"	162°14'25"	47 kT	
George	8/5/51	2130	200	Tower	11°37'37"	162°18'53"		
Item	24/5/51	1817	200	Tower	11°40'23"	162°14'55"		
IVY								
Mike	31/10/52	1915		Surface	11°40'14"	162°11'47"	10.4 MT	Experimental Thermonuclear Device
King	15/11/52	2330	1,480	Air Drop	11°33'44"	162°21'09"	High Yield	
CASTLE								
Nectar	13/5/54	1820		Barge	11°40'14"	162°11'47"		
REDWING								
Lacrosse	4/5/56	1825		Land Surface	11°33'28"	162°21'18"	40 kT	
Zuni	27/5/56	1756		Surface	11°37'24"	162°19'13"		
Erie	30/5/56	1815	300	Tower	11°32'40"	162°21'52"		
Seminole	6/6/56	0055		Land Surface	11°40'35"	162°13'02"	12 kT	
Blackfoot	11/6/56	1826	200	Tower	11°33'04"	162°21'31"		
Kickapoo	13/6/56	2326			11°37'41"	162°19'32"		
Osage	11/6/56	0114	680	Air Drop	11°32'48	162°21'39"		
Inca	21/6/56	2156			11°37'53"	162°18'04"		
Mohawk	2/7/56	1806			11°37'39"	162°18'49"		
Apache	8/7/56	1806		Barge	11°40'17"	162°12'01"		
Huron	21/7/56	1816		Barge	11°40'19"	162°12'09"		
HARDTACK, PHASE I								
Cactus	5/5/58	1815		Land Surface	11°33'23"	162°21'15"	18 kT	
Butternut	11/5/58	1815		Barge	11°32'28"	162°21'02"		
Koa	12/5/58	1830		Land Surface	11°40'30"	162°12'20'	1.37 MT	
Wahoo	16/5/58	0130	-500	Underwater	11°20'41"	162°10'44"		
Holly	20/5/58	1830		Barge	11°32'38"	162°21'22"		

NAME	DATE (GCT)	TIME (GCT)	HEIGHT OF BURST (FEET)	TYPE OF BURST	GEOGRAPHICAL COORDINATES NORTH LAT	GEOGRAPHICAL COORDINATES EAST LONG	YIELD	REMARKS
HARDTACK, PHASE I CONTINUED								
Yellowwood	26/5/58	0200		Barge	11°39'37"	162°13'31"		
Magnolia	26/5/58	1800		Barge	11°32'34"	162°21'14"		
Tobacco	30/5/58	0215		Barge	11°39'48"	162°13'48"		
Rose	2/6/58	1845		Barge	11°32'28"	162°21'06"		
Umbrella	8/6/58	2315	-150	Underwater	11°22'51"	162°13'09"		
Walnut	14/6/58	1830		Barge	11°39'37"	162°13'31"		
Linden	18/6/58	0300		Barge	11°32'39"	162°21'23"		
Elder	27/6/58	1830		Barge	11°39'48"	162°13'48"		
Oak	28/6/58	1930		Barge	11°36'28"	162°06'28"	8.9MT	
Sequoia	1/7/58	1830		Barge	11°32'39"	162°21'23"		
Dogwood	5/7/58	1830		Barge	11°39'48"	162°13'48"		
Scaevola	14/7/58	0400			11°32'39"	162°21'23"		One-Point Saf Test
Pisonia	17/7/58	2300			11°32'	162°21'		
Oliver	22/7/58	2030		Barge	11°39'48"	162°13'48"		
Pine	26/7/58	2030		Barge	11°39'22"	162°13'11"		
Quince	6/8/58	0215			11°32'59"	162°21'34"		
Fig	18/8/58	0400			11°32'59"	162°21'34"		

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3g Present Condition of Islands - Results of Radiological Survey

R. B. Leachman
Defense Nuclear Agency

Introduction

The radioactivity on Eniwetok Atoll results almost entirely from the nuclear explosions at the Atoll from 1948 until 1958. Some radioactivity results from fallout from nuclear explosion tests conducted elsewhere in the atmosphere, but this is probably insignificant compared to radioactivity produced by tests on Eniwetok Atoll. The minimum radioactivity observed on any island on Eniwetok Atoll in 1973 was more than an order of magnitude greater than that of world-wide fallout and of local natural radioactivity from cosmic rays and minerals. (Beir, 1972) Although the southern islands were the scene of only two underwater tests off Henry, an island downwind from most other southern islands, this low residual activity on the southern islands of Eniwetok Atoll are thus seen to result almost entirely from local fallout from tests conducted at Eniwetok Atoll.

Only after many decades, and in some places only after centuries, will the local radioactive debris from these tests undergo natural nuclear decay to the extent that the remaining radioactivity is as low as the radioactivity from natural causes, principally cosmic rays at this location. For the case of the plutonium-239 residual, actually many, many millennia would correspondingly be required. Of course,

our purpose is to consider what is involved, both in dollar cost and in further environmental insult to the islands, for a man-made cleanup to lower the residual radiological exposures presently existing in the islands to exposures that are commonly encountered elsewhere in the world in normal human activities that span lifetimes.

Radioactive Isotopes of Concern

The principal concerns existing radiologically at Eniwetok Atoll are presently:

- Cesium-137, a 30-year half-life isotope that is a fission product. When present in the top few centimeters of soil, its gamma rays externally result in whole-body exposures for inhabitants. Of less importance is the fact that when present on the top surface of soil its beta rays externally result in skin exposures. Being chemically similar to potassium, cesium-137 deposits in the muscle of the entire boyd upon entry to the human body via the food chain; the consequent health hazard is then principally the risk of inducing cancer.
- Strontium-90, a 29-year half-life isotope that is a fission product. Not being a gamma ray emitter, it externally provides only a beta ray exposure to the skin when present as deposits on the top surface of the ground. Being chemically similar to calcium, it deposits in the bone upon entry to the human body via the food chain; the consequent health hazard is then principally the risk of inducing leukemia.

• Plutonium-239, a 24,000 year half-life isotope that is either unconsumed remains from the plutonium-239 composition of the nuclear explosives or is formed by capture of a neutron into uranium-238 nuclei (followed later by two beta-particle decays completing the transmutation to plutonium-239) during the instant of the nuclear explosion. Being principally an emitter of alpha particles, which are very lightly penetrating, plutonium-239 is of very reduced concern regarding external exposures. The concern is instead in regard to internal exposure, principally to the lung following retention upon breathing the dust; the subsequent hazard is risk of cancer formation. (Retention of plutonium-239 via the food chain is of very reduced concern.)

Other radioactive isotopes exist on the Atoll as a result of the various test series, but the health hazards they produce are insignificant compared to cesium-137, strontium-90, and plutonium-239 and furthermore are insignificant on the bases of any of the several existing guidelines for safe radiological conditions for the general public. These less important isotopes resulted from the following processes during the tests:

• Other fission product isotopes resulting from nuclear explosions.

• Isotopes resulting from capture of neutrons by other materials nearby the nuclear explosive during the instant of explosion, for example iron-55 from neutron capture iron in towers, barges, and containers of the nuclear explosive and carbon-14 from neutron capture in carbon found in the natural surroundings.

• Other radioactive nuclear explosives that were unconsumed in the nuclear explosion, for example uranium-235.

Fallout Composition

The physical dimensions and the chemical composition of these radioactive particles from the tests (Freiling, 1965) depend upon where the nuclear explosion occurred. In particular, the composition differs if the test was over land compared to tests either over water or under water (Glasstone, 1964, and Heft, 1970). The fireballs from nuclear explosions over ground suck up vast quantities of soil and other materials. Due to the high temperature, these rise as a vapor in the fireball and cloud. The fission products are initially also vapors and these condense onto both solid and molten soil particles resulting from cooling and condensing. During the cooling, the more refractory (higher vaporization temperature) materials condense first. For example, fission products that are gaseous or have gaseous progenitors, or precursors, (parent element before beta-particle decay transmutation into a daughter element) adhere or are incorporated last to the fallout particles during these processes.

In general, this selective attachment of radioactive atoms to fallout material is called "fractionation." The occurrence of fractionation is shown, for example, by the fact that in a land surface burst the larger particles, which fall out of the cloud at early times and are found near ground zero, have radiological properties different from the smaller particles that leave the radioactive cloud at later

times and reach the ground some distance downwind. These more distant particles tend to have more cesium (daughter of gaseous xenon) and strontium (daughter of gaseous krypton) relative to other fission product activities than do the heavier, and thus nearby, particles. Thus, the rather few surface explosions at Eniwetok Atoll tended through fractionation to result in the amounts of cesium-137 and strontium-90 deposited on the test island and nearby islands being less relative to other fission products than the amounts produced by fission in the nuclear explosion.

An example of this fractionation is provided by analyses of the particles in the cloud from the La Crosse test (Nathans, 1970). La Crosse was a coral surface burst of about 40 kilotons on Runit Island. The sample of the radioactive cloud was collected at 6500 meters at 2.6 hours after the event. The specific activity (the radioactive disentegrations per unit time and per unit weight of the particle) was found to increase with decreasing particle size by the following factors when the largest particle of 50-microns diameter is compared with a smaller 9-micron diameter particle. (Little variation was found in specific activities between the smaller particle sizes ranging between 0.5 and 13 microns.)

Radionuclide	$\frac{\text{Specific Activity for 9 microns}}{\text{Specific Activity for 50 microns}}$
strontium-90	296
promethium-147	229
uranium	0.47

Both promethium (and its progenitors) and uranium have higher temperatures of condensation than the case for strontium and its progenitors. Thus, the fractionation observed for strontium and uranium are understandable, while promethium might be an example of one sample not being representative.

The radioactivity of interest at Eniwetok Atoll is, however, primarily local fallout rather than the cloud properties detailed above. The local fallout is largely from larger particles. A semiempirical model (Freiling, 1970) for land-surface explosions takes this into account in predicting the local fallout compared to world-wide and intermediate-distance fallout. (The local fraction is considered to be from particles greater than 50-microns in diameter, the intermediate fraction from 25- to 50-microns particles, and the world-wide fraction from less than 25-micron particles.) The percentage of the total radioactivity of a particular radionuclude that deposits in local fallout from these land surface bursts is estimated to be

Radionuclides	Percentage in Local Fallout
cesium-137 and strontium-89	10
strontium-90	15
barium-140 and lanthanum-140	25
tellerium-132	25
zincronium-90, niobium-89, molybdium-99 and plutonium-239	65

On the other hand, fractionation is usually much less from large explosions at or near the surface of the sea. In these cases, the condensed particles are sea-water salts and water. Condensation is late because cooling to 100°C or less is required for condensation, and even then the small size of the droplets allows escape of the radioactive gases. Much less variation then occurs in the composition of the radioactive fallout as a function of distance from these explosions near water. Thus, the most frequent form of testing at Eniwetok Atoll by means of surface barges in the lagoon just off islands tended not to result in depletion of particular fission products in the fallout on the local Eniwetok Islands. In particular, cesium-137 and strontium-90 are expected to be depleted much less in these local fallouts from tests over or under water compared to tests at the land surface.

An example of this reduction in fractionation for barge tests is provided by samples of the radioactive cloud from the Tewa test at Bikini Atoll. Tewa was 5 megatons, and the sample analyzed was taken at 16,000 meters at 2.2 hours after the event (Nathans, 1970).

Radionuclide	Specific Activity for 8.2 microns / Specific Activity for 41 microns
strontium-90	11
promethium-147	13
uranium	5

Leaving aside the dependence of fractionation upon particle size, an analysis has been made of fractionation for all particle sizes. (Freiling, 1961). These results also show relatively little strontium-90 and cesium-137 in the particles, consistent with the arguments above.

In fact, this study shows a definite relation between a radionuclide retention that increases (a fractionation that decreases) with increasing fraction of the time that the progenator, or precursor, elements are refractory, i.e., fraction of the time they are not halogens, rare gases, alkali metals, or tellurium. These results involving all particle sizes are shown qualitatively to apply for several test conditions including coral surface bursts and shallow-water surface bursts. However, we emphasize that for Eniwetok the local fallout is of interest rather than these overall conditions for both local and remote fallout.

The percentage of the total radioactivity of the explosion residues from all radionuclides that is present in the early fallout is called the "early fallout fraction" and produces residual radioactivity on islands and lagoon of the Atoll. For water surface explosions, the value is in the neighborhood of 30 percent. However, for land surface explosions the "early fraction fallout" is higher, with estimates ranging from 50 to 70 percent. Variations in environmental and meteorological conditions would result in variations in these fractions of local fallout (Glasstone, 1964, p. 437).

We now consider the composition of fallout particles from surface explosions on the coral of the Atoll. Fresh coral debris is largely CaO and $Ca(OH)_2$ (Crocker, et al., 1965) The calcium oxide particles from the surface have different radiological and structural properties depending on whether or not they were melted in the fireball from the nuclear explosion (Lowman, 1960, p. 107).

Unmelted calcium oxide particles can logically be expected not to have been in the hotter portions of the fireball. They then retain both their irregular shape and their porous structure. Fractionation effects result in relatively more of the radionuclides that are volatile or whose progenators are volatile depositing on these cooler, and consequently unmelted, particles than on the hotter melted particles.

On the other hand the spherical particles of calcium oxide are formed from melted calcium oxide in the hotter portions of the fireball. These then lose the porous structure of unmelted particles, with the result that hydration in the particles of melted origin proceeds at a much slower rate. These spherical particles can logically be expected to contain more radioactive debris of both structural material and fission products since more of these vapors would have been in contact with the molten calcium oxide.

Particle Sizes

Fallout particles range in size from particles smaller than fine sand, i.e., approximately 100 microns in diameter, in the more distant portions of the fallout area to pieces about the size of marbles, i.e., roughly 1 cm in diameter, close to the point of the explosion, (Glasstone, 1964, p. 41). For ground surface bursts, the distribution in the size of the fallout particles is lognormal (normal or Gaussian distribution law with the logarithm of the particle diameter as the variable) with mass medians in the order of 100 microns and with logarithmic standard

deviations of 1.68 to 1.98 (Nathans, Thews, and Russell, 1970). With the larger particles thus deposited as local fallout, smaller particles remain in the cloud. One cloud 1.5 hours after a megaton range of explosion at the surface of a coral island was found to have a particle size distribution made up of two lognormal functions, the larger particle group being dominant in abundance. Ninty-one percent of the particles were in the larger group, which was centered around 37 microns in diameter, and nine percent were in the smaller group centered around 2.9 microns in diameter (Heft, 1970, p. 264).

The Bravo test at Bikini Atoll in 1954 produced fallout whose size and composition was studied (Suito, 1956). The test was a 15-megaton surface explosion. The fallout on the Japanese fishing vessel Fukuru Maru consisted of calcite granules of approximately 300-microns in diameter with sizes ranging mostly between 100 and 400 microns.

As is expected, for subsurface bursts the particle sizes of local fallout are again found to be larger than the particle sizes of the cloud. This was true even for one particular measurement for which the cloud was sampled at the early time of only 15 minutes after the nuclear explosion. Again, lognormal distribtuions of sizes were observed, the dominant part of the distribution in the early cloud centered around 18-micron diameter. In contrast, the local fallout particles centered around 290-micron diameter (Heft, 1970, p. 271).

For nuclear explosions in the air, the cloud does not contain surface materials. Essentially all particles then consist of metal

oxide spheres produced from vapor condensation of structural material used to make the nuclear explosive (Crocker, et al., 1965. Radionuclides of refractory elements tend to be in the larger particles, while radionuclides of volatile elements tend to be the smaller particles. The particles tend to be of submicron size, and so even local fallout is similar in composition to worldwide fallout from any tests (Heft, 1970, p. 274).

Weathering

The radioactivity of the fallout remaining on the islands will decrease not only from the natural radioactive decay, but also from weathering effects. Wind can transfer surface deposits of fallout from one location to another. However, after 15 years of this action at Eniwetok Atoll, a significant decrease in radioactivity or repositioning of radioactivity seems unlikely henceforth to result from wind effects.

Furthermore, rain can wash the water soluble or loosely adhering radionuclides to deeper depths in the soil, from which depths the soil above would provide some radiation shielding protection for persons being exposed. The amount of this rain form of weathering, called leaching, depends upon the chemical and structural properties of the fallout particles as well as on climate conditions (Crocker, et al., 1965). Typically, leaching alone would halve the radioactivity over a period of years (Glasstone, 1964, p. 458). For Eniwetok Atoll, the future decrease of radioactivity by leaching is difficult to estimate

even roughly in view of the variations of conditions under which nuclear explosion tests were conducted and in view of the long period of natural weathering since that time. Some laboratory measurements exist for leaching of cesium from wedron sand, which of course is not the same as coral. For thermal treatment at 1200°C, which is certainly encountered in fireballs and clouds from nuclear tests, the time for leaching to halve the cesium is initially about four years; for treatment at 20°C it is about two years (Lane, 1970). After the 15 years at weathering at Eniwetok Atoll, certainly the easily leached radionuclides have been removed, and so the time for halving by leaching is probably much higher than the few years observed in these laboratory experiments. Thus, leaching and weathering are not very likely to significantly hasten the decay of radioactivity beyond the nuclear decay times. However, weathering processes are known to be complex and to depend upon many variables (Crocker, 1965).

Distribution of Fallout in Water

The distribution of radioactive contamination in the sea after having been deposited by fallout is largely determined in horizontal distances by oceanographic effects and in depth by gravity. Distribution is altered to a much lower extent by the movement of organisms in and out of the contaminated area (Lowman, 1960).

The horizontal, or geographical, spreading is probably determined primarily by ocean currents, although other factors in the horizontal dispersion are surface winds, currents, and horizontal density gradients.

The depth distribution of fallout depends greatly upon the thermocline, which is the layer of water between the warmer, surface zone and the colder, deep-water zone in a thermally stratified body of water. The thermocline is consequently a layer with a large temperature gradient with depth. In the area of Eniwetok Atoll, the surface layer is less than 100 meters thick. Because the temperature is fairly uniform throughout this upper layer, mixing in this layer requires only small amounts of energy and should occur easily. In contrast, transfer of materials across the thermocline layer by turbulent diffusion is much slower since the thermocline is a layer of high stability.

In studies during the 1958 test series at Eniwetok Atoll, analyses were made by filtration to distinguish between particulate matter and colloidal-soluble matter. The particulate fraction was considered in these studies to be greater than 0.45 microns and the colloid-soluble fraction was considered to be smaller. At 48 hours after the nuclear explosion, the major part of the total radioactivity was concentrated at the 100-meter depth of the upper edge of the thermocline. Logically, the particulate matter would be expected to sink much more rapidly. This was confirmed by observations up to six-weeks later, all of which showed that the colloid-soluble fraction was always on order of magnitude greater in the surface zone than the particulate fraction. At the 400-meter greatest depth observed, the particulate fraction increased in time from being an order of magnitude less until it approached the colloid-soluble fraction in magnitude at the end of this six-weeks period.

These considerations about the thermocline are not expected to apply to the lagoon at Eniwetok Atoll since the 60-meter maximum depth of the lagoon is shallower than the 100-meter depth of the thermocline. The results cited above indicate that although the particulate matter

from the fallout probably settled to the bottom of the lagoon within weeks after the nuclear explosion, it certainly would have settled to the bottom by now. During the past 15 years, much of the colloid-soluable fallout material could be expected to have passed out to the open ocean.

Early Time Radioactivity Measurements

The early time radiations at Eniwetok Atoll during the tests are now only a matter of historical interest because their effects have long since passed in importance; however, a short review is included here for completeness.

The prompt neutrons and gamma rays are emitted well within a second following the explosion. This is sometimes called the initial radiation. As noted above, the induced activities produced by these prompt neutrons are now only a minor consideration in the radiological condition of the Atoll.

Following the initial radiation is the fallout radiation. However, some time is involved before this local fallout reaches its maximum, a maximum resulting from radioactivity decreasing with time as seen in Figure 1 (labeled as Fig 9.16b) as a result of nuclear decay (Glasstone, 1964, p. 420) being offset initially by the delay until fallout reaches the ground (Glasstone, 1964, p. 454). The mean arrival time of early fallout at Eniwetok Atoll in the test series has been observed to be roughly 30 minutes for explosions in the megaton range. This time applies for upwind fallout and results from

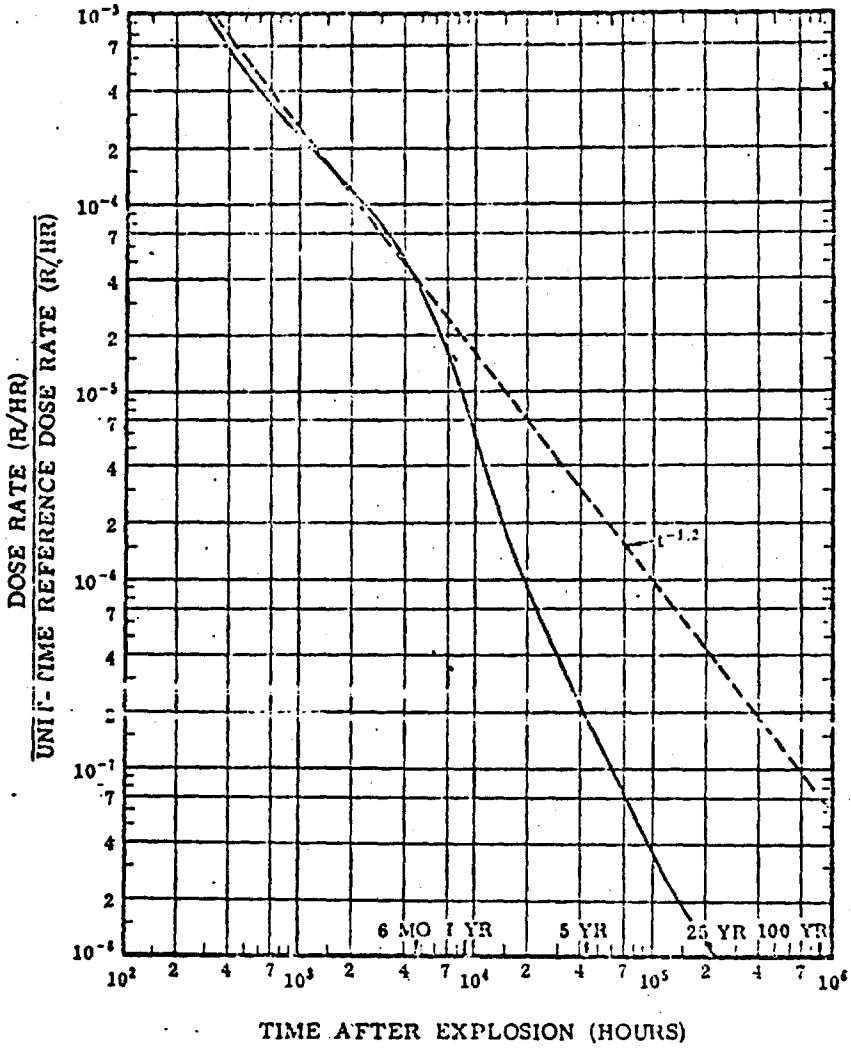

Figure 9.16b. Dependence of dose rate from early fallout upon time after explosion.

9.17 Suppose, for example, that at a given location the fallout commences at 5 hours after the explosion, and that at 15 hours, when the fallout has ceased to descend, the observed dose rate is 4.0 roentgens per hour. From the curve in Fig. 9.16a (or the data in Table 9.19), it is seen that at 15 hours after the explosion, the ratio of the actual dose rate to the reference value is 0.040; hence, the reference dose rate must be 4.0/0.040 = 100 roentgens per hour. By means

Figure 1
p. 14 A

the fact that the broad base / of the radioactive cloud is generally stabilized at the altitude of the tropopause, which is about 55,000 feet in this area.

For the kiloton range of explosions, the lower cloud heights result in fallout coming to earth sooner and at closer distances to the point of the explosion. Although the overall area recieving fallout containation is less than for megaton explosions, this local concentration results in downwind radioactivities that can be of the same order of magnitude as the explosions in the magaton range (Glasstone, 1964, p. 457).

The Test Mike had unusually large yield and produced significant amounts of radioactivity, and so we review the early time radiation from this test (Klein, 1958). Figure 2 (labeled Fig 6 on the copy) shows the maximum activity was reached at about one hour after the explosion and that the peak activity recorded on Engebi was 100 R/hr (Roentgens per hour). The quantity of fallout at crosswind and downwind positions varied from over 20 g/ft^2 at 4 miles to essentially zero at approximately 15 miles (Heidt et al., 1953, p. 41).

Although measured at times past the peak of radioactivity, measurements were / recorded for the four-hour time after the nuclear explosion for seventeen of the most recent nuclear explosions, namely those in the Hardtack I series (Jacks and Zimmerman, 1958).

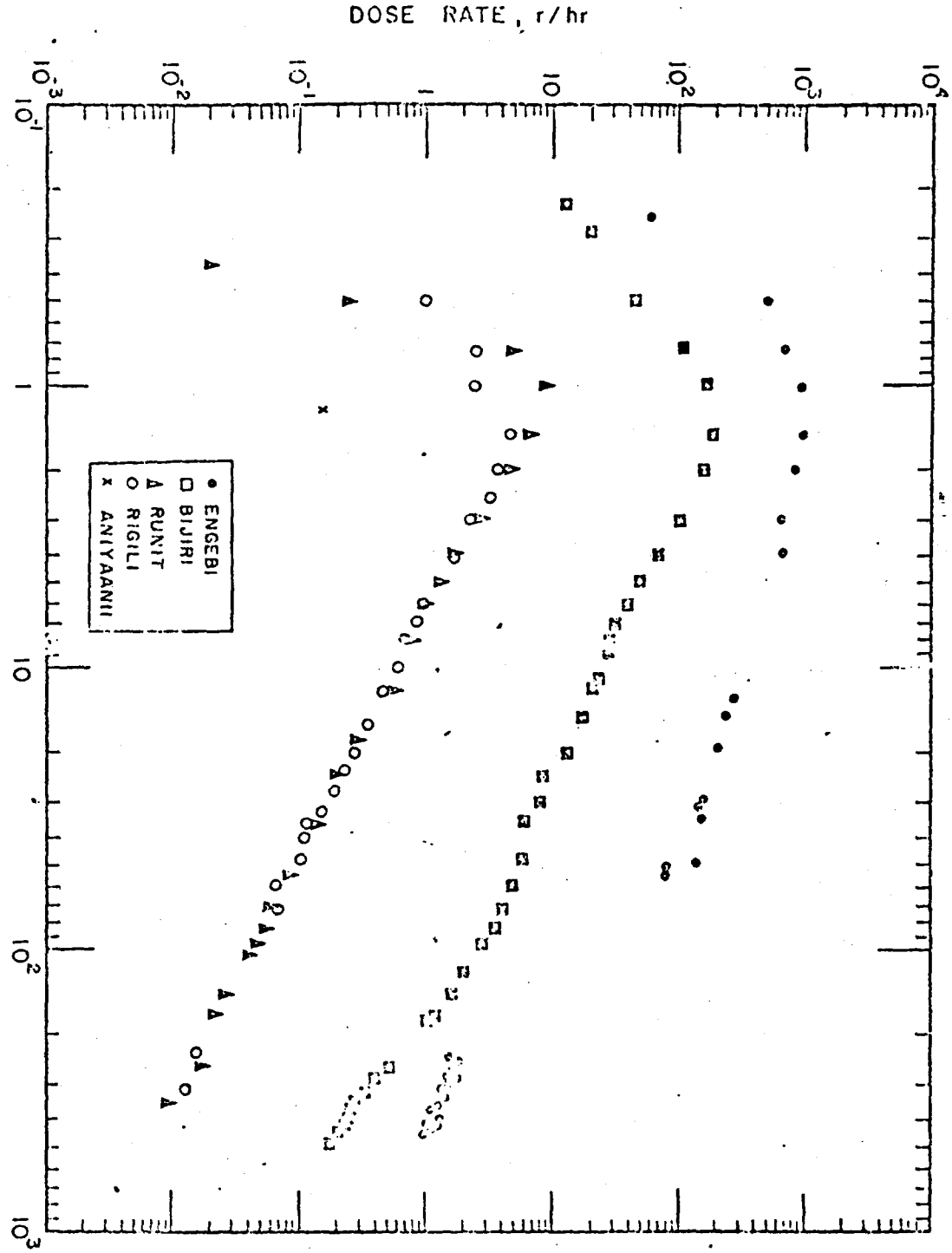

Fig. 6 - Mike fall-out intensity versus time.

Following are some of the recorded radioactivities (or lack of radioactivities) with the numbers indicating R/hr on that island:

Test Name	Test Location	Radioactivities
Cactus	Yvonne	Alice 0; Vera 0; Central Yvonne 1.5; South Yvonne 0
Butternut	Barge off Yvonne	Alice 0.3; Belle 0.01; Wilma 0; Leroy 0.04
Koa	Gene	Alice 40; Janet 14; Mary 2.1; Leroy 0.04
Holly	Barge off Yvonne	Alice 0.2; Helen 0.9; Janet 0.2; Yvonne 4.4; Leroy 0.01
Yellowwood	Barge off Janet	Alice 100; Belle 120; Janet 0.1; Mary 0.02
Magnolia	Barge off Yvonne	Wilma 0; Yvonne 7; Leroy 25
Tobacco	Barge off Janet	Alice 4; Belle 80; Helen 5; Janet 38; Mary 0.01
Rose	Barge off Yvonne	Wilma 0; Yvonne 0.2; Leroy 0.3
Walnut	Barge off Janet	Alice 4.2; Edna 17; Janet 0.8; Mary 0.04
Linden	Barge off Yvonne	Alice 0.3; Belle 0.2; Janet 0.02
Elder	Barge off Janet	Alice 1.4; Belle 0.6; Janet 0.4; Leroy 0.04
Oak	Barge off NW reef	Reef at gnd. zero 900; Alice 0.3; Helen 0.05
Seguoia	Barge off Yvonne	Wilma 0; Runit 0.4; Leroy 0.07
Dogwood	Barge off Janet	Alice 2.9; Belle 5; Janet 0.4; Leroy 0.02
Pisonia	Barge off Yvonne	Alice 0.2; Yvonne 0; Leroy 0.02
Olive	Barge off Janet	Alice 0.2; Gene 6; Janet 0.9; Wilma 0
Pine	Barge off Janet	Alice 0.1; Helen 2; Janet 0.3; Leroy 0.02

The decay histories on Figures 1 and 2 indicate that the peak radioactivities might have been a factor of two higher than these radioactivities at four hours after the explosion.

Among the islands listed, Alice is the most westerly of the northern islands and Leroy is the most westerly of the southern islands. Thus Alice, along with Belle and Clara, are generally downwind from the northerly island Janet, the location of many tests. The early-time fallout on these westerly islands from tests at Janet can be seen in the table above. On the other hand, Yvonne is on the eastern side of the Atoll, about midway in the north-south direction. The other side of the Atoll, in the prevailing downwind direction, is largely a reef, with Alice to the north and Leroy to the south. The table shows that the early fallout of significance was on one or the other of these islands.

Sea-Based Surveys

Much of the information on radiological conditions in the oceanic areas around the Bikini and Eniwetok Atolls and in the lagoons has been obtained from repeated surveys by the Applied Fisheries Laboratory of the University of Washington (Hines, 1962).

In June 1946 before the first tests at Bikini Atoll, almost two thousand fish were taken at Bikini as controls to ascertain the normal Bikini fish population. Between Able and Baker tests and after these tests similar numbers of fish in this vicinity were collected to study radioactivities (Hines, 1962, p. 44). In September 1946 migratory fish caught at nearly atolls were found not to have detectable radioactivity (Hines, 1962, p. 49).

Resurveys were conducted in 1947 and 1948 with scientific representation broadened to other military, governmental, and institutional

representatives as a concluding phase of Operations Crossroads tests at Bikini Atoll. In 1947 collections were made in Bikini Atoll and in the oceanic area in the direction of the Able test fallout. About six thousand samples were collected (Hines, 1962, p. 65). A smaller survey by the Applied Fisheries Laboratory studied both Bikini and Eniwetok Atolls in 1948 (Hines, 1962, p. 24), with the July 1948 survey following the April and May tests of Operation Sandstone. Samples of fish, algae, invertebrates, and plankton were taken. In general, the Eniwetok results of 1948 were that low-level aquatic radiation was present generally as expected across the Atoll. The Applied Fisheries Laboratory survey of 1949 included samplings at the uncontaminated "control" Atoll of Likiep. The Eniwetok survey in August also made observations of plants on shore.

Prior to the thermonuclear test Mike on Eniwetok Atoll on 31 October 1952, the Applied Fisheries Laboratory made preliminary collections at Eniwetok (Hines, 1962, p. 137), usually on the lagoon side. Between 3 and 8 November after this large test, samples were taken from southern islands progressively to the northern islands. Also, rat traps at Rojoa Island were collected. On Engebi on 8 November, the radiation was 2 to 2.5 R/hr, no living animals were seen, and only stumps of vegetation remained. Plankton had a radioactivity of 140,000 disintegrations per minute and per gram (d/min·g) and algae had as high as 5 million d/min·g at that time. Fish in the vicinity of Engebi had a factor of 400 increase in activity after the test with 340,000 d/min·g.

The thermonuclear tests of Mike on Eniwetok Atoll in 1952 and particularly the Bravo test on Bikini Atoll on 28 February 1954 sharply increased the radioactive fallout in the surrounding oceanic areas in 1954. To measure this, the Japanese survey ship Shunkotsu-Maru during May and June of 1954 made several traverses of the Pacific currents to determine the amounts of radioactivity present in sea water and marine life (Hines, 1962, p. 182; and Miyake et al, 1955). The technique of precipitation used by this Japanese expedition eliminated natural potassium-40 and also eliminated some fission products such as cesium and some of the ruthenium and niobium. Nevertheless, the maximum activity found in sea water was about 91,000 disintegrations per minute and per liter on 21 June 1954 at 450 kilometers west of Bikini. Over 1,000 disintegrations per minute and per liter were found as far as 2000 kilometers WNW of Bikini. The Japanese found this activity largely to be in solution, since it passed through a fine filter paper. Samples taken with depth showed the activity at some locations was present down to several hundred meters depth.

Less than a year later, the United States sent a survey ship, the U.S. Coast Guard cutter Taney, also to collect radioactivity samples (Harley, 1956; and Hines, 1962, p. 201). The survey was from 7 March 1955 until 3 May 1955. As with the Japanese survey, potassium and cesium were not precipitated in the samples counted, and the ruthenium, niobium, and promethium were only partly precipitated. Water activity at zero to 570 disintegrations per minute and per liter was far less than observed by the Japanese in the previous year. Plankton activity was 3 to 140 d/min·g), while the highest activity for fish was 3.5 d/min·g for

ash of tuna. This was less than one percent of the permissible level at that time. Although the activities were too low for accurate radiochemical analyses, the strontium-90 levels in the edible portions of fish were less than two percent of the permissible level at that time.

For these open ocean surveys, the radioactivity in fish was less by factors of 10 or more than for fish at Eniwetok or Bikini Atolls, but was several to many times as much as for fish from Puget Sound, an area then considered to be free from fission product contamination.

The next oceanic survey was conducted during June and September 1956 during the Redwing series. The cruise zig-zagged west of Bikini Atoll and Eniwetok Atoll to collect plankton samples (Hines, 1962, p. 223; and Lowman, 1958). The fallout was found not to have penetrated the surface layer. Since megaton explosions had occurred at Bikini Atoll, radioactivity was high. Although the greatest radioactivity found for plankton was 1.2 million d/min·g north of Bikini, the minimum level of 1,300 d/min·g was almost as high as the maximum level recorded in Operation Troll in 1955. Another cruise on the ship Marsh acted as a sequel to the Shunkotsu-Maru by covering approximately the same sea area in attempting to follow the Redwing contamination in September 1956. At these later times after nuclear explosions and at these greater distances, the radioactivity in plankton was lower. The maximum was 21,000 d/min·g eighty miles north of Eniwetok.

For Operation Hardtack in 1958, the U.S.S. Rehoboth was used for radioactivity observations (Hines, 1962, p. 275). Plankton radioactivity was as high as 32 million d/min·g following the Wahoo underwater explosion on the ocean side at the south of Eniwetok Atoll. Fish, shrimp, and

squid were also radioactive the day after this underwater test. Data of radioactivity in plankton and water were also taken following the Unbrella test underwater in the Eniwetok lagoon. At about the end of the Hardtack test series, two other ships, the Collett and Silverstein started a local-area survey and a cruise to Guam, respectively (Hines, 1962, p. 285). Plankton radioactivity was as high as 39,000 d/min·g as found 110 miles northeast of Guam on 7 September.

Land-Based Earlier Surveys

As seen by the above summary, expeditions were made to one or both of the Eniwetok and Bikini Atolls in 1947, 1948, 1949, 1951, 1952, 1954, 1955, 1956, and 1958 to study biological effects of the detonations. However, these were primarily to study marine effects. Thus relatively less was done in these sea-based studies in following the residual radioactivity on land and in plants and animals, although some of these expeditions did make land observations. Of course, during each test operation extensive measurements of fallout radioactivity and instantaneous radioactivity were made at the time of each test and generally for the months involved in the duration of the test series.

Studies were made on Bell (Bogombogo) Island in 1954 following the 13 March 1954 Nectar test during Operation Castle. This was a barge test located over the Mike crater 2.3 miles to the northeast of this island. The external radiation was found to decrease from 1000 mR/hr on 15 May 1954 two days after the test to 1 mR/hr on 21 March 1955 almost one year after the test. Essentially all the damage to land plants could be attributed to heat and blast, although possibly some could be attributed to radiation effects (Palumbo, 1962). Observations were made of land hermit crabs,

Coenobita perlatus, from this island. Collections were made at approximately daily intervals commencing with the third day following the Nectar test until the ninth day and thereafter at lengthened intervals until approximately monthly intervals. Sampling continued until about two years after the test. Strontium-89 and -90 were detected in the exoskeletons and other parts of the crab. The amount in the exoskeletons remained at a nearly constant level, excepting nuclear decay. Levels of activity, three days after the Nectar test were a high of 5 million d/min·g in the gut, but at the end of the two years were typically about 10 thousand d/min·g (Held, 1960).

The first large-scale land-based study of residual radioactivity was in 1964 by the Laboratory of Radiation Biology of the University of Washington. The study was at Eniwetok, Bikini, and Rongelap Atolls. This was eight years after the last test in this area of the world, and so allowed observation of long-term effects of nuclear detonations (Welander et al, 1966). Hundreds of specimens of a broad range of organisms were collected for radioanalyses and later evaluation at the University.

External radioactivity was measured by beta-gamma survey meters at three feet above ground level. Following are some of the observations:

External Radiation in mR/hr

Island	Average	Maximum
Runit (Yvonne)	0.13	1.0 (Near craters at north)
Rigili (Leroy)	0.04	
Bogombogo (Belle)	0.80	0.23
Engebi (Janet)	0.22	0.70

In the extensive results from these 1964 surveys, the radioactivity was found generally to be somewhat greater in the plants and marine life on Bikini Atoll than on Eniwetok Atoll. Furthermore, radioactivity in the vicinity of previous nuclear tests was greater than on islands remote from tests (Welander, 1967), (Beasley and Held, 1969), (Beasley and Held, 1971).

The next extensive land-based survey was conducted by the Air Force Weapons Laboratory in July 1971 (E. L. Kinsey, 1973). The following islands were surveyed: Bogariik, Bogon (Irene), Engebi (Janet), Eberira , Aomon (Sally), Biijiri (Tilda), Rojoa (Ursula), and Runit (Yvonne). In general, the measured exposure rates were 0.002 mR/hr to 1.2 mR/hr, the latter at the lip of Cactus crater on Runit. On Runit, readings of beta- and gamma-ray activity were taken every 50 feet along four equally spaced traverses of the island, one 4,200 feet long. On Aomon the highest reading was 0.035 mR/hr, with an average of 0.015 mR/hr.

In early May 1972 a team composed of Atomic Energy Commission and Environmental Protection Agency specialists conducted a brief radiological survey of Runit Island (Kinsey, 1973). During the course of this survey, the AEC representative recommended to SAMTEC, the custodian of the Atoll, that this island be quarantined until a more detailed radiological survey could be made of the plutonium contamination on the ground at about the "waist" of this long island and more could be learned about the disposition of radiological materials and debris left from the previous nuclear test.

Following a meeting at AEC in Germantown, Maryland, on 30 June 1972, about this precautionary quarantine situation, a survey team from the AEC and the Department of Defense, along with the support from EPA,

conducted a survey of Runit Island in May 1972. Both beta-gamma survey meters and Fiddler meters (for plutonium detection, by means of americium-241 content) were used, the former for beta- and gamma-ray detection and the latter for plutonium detection. Measurements were made on 10-foot grids. Soil samples were taken for plutonium analysis in laboratories in the U.S. Air samplers were used to test for plutonium in the dust. Generally, these air samplers showed no detectable activity, but did record as high as 0.24 d/min·meter of alpha particle activity and 28.4 d/min·meter of beta-gamma activity. Urine samples of full-time workers in the area never showed alpha-particle activities larger than a very small fraction of tolerance (Kinsey, 1973). As a consequence of these findings, the precautionary quarantine on Runit was lifted on ? without any corrective actions needed for the island.

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