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VOLUME I

ENEWETAK RADIOLOGICAL SURVEY

OCTOBER 1973

UNITED STATES ATOMIC ENERGY COMMISSION

NEVADA OPERATIONS OFFICE

LAS VEGAS, NEVADA

Contents

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Abstract

The AEC has conducted a survey of the total radiological environment of Enewetak Atoll in order to provide data for judgments as to whether or not all or any part of the Atoll can be safely reinhabited. More than 4500 samples from all parts of the marine, terrestrial, and atmospheric components of the Atoll environment were analyzed by instrumental and radiochemical methods. In addition, an aerial survey for gamma-radiation levels was conducted over all land areas.

^{90}Sr, ^{137}Cs, ^{60}Co, and ^{239}Pu are the predominant radioactive isotopes now present, but their distribution is far from uniform. Islands on the southern half of the Atoll from ALVIN to KEITH have levels of contamination comparable to or less than those due to world-wide fallout in the United States. On the northern half, islands ALICE to IRENE are most heavily contaminated, KATE to WILMA are least contaminated, and JANET is at an intermediate level.

These radiological data have been combined with the best information currently available on the expected diet of the Enewetak people to estimate potential whole-body and bone doses to the population for six living patterns at 5-, 10-, 30-, and 70-yr intervals after return. Thirty-year integral dose estimates for unmodified (i.e., current) conditions are shown in Table A.

Table A. The 30-yr integral dose for six living patterns, assuming unmodified conditions.

	30-year integral dose, rem Unmodified conditions									
Living pattern	Inhalation			External	Terrestrial		Marine		Total	
	Bone	Lung	Liver	Bone, W.B.	W.B.	Bone	W.B.	Bone	W.B.	Bone
I	7(-4)	9(-4)	4(-4)	0.83	0.14	2.1	0.053	0.84	1.0	3.8
II	0.029	0.036	0.016	1.6	2.7	33	0.053	0.84	4.4	35
III	0.10	0.13	0.056	4.0	6.1	75	0.053	0.84	11	80
IV	0.47	0.59	0.24	10	21	210	0.053	0.84	31	220
V	0.11	0.13	0.058	2.9	2.7	33	0.053	0.84	5.7	37
VI	0.090	0.11	0.049	4.4	9.6	130	0.053	0.84	14	135

Living pattern	Village island	Agriculture	Visitation
I	FRED/ELMER/DAVID	ALVIN through KEITH	Southern islands
II	FRED/ELMER/DAVID	KATE through WILMA plus LEROY	Northern islands
III	JANET	JANET	Northern islands
IV	BELLE	BELLE	Northern islands
V	JANET	KATE through WILMA plus LEROY	Northern islands
VI	JANET	ALICE through IRENE	Northern islands

The main contribution to the population dose comes through the terrestrial food pathway, followed in decreasing order of significance by the external gamma dose, marine, and inhalation pathways. In the terrestrial food pathway, the main contribution to both whole-body and bone dose is due to pandanus and breadfruit. Percentage contributions to the 30-yr integral dose for each of the terrestrial food items for a population engaged in agriculture on JANET are shown in Table B.

Corrective actions to reduce population doses will be most beneficial if they are directed at the primary contributors, i.e., pandanus and breadfruit in the diet and external gamma dose in the residence areas. Since neither pandanus nor breadfruit are now growing on the Atoll in sufficient amounts to provide a significant dietary component, control of the location and manner in which they are reestablished will have a direct influence on the population doses from these fruits. If their growth were limited to the southern islands, for example, and the population living on JANET were to import them rather than grow them locally, the expected 30-yr bone dose would be reduced from 80 to 25 rem and the whole-body dose from 11 to 6.5 rem. Similar results would be obtained if uncontaminated soil were imported to JANET for the establishment of these plants. Attempts to obtain the same results by removal of ^{90}Sr- and ^{137}Cs-contaminated soil from JANET would require denuding of the entire island because of the relatively uniform distribution of these isotopes over the land surface.

Table B. Percentage of total 30-yr terrestrial food dose to a population engaged in agriculture on JANET.

Food	^{90}Sr dose to bone, %	^{137}Cs dose to whole body, %
Domestic meat	17	26
Pandanus fruit	40	35
Breadfruit	34	29
Wild birds	0.005	0.003
Bird eggs	0.05	0.002
Arrowroot	2	0.3
Coconut meat	6	9
Coconut milk	0.9	1

Significant reduction of the external gamma dose may be achieved by placing a 2-in. layer of clean gravel in the village areas and by plowing the agricultural areas. On JANET, for example, use of these procedures reduces the expected 30-yr external dose from 4.0 to 1.7 rem.

Thus, from Table A it is clear that a very broad range of population doses may be expected, depending on village island, agricultural island, and living pattern. It is equally clear that substantial reductions of the higher doses can be achieved through relatively simple modification of the agricultural practices and of the soil. Table C summarizes the reduction that could be expected from these actions for a population living on JANET.

The island of YVONNE presents a unique hazard on Enewetak Atoll. Pure plutonium particles are present on or close to the ground surface, randomly scattered in "hot spots" over most of the area from the tower to CACTUS crater. Examination of these "hot spots" has revealed the presence of occasional milligram-size pieces of plutonium metal as well as smaller pieces which are physically indistinguishable in size from the surrounding coral matrix. Given these current conditions, it must be assumed that pure plutonium particles of respirable size are now also present on the surface or may be present in the future as weathering effects oxidize and break down the larger particles. Lung dose assessments for this area, therefore, must be based on inhalation of pure plutonium particles rather than those having the average plutonium content of the soil.

The potential health hazard via the inhalation pathway is sufficiently great to dictate two basic alternatives for remedial action for this island: (1) Make the entire island an exclusion area—off limits to all people, or (2) conduct a cleanup campaign which will eliminate the "hot-spot" plutonium problem and remove whatever amount of soil is necessary to reduce the soil plutonium concentration to a level comparable to other northern islands. As an indication of the volumes of soil involved, removal of a 10-cm thick layer of topsoil in the area in which "hot spots" have been detected involves approximately 17,000 m^3 of material. Further removal of soil to reduce the maximum plutonium contamination levels to 50 pCi/g or less involves an additional 25,000 m^3 of material.

Table C. 30-yr integral doses from all pathways compared to U.S. external background dose.

	30-yr integral dose, rem[a]			
	Unmodified soil case		Modified soil case[b]	
Location	W.B.	Bone	W.B.	Bone
Enewetak Atoll living pattern III (JANET-current conditions)	11	80	8.9	78
Enewetak Atoll living pattern III (JANET-pandanus and breadfruit imported)	6.5	25	4.2	23
Enewetak Atoll living pattern III (JANET-all agriculture confined to southern islands)	4.2	7.0	1.9	4.7
Enewetak Atoll living pattern I (southern islands)	1.0	3.8	1.0	3.8
U.S. background only[c]	3.0	3.0	3.0	3.0

[a]Sum of all pathways for the Enewetak living patterns (i.e., external, inhalation, marine, and terrestrial).

[b]Soil modified by placing 2 in. of clean gravel in the village area and plowing the agricultural area.

[c]Based upon background of 100 mrem/yr at sea level.

Acknowledgments

Successful completion of the Enewetak Radiological Survey was the result of the effort and cooperation of many organizations. However, organizations are composed of individuals, and it really has been the attitudes and abilities of these people upon which so much has depended. We wish to acknowledge most heartily the efforts of all participants—those who worked in the field, those who worked in the laboratories at home, and those who provided support services so important to an efficient operation.

The list is long, but that is indicative only of the size and complexity of the operation. Very likely, in spite of our most diligent efforts, the names of some who participated have been omitted. To them we extend our apologies and our appreciation.

All of the following organizations and individuals have made significant contributions to the success of the AEC Enewetak Radiological Survey. To them, collectively and individually, we express deepest thanks for a difficult job done well. This report is long, and it contains an enormous amount of information, but it does not come close to telling the whole story of what happened to all the individuals concerned from September 1972 to October 1973. That is the stuff of which reminiscences are made.

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I. Introduction

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On April 18, 1972, Ambassador Franklin Haydn Williams, U.S. Representative to the Micronesian Status Talks, and TTPI High Commissioner Edward E. Johnston issued at Saipan a joint announcement which stated that "the United States Government is prepared to release legally the entire (Enewetak) Atoll to the Trust Territory government at the end of 1973, subject to the retention of some minor residual rights." This announcement was welcomed by the Enewetak people, who for many years have sought to obtain a commitment from the U.S. Government for return of their ancestral homeland to their own jurisdiction. They had been moved from Enewetak in December 1947 in order that the Atoll could be used for the nuclear weapon testing program and ever since have been living on Ujilang, an atoll approximately 125 mi southwest of Enewetak.

The announcement went on to state that "prior to the actual settlement of the Atoll, it will be necessary to carry out the same type of survey, cleanup, and rehabilitation procedures that have been utilized for Bikini Atoll. As in Bikini, the schedule for resettlement will depend on the results of the survey and the pace of the rehabilitation program."

In May 1972 a U.S. Atomic Energy Commission (AEC) survey team visited Enewetak Atoll to conduct a preliminary radiological reconnaissance. They could not visit all islands in the Atoll in the time available, but of those they visited, they found what they considered to be significant radiological hazards still existing on BELLE, JANET, SALLY, URSULA, and YVONNE.* Initial cleanup and rehabilitation cost estimates based on data from this survey had, of necessity, to incorporate a wide range of assumptions, due partly to the lack of information on the extent of the radiological contamination, partly to the lack of a detailed analysis of the dose-to-man implications for each isotope comprising that contamination, and partly to uncertainties as to the manner of disposal of radioactive debris. Acceptability of disposal methods and plans would require detailed consideration of bioenvironmental impact, of political concerns, and of the desires of the Enewetak people. Since estimates based on these assumptions indicated that cleanup costs could run to tens of millions of dollars, it was considered essential that much more comprehensive

*For the sake of simplicity, U.S. alphabetical designators for all islands will be used in this report. A cross-reference to all names we understand to be in use for each island may be found on p. v of Appendix II. An exception to this approach applies to the name for the Atoll itself. As Dr. Jack Tobin points out, "It is called Enewetak by the Atoll people and the rest of the Marshallese. The people of the Atoll say that it means island (ene) toward, or pointed toward, the east or wetak; hence, Enewetak." Since there is a commitment to return the Atoll to TTPI jurisdiction in the near future, this seems an appropriate time and place to begin using the Marshallese spelling.

and detailed information on the radiological condition of the Atoll be obtained before the start of cleanup and rehabilitation operations.

On September 7, 1972, at an inter-agency meeting in Washington, the AEC agreed to assume responsibility for conducting this comprehensive radiological survey; the Department of Defense agreed to assume responsibility for conducting such cleanup operations as were required; and the Department of the Interior agreed to assume U.S. Government responsibility for rehabilitation and resettlement of the native population.

This report describes the radiological survey which has been executed by the AEC as a consequence of the September 7 commitment and presents data which have been obtained from that survey. Recommendations for cleanup and/or other corrective action based on these data will be the subject of separate action by the Atomic Energy Commission.

In Section II a fairly detailed description of the Enewetak Atoll and a history of the Enewetak people are presented to set the framework within which the Survey has be conducted.

Section III contains a separate chapter for each major component of the Survey, including Plans, Aerial Survey, Terrestrial Soil and Radiation Survey, External Dose Estimation, Marine Survey, Terrestrial Biota Survey, Air Sampling, Engineering Survey, Analysis Program, Radiological Controls, and Dose Assessments.

Section IV contains a Summary of Findings.

The large number of photographs and figures needed to present the data are contained in the Appendix as Volumes II and III.

II. Enewetak

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FOREWORD

Portions of this chapter are largely drawn from a working draft of the manuscript which is to become the Draft Environmental Impact Statement for Enewetak cleanup. This statement is being prepared by Holmes and Narver, Inc. under contract to the Department of Defense. We are indebted to the Defense Nuclear Agency for permitting use of the statement and to Dr. Stanley Kaplan of Holmes and Narver for his assistance toward its timely availability. Dr. Jack Tobin, a major contributor to the Kaplan effort, was also consulted extensively on history and anthropology in relation to other sections of this report. The last section of this chapter is drawn from field trip reports of Kenneth Marsh and Victor Nelson.

ENEWETAK ATOLL—HISTORY AND STATUS

Enewetak Atoll Island Names

Because the native names of most of the islands in the Enewetak Atoll are difficult for English-speaking people to pronounce and spell, male and female first names were assigned to the islands during the U.S. occupancy. Site names were also given to several points in the lagoon and on the reef where scientific structures had been erected. Nearly all documents and maps made subsequent to 1952 include these site names, and in some cases the native names are also shown in parentheses.

Table 1 presents a correlation of these site names with the native names obtained from the Enewetak people during the Ujilang field trip in August 1973, and from the U.S. Hydrographic Office Charts. It is interesting to note the influence of the Japanese romanization on the names given in the hydrographic charts.

Physical Description of Enewetak Area

Geography

Enewetak Atoll is the northwestern-most atoll in the Western (Ralik) Chain of the Marshall Islands, forming the northern part of Micronesia in the central Pacific Ocean (regional map, Fig. 1). The location is 11° 21'N, 162° 21'E, approximately 550 naut mi southwest of Wake Island, 189 naut mi west of Bikini Atoll, and 2380 naut mi southwest of Honolulu.

The Atoll consists of 40 islands on an elliptical reef approximately 23 by 17 naut mi, with the long axis running northwest to southeast. The total land area is 2.75 mi^2, with the land height generally averaging 10 ft above mean sea

Table 1. Comparison of site and native names.

Site	Native names from U.S. Hydrographic Office charts 1946	1958	Native names[a]
ALICE	Bogallua	Bogailua	BOKOLUO
BELLE	Bogombogo	Bogombogo	BOKOMBAKO
CLARA	Ruchi	Eybbiyae	KIRUNU
DAISY	—[b]	Lidilbut	LOUJ
EDNA	—[b]	—[b]	BOCINWOTME
HELEN	Bogairikk	Bogeirik	BOKAIDRIK
IRENE	Bogon	Bogon	BOKEN
JANET	Engebi	Engebi	ENJEBI
KATE	Muzinbaarikku	Mujinkarikku	MIJIKADREK
LUCY	Kirinian	Billee	KIDRINEN
PERCY	—[b]	—[b]	TAIWEL
MARY	Bokonaarappu	Bokonarppu	BOKENELAB
NANCE	Yeiri	Yeiri	ELLE
OLIVE	Aitsu	Aitsu	AEJ
PEARL	Rujoru	Rujiyoru	LUJOR
RUBY	Eberiru	Eberiru	ELELERON
SALLY	Aomon	Aomon	AOMON
TILDA	Biijiri	Biijiri	BIJILE
URSULA	Rojoa	Rojoa	LOJWA
VERA	Aaraanbiru	Arambiru	ALEMBEL
WILMA	Piiraai	Piirai	BILLAE
YVONNE	Runit	Runit	RUNIT
SAM	—[b]	—[b]	BOKO
TOM	—[b]	—[b]	MUNJOR
URIAH	—[b]	—[b]	INEDRAL
VAN	—[b]	—[b]	—[b]
ALVIN	Chinieero	—[b]	JINEDROL
BRUCE	Aniyaanii	Japtan	ANANIJ
CLYDE	Chinimi	Chinimi	JINIMI
DAVID	Japtan	Muti	JAPTAN
ELMER	Parry	Parry	MEDREN
WALT	—[b]	—[b]	BOKANDRETOK
FRED	Eniwetok	Eniwetok	ENEWETAK
			Native names fror Dr. Jack A. Tobi
GLENN	Igurin	Igurin	IKUREN
HENRY	Mui	Buganegan	MUT
IRWIN	Pokon	Bogan	BOKEN
JAMES	Ribaion	Libiron	RIBEWON
KEITH	Giriinien	Grinem	KIDRENEN
LEROY	Rigili	Rigile	BIKEN
REX	Jieroru	Bogen	JEDROL
OSCAR	—[b]	—[b]	DREKATIMON
MACK	—[b]	—[b]	UNIBOR

[a] As confirmed by the Enewetak people during the Ujilang field trip of July 1973.

[b] No native name.

level. The vicinity map (Fig. 2) shows the Atoll configuration.

The lagoon, which is about 388 mi^2 in area, has three entrances: an east channel approximately 180 ft deep, between DAVID and ELMER; a 6-mi wide channel to the south; and a shallow (approximately 4 fathoms maximum depth) channel to the southwest. Tidal currents vary from up to 2 knots in the deep channel to 1 knot in the south channel.

Geology

Enewetak Atoll is 15,000 ft above the ocean floor, while the top of the eroded volcano forming the island base is approximately 4200 ft below the surface. Steep coralline reefs reaching to the surface form a flat oval ring of reef and low-lying islands, within which is a shallow lagoon with a maximum depth of about 200 ft.

Enewetak is a classic example of the Darwinian concept of atoll formation in which an atoll is born when an oceanic volcano surrounded by a fringe coral reef begins to slowly subside below the ocean level. As the coral and coralline algae (which require shallow, clear, warm, oxygenated marine waters) maintain an upward growth commensurate with the subsidence, a fringe reef flourishes, particularly on the ocean side. As the volcano continues to subside, the fringe reef gives way to a barrier reef, and then to an atoll.

Since the northeast trade winds vary little in their direction, the reefs on the windward and leeward sides of the atoll are distinctly different. A greater volume of ocean water, carrying nutrients necessary for coral growth, flows over the windward side due to the wind-generated ocean currents. Therefore,

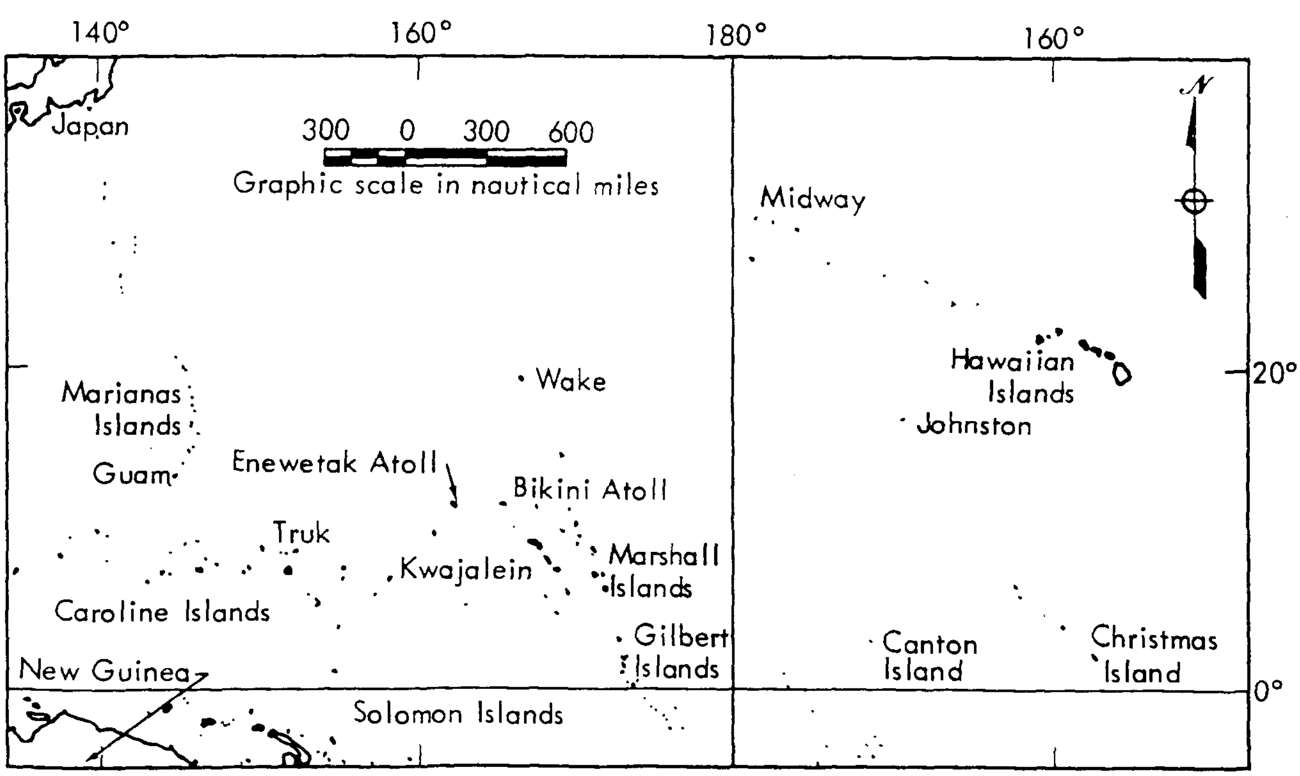

Fig. 1. Regional map—Central Pacific Ocean.

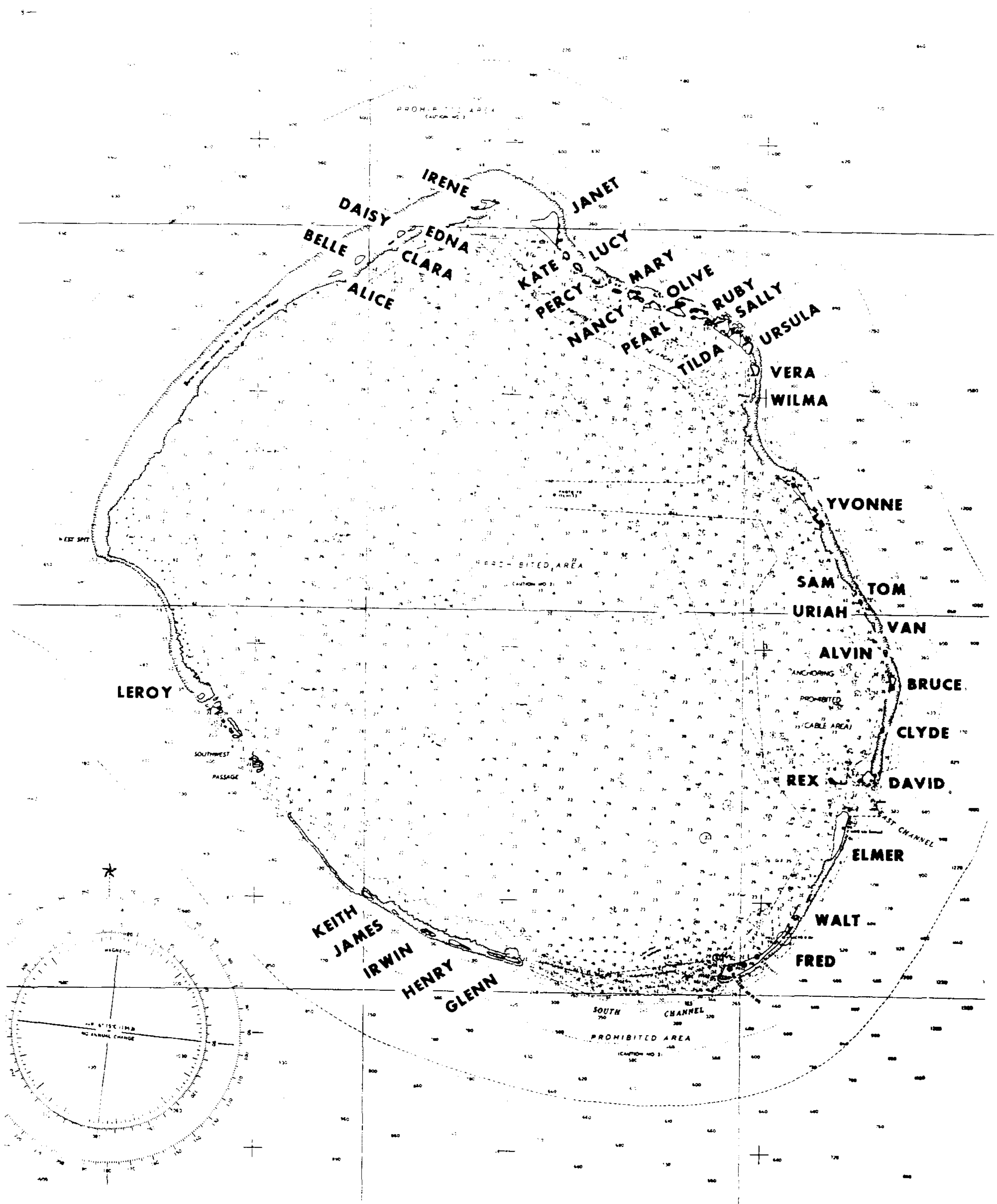

Fig. 2. Vicinity map—Enewetak Atoll.

more rapid growth occurs on the windward side, which has a slightly elevated ridge at the reef edge, while there is none on the leeward side. The leeward side drops sharply to ocean depths up to 200 ft, whereas the windward reef slopes seaward at about a 45-deg angle.

Four near-surface geologic regions can be distinguished at Enewetak Atoll: island, interisland, ocean reef, and lagoon. Descriptions of the island and ocean reef geology can be given, based on core samples from 50 holes drilled during the nuclear testing program (Cooper and Pratt, 1968). No records are available of the interisland and lagoon geologics; hence, these can only be inferred.

The island geologic profile consists of unconsolidated coral sands and gravels, saturated below the water table and extending from the surface to a maximum depth of 150 ft. The water table varies with the tide; its amplitude decreases rapidly with distance from shore. Typical water depths (elevation of island above mean tide) are 5 to 8 ft. At the intertidal level, a 1- to 5-ft layer of beach rock (calcium-carbonate-cemented coral sands and gravels) is usually found; the exposed portions of the rock form most of the shore line. The rock strength ranges from hand-crushable to high-strength sandstone, decreasing in strength as well as thickness from ocean to lagoon. Below the unconsolidated coral sands and gravels, there is an old reef horizon going from the ocean to lagoon side at depths of 50 to 150 ft. This reef horizon is gradational and porous, consisting of large detrital and in situ coral fragments, with fine sands and muds occupying the voids.

The ocean reef profile shows a similarity to the island profile, except that the upper surface layer consists of a wave-planeated, dense, algal-limestone reef flat composed of detrital and in situ coral. The thickness of the upper reef horizon varies from 0 to 15 ft, progressing outward from the island, and is composed of a dense algal limestone. Of two holes drilled into the SALLY reef proper, one penetrated a 35-ft sand and gravel horizon between the upper and lower reefs; the other did not. It is inferred, based upon limited drilling and general atoll physiography, that the ocean reef geology is more heterogeneous than the island geology, containing numerous large coral heads, caverns, etc.

The interisland geologic profile can be presumed to be similar to the island geologic profile, except for the possibility that the top 10 to 40 ft of rock and sand has been eroded away by the sea.

The lagoon geologic profile probably consists of soft, fine sediments to a depth of a few hundred feet, with intermixed and sporadic lagoonal coral heads. The depth of the lower reef horizon, if it exists, is probably greater than a few hundred feet.

Climatology

Enewetak's climate is the tropical marine type, with temperatures ranging from 71 to 94°F and relative humidity in the 73 to 80% range. There is much cumulus cloud cover, moderate rainfall (57 in. mean annual rainfall), and, to a lesser extent, constant northeasterly trade winds (0 to 30 knots). Most depressions or tropical storms occur during the months of September through December, although they are possible at any time of the year. A climatological summary of Enewetak Atoll for a 12-yr period, as prepared by the U.S. Air Force Environmental Technical Applications Center, is shown in Table 2.

Hydrology

Enewetak Atoll relies on rainfall for its supply of fresh water. Since the soil is extremely porous, drainage of rainfall by downward percolation through the ground is rapid. This "groundwater" makes contact at its lower face with marine water that has infiltrated through the porous rock from the sea and lagoon. Fresh water poured on an open body of salt water will quickly spread over the surface of the salt, and through currents and waves will become thoroughly mixed with the salt water. Porous rock, however, interposes an obstacle to this rapid spread and restricts the mixing of the light fresh water with the denser salt water. The fresh water is only about 40/41 as heavy as salt seawater and floats on the salt water, displacing 40 parts of seawater for each part of fresh water floating above the normal saltwater level. That is, fresh water seeping to basal groundwater level on coral atolls and other porous islands has a depth that is about 40 times the head or elevation of its water table above sea level (Fig. 3). This head or hydraulic gradient of water tends to seek sea level by lateral flow through the restricting rock. This principle of freshwater displacement of salt water in islands and coastal areas is known as the Ghyben-Herzberg law, after its discoverers. As the head of water

Table 2. Meteorological observations for Enewetak Atoll over a 12-yr period.

Parameter description	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Absolute max temp, °F	88	88	89	90	91	90	92	91	93	91	94	88	94
Mean max temp, °F	85	85	86	86	86	87	87	87	88	87	86	86	86
Mean min temp, °F	78	78	78	78	78	79	79	79	79	79	79	78	79
Absolute min temp, °F	71	73	73	72	73	73	71	72	72	71	72	71	71
Mean relative humidity, %	73	73	75	76	78	79	80	80	79	79	78	76	77
Mean precip., in.	1.03	0.85	1.73	2.47	5.65	4.06	7.12	6.67	6.76	9.76	7.26	3.61	57.0
Mean No. days precip. ≥ 0.1 in.	3.4	2.5	4.3	5.3	9.2	9.6	13.0	13.1	13.1	14.0	13.0	7.2	108.3
Mean No. days of thunderstorms	0.0	0.0	0.0	0.0	0.2	0.4	1.3	0.9	1.4	1.9	0.5	0.2	6.0
P freq. wind spd ≥ 17 knots	47.4	56.2	49.4	47.9	38.7	27.8	11.4	9.3	7.0	9.1	34.7	47.5	32.2
P freq. wind spd ≥ 28 knots	0.2	0.3	0.5	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.7	1.5	0.3

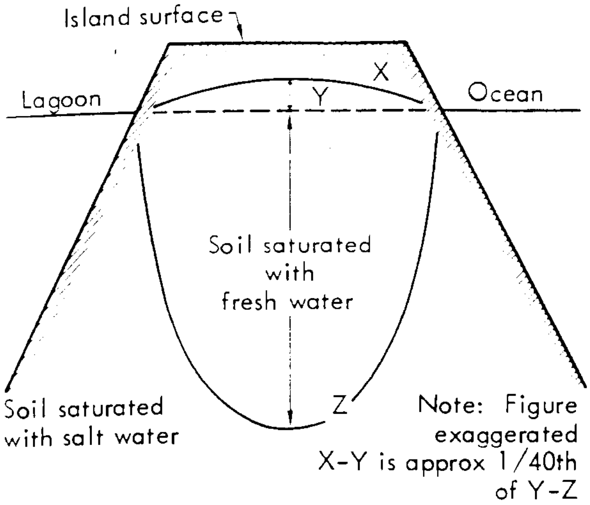

Fig. 3. Schematic representation of an island freshwater lens.

moves outward, the depth of the fresh water becomes less until at the edge of the shore, where the fresh water seeps into the sea, it is just about at sea level, disregarding the fluctuations of the tide.

In a roughly round island of uniform permeability, the body of fresh water floating upon the salt water assumes the shape of a lens, the edges of which approximate the edges of the island, with the upper face of the lens only slightly convex compared with the deeply convex lower surface at the salt water interface. A pictorial representation of an ideal freshwater lens is shown in Fig. 3. It should be noted that the water shown in Fig. 3 does not lie in a large pool beneath the island, but is trapped within the porous media making up the island. Ideally, the saltwater/freshwater interface would be clearly defined; however, this is the exception to the rule because the lens is a dynamic system rather than a static system. When the interface moves with respect to the porous fluid-containing medium, the sharpness is diffused, creating a transition zone in which the quantity of mixing is proportional to the rate of movement of the interface (Fig. 4).

Normally, the interface moves constantly due to tidal action and seasonal changes in the amount of recharge (rainfall percolation) which affects the thickness of the lens. This movement of the interface up and down alternately brings the invasion of salt and the dilution of salt water with fresh water. Thus, the contact zone is not sharply defined in terms of salinity or freshness, but shows a transition in salinity. At the center of an island of uniform permeability, the tidal fluctuation is at a minimum, and the depth of fresh water is at a maximum. At the shore the tidal range is at a maximum and there is a reverse gradient at high tide carrying salt water into the island. Therefore, all of the water emerging at the shore line is brackish.

Terrestrial Ecology

The terrestrial ecology of Enewetak Atoll in the northern Marshall Islands presents many interesting facets of plant and animal adaptation, biogeography, and

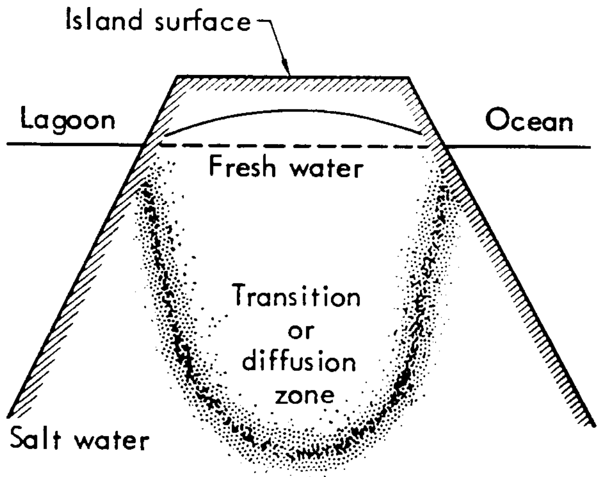

Fig. 4. Freshwater lens diffusion zone.

trophic relationships in a relatively discrete ecosystem. The geology and soils of the Atoll are derived from the skeletal and structural residues of plant and animal organisms that are present as coralline and algal limestone and their erosional products. On this unique substratum, a terrestrial ecosystem has evolved—the product of the disseminative agents of the Pacific basin, namely, wind, water, and biotic vectors, including man, who has played a prominent role in determining the present biota.

In its greatest expression, the terrestrial ecosystem of Enewetak Atoll is represented by a forest habitat that is comparable to those found on continents. The diversity in species composition of that forest is admittedly low because of historical, geographic, and climatic factors which have influenced the evolution of the Atoll biota. Isolation from source regions, oceanic current circulation, and the relative aridity of the northern Marshall Islands determine the plant and animal species that will arrive at the Atoll, and then subsequently determine which of those species will survive.

The indigenous biota of Enewetak Atoll therefore are characterized by organisms highly adapted to the marine environment; they arrived at the Atoll primarily by ocean currents in the prehistoric past. A second component of the biota is represented by organisms introduced from other regions by man, either intentionally or by accident. Weedy plants and roof rats are examples of this biotic component. The flora of Enewetak Atoll demonstrates the dual origin of the biota very well. St. John (1960) (see Table 3) describes the Enewetak flora and lists 42 species of plants, four of which are native to Enewetak Atoll and all in the genus Pandanus. Although Pandanus was disseminated by both primitive and contemporary man, the endemic species are believed to have evolved on Enewetak, and their initial colonization occurred long ago when seeds or fruits reached the Atoll by ocean currents. The number of adventive weeds introduced by man on Enewetak Atoll is 27 species, and the food and ornamental species which may not persist number 26. There are seven species of plants that are known only from their seeds and fruiting structures that were found on Enewetak beaches, such as Barringtonia asiatica. The entire flora is represented by 95 species, more than half of which were introduced by man.

The natural climax vegetation of Enewetak Atoll, based on the relatively undisturbed examples available for study, appears to be the Pisonia grandis forest. Only a few other tree species are found in this almost pure forest type. The Pisonia forest is best expressed on the larger islands, although single individuals or clumps of trees may be found on smaller islands, but mainly those that are recovering from disturbance. Ochrosia oppositifolia, another large broad-leaved evergreen tree, is occasionally found in small clumps in the Pisonia forest on DAVID and GLENN Islands, but seldom forms a continuous stand on these islands.

The Pisonia forest on Enewetak Atoll usually occurs in dense stands where the only reproduction within the stand is Pisonia. Scattered individuals of the coconut palm, Cocos nucifera, occur in

Table 3. The flora of Enewetak Atoll (as reported by St. John, 1960).

Species			
Scientific name	Common name	Vernacular name	Remarks
Trees			
Pandanus brachypodus	Pandanus	Punmusi	Pandanus leaves are used for weaving plaited goods and thatch.
Pandanus enchabiensis		Maok	
Pandanus korrorensis		Bop	
Pandanus odoratissimus var. *novocaledonicus*		Bop	
Pandanus odoratissimus var. *novoguineensis*		Bop	
Pandanus pulposus		Jilebar	
Pandanus rectangulatus		Anilip	
Pandanus rhombocarpus		Papparawa	
Pandanus utiyamai		Bop	
Cocos nucifera	Coconut palm		Used for food and copra production.
Artocarpus incisus	Breadfruit	Me	Of aboriginal cultivation. Tree 8 m tall observed on Japtan, 1944.
Pisonia grandis		Kangae	Abundant, forming forests on better habitats.
Hernandia sonora		Bingbing	Fruits found on beaches, 1958.
Aleurites moluccana			Found only as seed on sea drift.
Sapindus saponaria			Found as seeds on beaches.
Carica papaya	Papaya	Keinapu	Recently introduced fruit tree. Observed 1958.
Rhizophora mangle			Introduced tree, restricted to tidal salty shores.
Terminalia samoensis		Kugung	
Ochrosia oppositifolia		Kijebar	Tissues poisonous.

Table 3 (continued)

Species			
Scientific name	Common name	Vernacular name	Remarks
Trees (cont.)			
Cordia subcordata	Heliotrope	Kono	Evergreen tree to 16 m.
Messerschmidia argentea		Kirin	Small tree. Leaves may be eaten.
Guettarda speciosa		Wut	A tree to 8 m.
Morinda citrifolia	Indian mulberry	Nen	Medicinal use.
Large Shrubs			
Ximenia americana		Kalikelik	Sour, edible fruit.
Suriana maritima		Ngiungi	
Ricinus communis			Introduced ornamental.
Pemphis acidula		Kungi	Hard wood. Leaves edible.
Nicotiana glanca	Tree tobacco		Introduced weed.
Scaevola frutescens var. frutescens		Mar kinat	The most abundant shrub, especially near the shore. Leaves used medicinally; wood hard.
Scaevola frutescens var. sericca		Mar kinat	
Wedelia biflora		Marguegue	
Small Shrubs			
Phymatodes scolopendria		Kino	Recorded only in 1944.
Cyperus javanicus		Wujoet in ion buil	Probably of aboriginal introduction.
Fimbristylis atollensis		Berelitchman	Native sedge, abundant on most habitats.
Achyranthes velutina			
Sida fallax		Kio	
Pluchea indica			Introduced weed.
Vines and Creepers			
Caesalpinia bonduc			Found only as drift seeds on the beaches.

Table 3 (continued)

Species			
Scientific name	Common name	Vernacular name	Remarks
Vines and Creepers (cont.)			
Canavalia microcarpa		Marlap	
Dioclea reflexa			
Entada phaseoloides			Known here only as seeds in the sea drift.
Maguna urens			Drift seeds on beach of Engebi.
Phaseolus vulgaris	String beans		In gardens.
Vigna marina		Markinejojo	
Triumfetta procumbens		Adat	A trailing vine used in weaving.
Ipomoea pes-caprae		Marginejojo	
Ipomoea purpurea	Common morning glory		Cultivated ornamental.
Ipomoea tuba		Marbele	
Citrullus vulgaris	Watermelon		Once grown in gardens.
Cucumis melo	Cantaloupe		Once grown in gardens.
Cucurbita maxima			Observed in gardens, 1944.
Grasses			
Cenchrus brownii			Introduced weed.
Cenchrus echinatus	Sandbur	Legalek	Introduced weed, abundant and troublesome in disturbed soils.
Chloris inflata			Introduced weed.
Cynodon dactylon	Bermuda grass		Deliberately introduced as lawn grass and as sand binder.
Dactyloctenium aegyptium			Introduced weed.
Digitaria pruriens	Crab grass		Introduced weed.
Eleusine indica	Goose grass		Introduced weed.
Eragrostis amabilis	Love grass	Wujoich	Common, but apparently an introduced weed.
Lepturus repens var. repens		Ujos aitok	The commonest native grass.
Setaria verticillata	Bristly foxtail		Introduced weed, abundant in disturbed soil near settlements.

Table 3 (continued)

Species: Scientific name	Common name	Vernacular name	Remarks
Grasses (cont.)			
Sorghum bicolor var. technicum	Sorghum		Cultivated crop grain.
Thuarea involuta		Ujos maroro	Local, uncommon, found on or near the sea beaches.
Tricachne insularis			Introduced weed.
Tricholaena repens			An introduced weed.
Zea mays			Once cultivated, observed 1944.
Herbs			
Cyperus odoratus	Sedge	Ujoet	Introduced weed, wet places.
Allium cepa	Onions		Onions reported in gardens in 1944.
Crinum asiaticum	Spider lily		Observed in gardens, 1944.
Tacca leontopetaloides	Arrowroot	Mokmok	Tubers grated and washed to obtain edible starch.
Fleurya ruderalis		Nenkutkut	
Achyranthes aspera		Kaleklek	Introduced weed.
Amaranthus dubius			Introduced weed.
Amaranthus viridis			Introduced weed.
Boerhavia diffusa var. diffusa		Matok aitok	Abundant.
Boerhavia diffusa var. tetrandra		Rabitchragai	
Mirabilis jalapa	Four-o'clock	Emen aur	Introduced, probably as an ornamental.
Portulaca lutea		Kiran	
Portulaca oleracea			
Portulaca samoënsis		Bujon	
Cassytha filiformis		Kenen	Parasitic entwining herb.

Table 3 (continued)

Scientific name	Species: Common name	Species: Vernacular name	Remarks
Herbs (cont.)			
Brassica oleracea	Cabbage		Cultivated vegetable.
Brassica pekinensis			Cultivated vegetable.
Raphanus sativus	Radish		Cultivated vegetable.
Tribulus cistoides	Caltrop		
Euphorbia chamissonis	Spurge	Berol	
Euphorbia hirta	Spurge		Introduced weed.
Euphorbia thymifolia	Spurge		Introduced weed.
Phyllanthus amarus			Weed introduced from America.
Malvastrum coromandelianum			Introduced weed.
Physalis angulata	Ground cherry		Weed introduced from North America.
Solanum lycopersicum	Tomato		Cultivated for its edible fruit.
Erigeron bonariensis			Introduced weed.
Lactuca sativa	Lettuce		In gardens, 1944.
Pluchea odorata			Introduced weed.
Vernonia cinerea		Senailing nagailing	Introduced weed.
Zinnia elegans	Zinnia		In American gardens, 1944.

some of the Pisonia forests. The canopy is usually complete, creating deep shade in the interior of the forest of pale, cream-colored compound trunks. Reproduction is both vegetative and by seedlings. The accumulation of organic matter is obvious in the Pisonia forest and is produced by the leaf fall which may occur during the drier portions of the year. Acidification of the alkaline soil materials eventually occurs after organic matter has accumulated, resulting in the dissolution of the calcareous soil materials, and in the precipitation of phosphates if significant quantities of bird excrement are present. There is a strong correlation between the occurrence of Pisonia forests and phosphatized soil materials.

Occasionally a large specimen of Messerschmidia argentia may persist in the Pisonia forest stand, usually at the outer edge. The other ubiquitous tree species, Scaevola frutescens, is seldom found in the Pisonia forest.

Two halophytic tree species are widespread on Enewetak Atoll and are found on most land surfaces, creating dense scrubby stands on islands recovering from test-period activities. The scattered to continuous stands of Messerschmidia argentea and Scaevola frutescens very likely represent a subclimax stage of the Atoll vegetation which will eventually develop into the Pisonia forest. Two other woody species occur occasionally in the vegetation types found on the Atoll, either in the Messerschmidia-Scaevola stands or at the edges of the Pisonia forest. These trees are Morinda citrifolia and Guettarda speciosa. Scattered individuals of these species are found on most of the islands, even those recently disturbed, which seems to indicate an effective means of seed dispersal. Another tree, Cordia subcordata, occurs on islands with well-developed forest types on them, but stands of any great extent have not been seen. Four other species of woody plants may be found occasionally, mixed in with Messerschmidia and Scaevola or at the edges of the Pisonia forest. These are Ximenia americana, Suriana maritima, Pemphis acidula, and Terminalia litoralis. Most of the woody plant biomass of the islands on Enewetak Atoll is formed by the four species, Messerschmidia argentea, Scaevola frutescens, Pisonia grandis, and Cocos nucifera.

The following simplified vegetation types are suggested and provide a useful framework of habitats upon which the rest of the biota depends, either for food or shelter and nesting sites:

- Pisonia grandis forest with coconut palms.
- Messerschmidia-Scaevola scrub forest: scattered to dense stands, with young coconut palms.
- Sedge-grass-morning glory meadows: often with the parasite Cassytha, scattered shrubs such as Pluchea and Sida.
- Grassy flats and beaches: usually near bird rookeries on small, recently formed islands.

Obvious relationships between plant species distribution and the low-relief topography are not apparent, although the general pattern of Messerschmidia-Scaevola scrub vegetation surrounding a central forested area occurs on most of the larger, undisturbed islands. The unobservable factor of substratum water conditions is very likely a strong determinant in the plant ecological characteristics of a given site. The vascular plants depend either upon rainwater held in the interstitial space of the coral sand or deeper groundwater for their water requirements. The presence of Ghyben-Herzberg lenses of fresh or brackish water at shallow depths in lenses beneath the central portions of the larger islands undoubtedly affects and promotes the lusher growth of these habitats.

The position of the island on the reef and exposure to storm waves may create conditions that favor the growth of the more halophytic species in the flora. Of the two common trees, Scaevola is apparently more salt-tolerant than Messerschmidia. It is often found at the edges of the beaches with Pemphis acidula and Suriana maritima, and is occasionally found in this exposed position. However, Messerschmidia is the primary woody plant invader of a newly formed islet or sandbar, and is often the only woody species on small islands.

The three woody species described above (Messerschmidia-Scaevola-Pisonia), plus the coconut palm, Cocos nucifera, are the most common component of the terrestrial flora on Enewetak Atoll. The coconut palm was introduced into the Marshall Islands sometime in the early 1800's. Hager (1885) provides the first descriptions of the northern Marshall Islands; very few observations of coconut palms were mentioned in his account, which placed the population of Enewetak Atoll at 40 people. The present pantropical distribution of the coconut palm is now generally attributed to deliberate dispersal by man. The lifespan of the coconut palm has been estimated at 50 to 60 yr, at which time nut production is declining. It is likely that the zenith of coconut-palm development on Enewetak Atoll was before World War II. Most of the trees on the Atoll at this time (1973) were planted after World War II or during the nuclear test period.

Within the rather limited framework of the vegetation types present on Enewetak Atoll, a small terrestrial fauna exists and perpetuates itself in this almost closed ecosystem. Mammals are represented by rats of two species, all of which were introduced to these islands, either during man's recent activities on the Atoll or in the prehistoric past. The Polynesian rat, Rattus exulans, is found on most atolls of the Marshall Islands, and is quite abundant on some of the southern atolls. This rat feeds on seeds of native plants and will eat fallen coconuts, although the general opinion is that their use of coconuts does not affect crop production when it is being harvested for copra. This rat is generally found in the sedge-grass-morning glory meadows and at the edges of the Messerschmidia-Scaevola thickets.

A second and larger animal, Rattus rattus, the roof rat, was introduced by man, earlier on trading vessels and more recently from ships carrying men and equipment during World War II, and during the nuclear test period. This larger rat is usually associated with dwellings and even though it competes successfully with Rattus exulans, it does not seem to thrive in the natural environments of the Atoll. The roof rat is said to eat green coconuts and has been known to seriously damage stored copra.

A third small rodent that may be found on the Atoll is the house mouse, Mus musculus, and is another product of man's activities on the Atoll. These rodents are probably found today only on DAVID Island, and possibly on ELMER and FRED Islands. They are not a significant component of the terrestrial fauna and are usually found around dwellings, where they scavenge food scraps.

No birds that are considered strictly land birds were seen on Enewetak Atoll during the recent survey of the islands. It is possible that the New Zealand cuckoo (Eudynamis taitensis) could be seen in the northern Marshall Islands as a migrant species. Most bird species observed at Enewetak Atoll are either reef or seabirds. The seabirds range across the open sea and some may be considered pelagic, coming to rest only occasionally on remote atolls. The reef birds typically obtain their marine food source within the Atoll, either on the reefs or in the lagoon. A third avian component of the biota is represented by migrant species. The migrant birds typically nest in the high latitudes of the northern hemisphere and winter in the South Pacific area. The golden plover, *Pluvialis dominica fulva*, is a good example of a migrant atoll bird species.

The fairy tern, *Gygis alba*, and the common noddy, *Anous minutus*, are examples of reef birds frequently seen at Enewetak Atoll. The sooty tern, *Sterna fuscata*, and the red-tailed tropic-bird, *Phaeton rubricauda*, range offshore on the open sea. Reef herons, *Demigretta sacra sacra*, are frequently seen at the water's edge on the islands of the Atoll. The bristle-thighed curlew, *Numenius tahitiensis*, and the whimbrel, *N. phaeopus*, and various species of sandpipers are migratory species in the Atoll avifauna.

Two crustaceans are found in the terrestrial habitats on Enewetak Atoll. The coconut crab, *Birgus latro*, occurs on most islands that support producing coconut palm trees. The islands in the southwestern portion of the Atoll have comparatively large populations of coconut crabs, and islands such as Igurin (HENRY) may be supporting maximum populations of this crustacean. The coconut crab excavates a shallow burrow in the organic matter around the bases of coconut trees, often beneath the crown of the tree itself. The coconut crab spawns in the lagoon waters, and the larvae leave the water and grow to maturity on land.

Another crab, the hermit crab, *Coenobita perlatus*, may be found on islands of Enewetak Atoll, scavenging vegetal and animal debris within the forests and along the beaches. Another species of *Coenobita* occurs on the Atoll, but it is primarily an inhabitant of the beaches.

The previously described Atoll habitats and the animals constitute the major features of the Enewetak terrestrial ecosystem. Other species are present and may play small roles in the functioning of this unique ecosystem, but the ones described here are the most prominent biotic features of the Atoll. The uniqueness of the Enewetak environment lies in the relative isolation of the Atoll, the evolution of the specialized biota, and the functioning of the terrestrial ecosystem, which is strongly affected by the local marine environment.

Marine Ecology

General features of the ecology of the Enewetak marine fauna may be described as follows:

On the reef and in the lagoon there is an abundance of plant and animal life in which the competition between different species for space and food is evident. Masses of reef-building coral are competing with the coralline marine algae for space, one often overgrowing the other. Fleshy patches of algae are pressed tightly against the surface of the coral and thus hold against the surges of the water pushed across the reef by the crashing breakers. Sea urchins and clams grind niches into the hard coral; some of them feed on the cover of bacterial and algal film which is constantly being replaced. The clams, the corals, some small fish, and other forms are ceaselessly removing from suspension in the water the small, often microscopic, plants, animals, and bits of debris which make up the plankton. In regions of quieter water, where sand has been deposited, sea cucumbers and spider snails, among the larger forms, turn the sand continuously in their gleaning for food.

Large schools of goatfish, mullet, surgeonfish, and other plant and plankton feeders are a common sight. Preying on unwary or disabled members of these schools are the carnivorous fish—the groupers, tuna, jacks, and sharks. Ultimately the waste products and carcasses of these and other carnivores are returned to the lagoon and reef to complete the cycle. In the biological cycling of materials, there is not only an abundance of organisms, but also a wide variety of species, some 700 among the fishes alone, so that whatever is not utilized by one is quickly taken by another. There is here a perfect economy of use of substance essential to life. The phytoplankton comprise the foundation of the food chain in the sea. By their diurnal vertical migration, plankton carry materials from the deeper waters of the lagoons to the surface or even up onto the reefs and eventually to the islands. Minerals as well as organic materials, concentrated and incorporated into the algae, are passed on in the food chain to the animals that feed upon them.

Invertebrates make up the great bulk of the animal life of an atoll. Sea cucumbers have been compared with earthworms in their ceaseless turning of the gravel and sand as they obtain their nutriment from bacteria and algae. Corals and clams remove microorganisms and particulate matter from the water and are eroded by algae and sponges, which bore holes in the skeleton or shell, thus contributing to a return of carbonates to the water. Crabs, sipunculid worms, and others also attack the skeleton of the corals. Some of the land crabs drag fish and algae ashore when feeding. In short, within the invertebrates and their symbionts alone, complete biological cycles occur from land to sea and back again.

Historical Background of Enewetak Atoll

The recorded history of Enewetak dates from the sixteenth century and can be separated into four distinct periods: the discovery era from 1526 to 1885; the German Protectorate from 1885 to 1914; the Japanese Mandate from 1914 to 1944; and the U. S. Trusteeship from 1944 to the present time.

Discovery Era

The Atoll was first reported sighted by Spaniards in 1526, three years before a landing was made by Alvaro de Saavedra in October 1529. Several other sightings were reported by the British from 1792 through the end of the 18th century. However, it appears that no significant contacts were made before the 19th century, although the first official survey and charting was made in 1798.

German Protectorate

In 1886, the Germans formally established a protectorate over the Marshall Islands, following some years of trading. The Marshallese, including the Enewetakese, accepted coconut seedlings from German traders and sold the resulting copra back to the Germans for trade goods and food. This involved the Enewetak people in a move from a subsistence economy to a mixture of a cash and a subsistence economy. The Enewetakese were somewhat on their own because the Germans did not have a resident agent, nor were there other resident Europeans, and foreign visitors were kept to a minumum.

Japanese Mandate

The Japanese Mandate commenced with the seizure of Enewetak and all other German Micronesian possessions in 1914. As in the case of the Germans, visits to Enewetak were made by the Japanese Navy in 1920, as well as by Japanese traders, but no attempts were made to establish a full-time administration. Both Enewetak and Ujilang were administered from Ponape in the Carolines, and the only foreign residents on Enewetak were a Japanese trader and his two assistants. Aside from a weather station, established in the 1930's, Japanese contact with the Atoll languished until the years 1939-1941. During this period, the Japanese decided to make Enewetak a strategic base in their conquest of the Pacific. The Atoll was elaborately fortified and a large airfield was built on JANET, using both Marshallese and imported labor. Thousands of Japanese military personnel then occupied the Atoll.

U.S. Trusteeship

Enewetak remained as a key bastion of the Japanese until it was captured by the U.S. forces in February 1944. The United States occupied the Atoll until the end of the war, using it as an advanced base for further operations to the east. The Enewetakese were moved to SALLY during the occupation.

At the conclusion of the war, the United States was given a trusteeship of the Marshall Islands by the United Nations.

Use as a Test Site—Between 1948 and 1958, the United States used Enewetak as a nuclear weapon proving ground and conducted 43 nuclear tests on the Atoll.

The U.S. Coast Guard has maintained a loran station on the island of Enewetak for several years; since the early 1950's, the University of Hawaii has operated the Eniwetok Marine Biological Laboratory under the auspices of the U.S. Atomic Energy Commission.

Relocation of Enewetak People—During the U.S. occupancy of Enewetak Atoll, 141 people were in residence. Prior to the 1944 invasion of Enewetak, the population of the Atoll was divided into two communities; one was located on Enewetak Island (FRED) and the other on Engebi Island (JANET). After the invasion, both communities were moved to Aomon Island (SALLY), which was under the authority of the Chief of the Enewetak Island Community (Chief Ioanej). Later, the Engebi community moved (at their own request) to Bijile Island (TILDA) because the latter was under the authority of the Chief of the Engebi community.

Thus, the Engebi people were moved twice prior to relocation to Ujilang (Engebi to Aomon to Bijile), whereas the Enewetak people were moved once (Enewetak to Aomon) prior to relocation to Ujilang. In December 1947, the people were transferred 124 mi to the southwest to then uninhabited Ujilang, where they have remained.

Anthropology—Enewetak People

Most anthropologists are of the opinion that the Marshalls and other islands of Micronesia were settled by peoples who migrated from the area of Indonesia and into the insular Pacific centuries ago. Reflecting the ancient migration patterns in Oceania, the Marshallese language belongs to the large Malayo-Polynesian language family which is spread from Madagascar, through the Indonesian area, and across Micronesia, Polynesia, and some regions of Melanesia. With regard to physical type, the Marshallese are relatively short in stature and of slender build. They have brown skin, brown eyes, broad flat noses, straight to curly black hair, and sparse body hair.

According to their own oral traditions, the people of Enewetak had always lived on Enewetak Atoll prior to their relocation to Ujilang; in their own words: "We were there from the beginning." Because of Enewetak Atoll's isolated location in the northwestern region of the western of the two island chains which comprise the Marshallese archipelago, the people had relatively little contact with others prior to the European era. As a consequence, the language and culture of the Enewetakese became differentiated from those of other Marshall Islanders, and the people did not identify themselves with the others. Rather, they thought of themselves as a people who were separate and unique, "the people of Enewetak" as opposed to the islanders to the east and south.

The past and current accomplishments of the Enewetakese reflect intelligence and qualities of ingenuity, self-reliance, and hardiness which have allowed them to meet the challenge of the atoll environment which is quite restrictive in comparison to the high volcanic islands of Oceania. Long before the advent of Europeans, they had developed a culture which represented a sophisticated adaptation to their ecological setting. They were skilled navigators (an art which has been lost with the availability of travel on the vessels of foreigners); they remain expert builders of sailing canoes and are among the world's best fishermen. In response to traders, missionaries, and the successive colonial governments which have dominated the islands over the past century, they have been quick to learn and adjust to the different categories of outsiders. Today, they have achieved a good understanding of the behavior and values of Americans, and several have distinguished themselves in government and mission schools.

Economic and Cultural Resources

Throughout the Marshall Islands, the traditional forms of settlement pattern and exploitation of the natural resources are characterized by several general features. First, the people of an atoll reside on one or more of its largest islands. Secondly, the people are quite mobile as a nonintensive type of agriculture and various fishing and collecting activities are extended to embrace every niche of the environment. Regular expeditions are made to all islands in an atoll to make copra and collect coconuts, breadfruit, pandanus, arrowroot, and other vegetable foods in season. The brush is cleared and crops are planted during these visits. The marine resources are also exploited and a wide variety of marine animals are utilized. Routine expeditions are made to catch fish, collect shellfish, and capture turtles and gather their eggs. Several species of birds are also captured as a food source. The Enewetak people may be expected to continue this way of life to some degree when they return to their home atoll, as influenced by their contacts with Western culture.

Sociopolitical Pattern

Before their relocation to Ujilang, the Enewetakese were divided into two separate and distinct communities (community is defined as the maximal group of persons who normally reside together in face-to-face association) which were located on the two largest islands of the Atoll. One was situated on Engebi Island on the northern rim, and the other was located on Enewetak Island, across the lagoon in the southeast quadrant of the Atoll. The traditional settlement pattern of both communities was dispersed; residences were located on separate land parcels and were scattered along the length of the lagoon beach.

Members of the two communities intermarried and cooperated in certain economic activities. Each functioned, however, as a separate sociopolitical unit, and its members had their own identity. In contrast to the identity of "the people of Enewetak," as they defined themselves in reference to all other populations, the people of the Engebi community were identified as driEngebi, "the people of Enjebi Island," and those of the Enewetak community were driEnewetak, "the people of Enewetak Island."

The sociopolitical structure of the two communities was identical. Each was headed by an hereditary iroij or chief, and succession to the office was patrilineal. Chiefs directed the affairs of their respective communities, arbitrated disputes, and consulted one another with regard to concerns of the entire Atoll and the total population's relations with outsiders. Each of the chiefs had authority over one of the two domains into which the Atoll was divided. The domain of the Enewetak chief began with the Islands of Kidrenen, Ribewon, Boken, Mut, and Ikuren in the Atoll's southwest quadrant, extended counterclockwise around the Atoll's south and western rims up to and including Runit Island, and also included Aomon on the northeast rim. With the exception of Aomon, the Engebi chief's domain began north of Runit with Billae Island and extended counterclockwise around the Atoll's northern and western rims, up to and including Biken Island.

Relations between the two communities and the traditional dispersed pattern of residence were altered with the invasion of Enewetak Atoll. Because Enewetak and Engebi Islands were devastated by warfare, the U.S. Navy resettled all of the people in a compact village on Aomon Island which, as indicated above, fell within the domain of the Enewetak Island chief. After several months, the Enjebi people moved to the nearby and adjacent Bijile Island which was within the domain of their own chief. With these relocations within Enewetak Atoll, the Engebi and Enewetak peoples were no longer separated by the Atoll's large lagoon, and while retaining their dual political structure, they in fact became a single community.

The consolidation of the population into one community and the new compact settlement pattern were perpetuated with the islanders' resettlement on Ujilang Atoll. It has only one sizable island, Ujilang Island, and the entire population was resettled there. Navy officials established a dividing line at the midpoint of the island and allotted the western half to the Engebi people and the eastern half to the Enewetak people. A compact village was constructed in the middle of the island, with the Engebi and Enewetak peoples occupying houses on their respective sides of the dividing line. Later, each group divided the land on its portion of the island. At a still later date, other islands in the atoll were divided among members of the two groups.

During the initial years on Ujilang, the traditional political structure remained intact. The chiefs functioned in their accustomed roles, and they resisted American efforts to introduce democratic institutions. (According to American designs, each atoll population was to be governed by an elected council of elders headed by an elected magistrate.) By the early 1960's, however, some change was observable. Both chiefs were by then aged men, and because they were men who had matured in a former era, some contemporary problems required that the decision-making process be opened to include younger men who had attended schools and/or had some other experiences with the American administration. Meetings of all males were occasionally held, and some decisions about community affairs were decided by a majority vote. The authority and status of the chiefs further declined in the late 1960's, when the old Engebi chief died and was succeeded in office by his younger brother, who was also aged and suffered from frequent poor health.

The combination of the above events precipitated a major transformation in the political structure. The chiefs yielded to younger men who desired and had been gaining a greater voice in community affairs. Then, in 1968, a magistrate and a council of 12 men were elected; reflecting the traditional division of the population, the Engebi people elected six councilmen from among their ranks, and the Enewetak people elected six. The magistrate became the head of the entire community, and the council became the legislative body governing the people's affairs. In a very recent election, however, the 12 councilmen were elected from the population at large and not from the two groups. Thus, the current council reflects a demise of the traditional system and indicates that the old division between the Engebi and Enewetak peoples has lost much of its meaning. The council is now a representative body drawn from the entire population and reflects a unified community with acknowledged common goals. The chiefs, however, remain important figures as advisors and men of influence.

Church and Religion

The church is the focal point for many community social activities of the Enewetak people. The prevailing religious system is a conservative type of Protestantism in which church services, Bible classes, church group meetings, and hymn singing have replaced traditional intertribal wars, sports, games, and dancing.

The minister is the spiritual leader of the community and is supported and assisted by the chiefs of the clans. The church functions are time-consuming and require a considerable effort from the membership. Sundays in particular are devoted almost entirely to church services and related activities. Thus, it is apparent that the church influences the life ot the Enewetakese to a great degree.

Land Ownership

The Enewetak Atoll soil is poor, and thus agriculture is limited. For centuries, subsistence has been marginal and precarious for the island inhabitants, despite hard work. Nevertheless, the residents have always maintained a deep emotional attachment to their home islands and ancestral land.

The land parcels, or wato, at Enewetak Atoll were like those found elsewhere in the Marshalls. Most commonly, each was a strip of land stretching across an island from lagoon beach to ocean reef and varying in area from about 1 to 5 acres. The resources of all ecological zones were thus available to the individuals who held right to the land. Less commonly, a parcel was divided into two or more portions with transverse boundaries. This usually occurred when an island (e.g., Engebi) was very wide. Boundaries were usually marked by slashes on the trunks of coconut trees, or less commonly, ornamental plants. Also, other features of the natural topography (e.g., large boulders on the ocean reef and the very configuration of an island) were used to fix the position of landholdings. The latter type of markers were employed by the Bikini people, for example, after all other markings had been obliterated.

One facet of Enewetak Atoll culture that differed from that of the rest of the Marshalls was the system of land tenure and inheritance. In contrast to the rest of the Marshalls, where matrilineal descent groups known as bwij or lineage constitute landholding corporations, the land tenure system at Enewetak was in ideal and practice a bilateral one. In most cases, a married couple divided the land they had each inherited among their children, and a child usually received some land from both his father and mother. As younger islanders matured, they worked the land with their parents. As the parental generation died and as members of the next generation married and produced children, the process was repeated with parents allocating land among their offspring.

The islanders resided on their landholdings on Engebi and Enewetak Islands. Households were either extended or nuclear family groupings. In most cases, households were headed by males and were situated on land held by them. Ideally, residence was patrilocal; i.e., upon marriage, females moved to their husbands' households, although exceptions to the rule did occur.

Every individual possessed rights to some land on islands away from the settlements on Enewetak and Engebi. All land in the Atoll was held by someone, except for one parcel on Enewetak Island which was donated to the mission.

PRESENT STATUS OF THE ENEWETAK PEOPLE ON UJILANG

Comparison of Ujilang and Enewetak

Ujilang lies 124 mi southwest of Enewetak (see Fig. 5). In pre-European times, Ujilang was inhabited by a Marshallese population. In the 1890's a typhoon decimated the atoll, and killed all but a handful of people who were moved to the southern Marshalls. The atoll was then developed as a commercial copra plantation during the German and Japanese colonial eras. During the plantation period, a small group of islanders from the Eastern Carolines served as wage laborers on the atoll. However, it was abandoned during World War II and was thus uninhabited and available for the relocation of the Enewetakese.

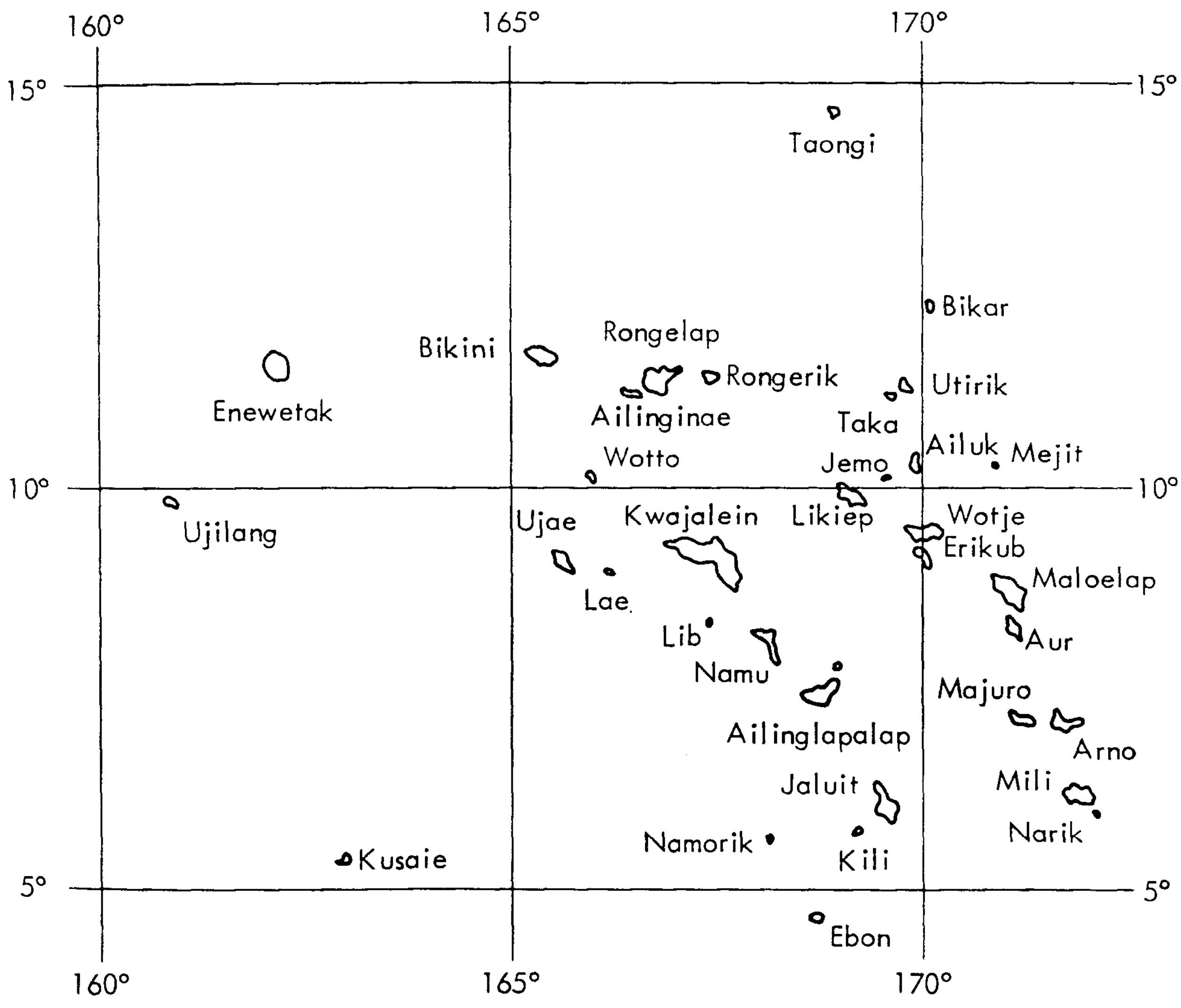

Fig. 5. Marshall Islands.

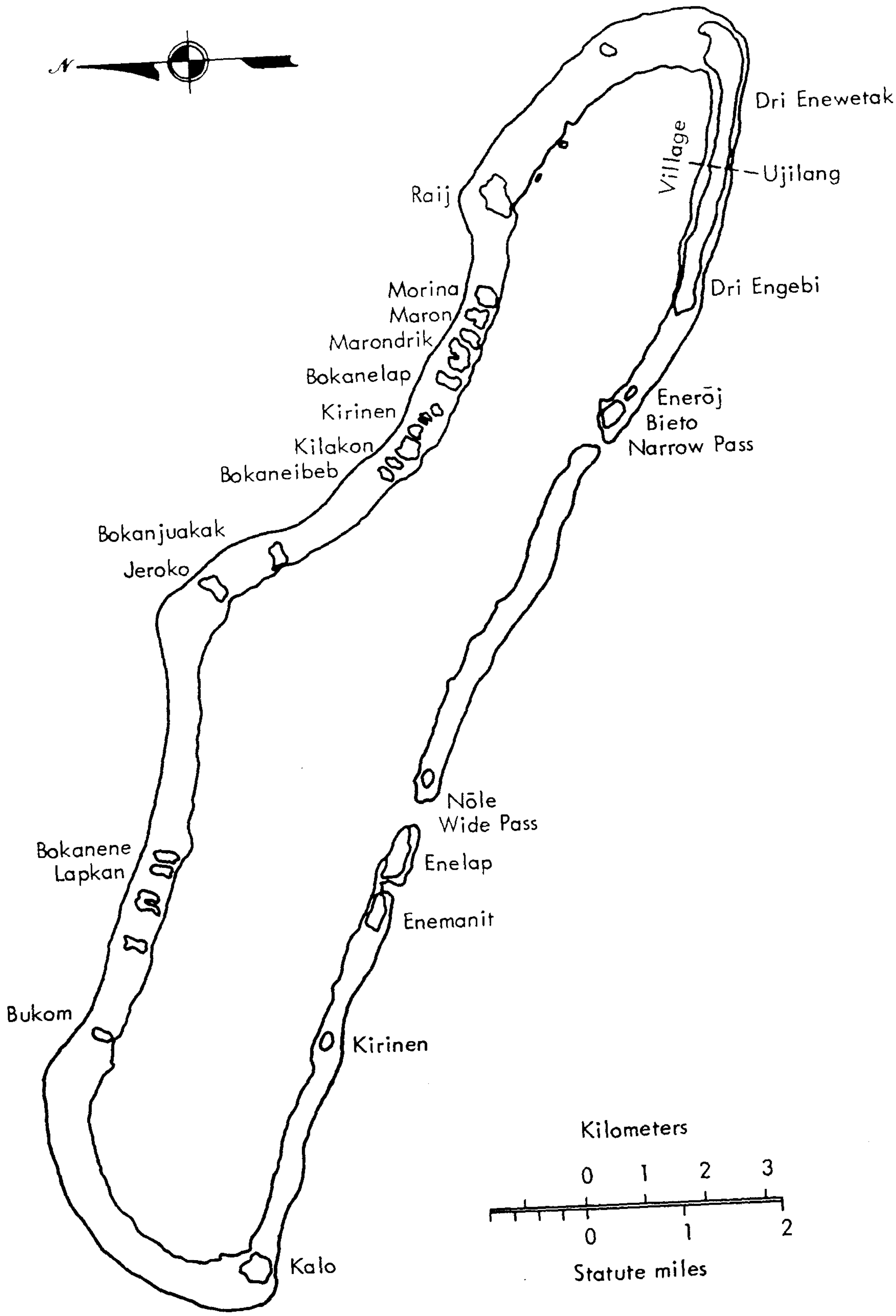

Fig. 6. Ujilang Atoll.

Ujilang is also smaller than Enewetak, both in size of the lagoon and in the total dry land area (see Fig. 6). A comparison of the areas of both atolls shows:

	Area, mi^2	
	Lagoon	Dry land
Ujilang Atoll	25.47	0.67
Enewetak Atoll	387.99	2.26

From this comparison, it is apparent that the potential for production of food from the reefs and lagoon is considerably less on Ujilang than it is on Enewetak. The limited food potential on Ujilang has made it necessary to import more commodities than would normally be required on Enewetak. This has been reported to have presented some difficulty because Ujilang is located further from the sources of the needed commodities than Enewetak.

Living Conditions on Ujilang

The U.S. Navy constructed a village on the main island of Ujilang for the displaced Enewetakese, and a brush-clearing program was in progress when they arrived on the atoll. Coconut trees planted during German and Japanese administrations were still standing and bearing. Seedlings of breadfruit and pandanus were brought ashore and planted. After the Enewetak people had settled in, the Navy departed. There was no U.S. official remaining on the atoll, nor was there any radio communication with the outside world.

The former Enewetak inhabitants attempted to adjust to their new location. They had, and still have, several formidable problems with which to cope. The most obvious, and one which they have uppermost in their minds, is the great disparity in the sizes of Ujilang and Enewetak, as previously mentioned. The traditional Marshallese pattern of habitation is for family units to live on their land parcels, not in a village cluster. While it is common for community buildings, church, school, dispensary, and warehouse to be centralized for convenience and access to all, dwellings are usually dispersed over the length of the lagoon beach of an island. This pattern is obviously desirable from the point of view of environmental sanitation and public health. As described, the traditional settlement pattern of the Enewetakese was disrupted because of their relocations.

Natural Resources

The people practice a nonintensive type of agriculture but utilize the environment to the maximum, using the plants that can survive and produce in the atoll environment. Coconut is converted to copra for cash sale to the visiting Trust Territory supply ship. Consumer goods are purchased from the ship with the proceeds of the copra sales. The interest payments from the trust funds provided by the TTPI administration also help buy needed commodities. Rice, flour, sugar, canned meats, and other canned goods are staple items of the diet and have been for many years. Fish, clams, lobster, turtles (flesh and eggs), sea birds (flesh and eggs), chickens, and pigs provide protein in the diet. The marine resources are extremely important in the diet of these people.

Coconuts, pandanus, breadfruit, and arrowroot are the main vegetable products used. Bananas, papayas, and squash are used to a lesser extent, probably due to the relative scarcity of the banana and papaya which do not seem to grow well on Ujilang.

The Enewetak population shares the upward trend of the rest of the Marshall Islands and Micronesia. Records show an increase from 104 in 1925 to 432 in 1972. This tendency toward increased population among the Enewetak people is resulting in a further drain on the inadequate resources of Ujilang. A census made in early November 1972 produced the following data on the location of Enewetak people:

Ujilang Atoll	340
Majuro Atoll (DUD)	31
Majuro Atoll, Rongron Is.	18
Maloelap Atoll, Marshall Is.	3
Kili Island, Marshall Is.	7
Ponape, Eastern Caroline Is.	5
Crew members on Trust Territory ships	4
Residing in the United States	3
Total Enewetak people	411
Married to Enewetak people and living on Ujilang (integral part of the community)	21
Grand total	432
Males	226
Females	204
Sex not reported	2
Grand total	432

(Tobin, 1973)

Economic Status

The TTPI administration has attempted to upgrade copra production and subsistence agriculture for the past several years with some noticeable improvement. However, the Enewetak people are not as economically well off as they would have been if they had not been uprooted from the larger Atoll.

The unfavorable economic situation and the persistent desire to return to Enewetak finally stimulated aggressive action by the people. They threatened to evacuate the atoll in 1967, and in 1968 the leaders petitioned the United Nations for assistance in returning to Enewetak. In 1968, they again threatened to evacuate the atoll and come to Majuro. Economic help was given them by the administration, and relief shipments of food were sent to the community. An ex gratia payment of $1,020,000 was made to them in 1969 and placed in a trust fund; the interest from the fund has helped. Funds were also allocated for a construction program to improve the housing on Ujilang and for the construction of badly needed public facilities on the atoll. The Ujilang community assumed the responsibility for doing the actual labor involved.

Preferences of the Enewetak People for their Future

Efforts to ameliorate living conditions on Ujilang, while welcome, did not lessen the desire of the people to return to their ancestral homeland. They continued to press for this goal. Discussions and meetings were held with government officials. Finally, on April 18, 1972, the High Commissioner informed the District Administrator that Enewetak Atoll would be returned to the jurisdiction of the TTPI by the end of 1973.

It is expected that all of the 432 Enewetakese will return to their Atoll. However, it is not known whether those who have interests elsewhere will remain permanently, or leave after visiting their relatives and old land claims. It is assumed that these people will eventually retire on Enewetak.

A planning council has been formed, consisting of Enewetakese, who are empowered by the people to make decisions within specified limits on matters pertaining to short-term, intermediate, and long-range planning. The council will be augmented by technical advisors to assist them in translating the desires of the Enewetak people into workable plans. The advisors will work closely with the planning group and other Enewetakese in their particular fields, e.g., architecture, short- and long-range economic development, and agriculture.

EXPECTED LIVING PATTERNS AFTER RESETTLEMENT

Introduction

The successful resettlement of the people of Enewetak will depend strongly on the interaction of their current life style with the provisions made for them by the U.S. Government. While the present life style is a result of over a hundred years of first German, then Japanese, and finally American influence, the greatest impact has occurred since the end of World War II. The creation, under U.N. charter, of the Trust Territory of the Pacific Islands, and the subsequent military development of strategic defense areas in the Marshall Islands, has brought the simple food-gathering culture of the Marshallese into close contact with twentieth-century technology.

In order to gather some first-hand information on the living habits, attitudes, and desires of the modern Enewetakese, a field team spent the period of July 21-31, 1973, on Ujilang. The team was composed of Carlton Hawpe (Holmes and Narver architect), Howard Schoss (Peace Corps architect), John Stewart (AEC/NVOO), Kenneth Marsh (LLL), and Thomas Makiphie (interpreter from Micronesian Legal Services). Hawpe and Schoss were to meet with the Enewetak planning council to determine where and how the people intended to live on Enewetak, what types of houses they preferred, and what they wanted in the way of cooking and sanitary facilities. Stewart and Marsh were to collect specific information on the people's daily activities and their diet, with particular regard for the implications to radiological dose-assessment calculations.

Victor Nelson, University of Washington marine biologist, was to be a member of the team, but transportation difficulties resulted in a two-week delay on Enewetak and, because of other commitments, Nelson had to return to Seattle. During the two weeks on Enewetak, however, he spent considerable time with Smith Gideon, a native of Enewetak who was then Magistrate of Ujilang, collecting data on the fish preferences of the Marshallese. In his report (see p.46) Nelson recommends that a composite of the Ujilang, Bikini, and Rongelap diets be used to estimate the average diet of the Enewetakese.[*]

Originally, the present residents of Ujilang lived as two tribes (<u>dri</u>) on separate islands around the Enewetak lagoon, the driEngebi on Engebi in the northern

[*] See Chakravarti and Held, <u>J. Food Sci.</u> <u>28</u> (2) (1963).

half of the atoll, the driEnewetak on Enewetak in the southern half. The Ujilang Atoll, by contrast, has only one island large enough for permanent habitation; hence, today everyone lives on the main island of Ujilang. This island, roughly the same size as Enewetak, is about 2.5 mi long by 0.1-0.2 mi wide. The "town square" divides the island in half and consists of the meeting hall, dispensary, church, and school. The half of the island east of the town square belongs to the Enewetak people, while the western half belongs to the Engebi people. Even though the two tribes have intermarried to such an extent that, as Magistrate Smith Gideon says, "we are one big family," the old division is maintained.

Almost everyone lives in the village, which extends a few hundred feet to either side of the town square. There are a few houses scattered over the rest of the island, but these are used only a few days at a time, mostly by older people on food-gathering trips. Houses are constructed of plywood and corrugated sheet metal, with the floors usually about 0.7-1 m above ground. The space under the houses is used for relaxing in the shade, and the pigs generally rest there as well.

An increase in the birthrate has resulted in a very young population. Ninety percent of the people are under 40 years of age, and almost 50% are under ten. During the field team visit, a population anomaly existed in that there were no children of high school age on the island, even though they comprise about 10% of the population. This is explained by the fact that the high school is located 800 mi away at Majuro and, while school had been out over a month for summer vacation, no ship had been available to return the students to Ujilang.

There were many opportunities for misunderstandings to occur. Makiphie spoke Marshallese and English fluently, but had no knowledge of radioecology. Hawpe and Schoss spoke good Marshallese, but also had no knowledge of the radiological aspects of Enewetak. On the other hand, neither Stewart nor Marsh, the radiological experts, spoke any Marshallese. The tendency of the people to want to be polite and to please their visitors by giving what they believed to be the desired answer, a problem mentioned by other investigators, was evident and probably had some effect, but much of the data in this report is based on personal observations. These problems do, however, lend weight to Nelson's suggestion that a composite of data would best forecast living habits after resettlement.

This section was reviewed in draft form by Jack Tobin, Trust Territory Community Development Advisor, and many of his comments have been incorporated into the final version.

Development of Island Communities

The islands of Medren (ELMER) and Engebi (JANET) are preferred for permanent dwellings, with possibly some people living on Enewetak (FRED), depending on facilities remaining after the rehabilitation. Japtan (DAVID) has been suggested as a temporary location for a work force during the cleanup, but might develop into a semipermanent settlement. If too many restrictions remain on and around Engebi for comfortable permanent habitation, the people may divide Medren in half and live there, probably as they do now on Ujilang. Second-home houses on Engebi would still be desired by some people, and could be built either as part of the rehabilitation or by the people themselves at a later time. If the plan suggested by Carlton Hawpe is adopted by the Enewetakese, there will be three to six houses per cluster on each wato. The houses will be located about 100 ft or so inland from the lagoon beach, behind a "green belt" of coconut trees. A wato is a strip of land extending from the lagoon side to the ocean side, occupied by a single family group (10-40 people). On wide islands, such as Engebi, the wato may not include both beaches, but access to both sides of the island will be provided.

Houses will be constructed with the floors about 0.7 m above grade, the intervening space filled with concrete and coral aggregate. The floors themselves will be either concrete or plywood, and the walls will be either poured concrete or concrete block. Roofs will be corrugated sheet metal, provided with troughs for collecting and transporting rainwater to cisterns. A high degree of resistance to typhoons is desired.

There is no furniture in a typical Ujilang house, and no decorations on the walls. Some food may be stored inside and a few possessions like mirrors, hand-cranked sewing machines, kerosene lanterns, or anything subject to rain or pig damage are kept there, too. These items are usually on the floor and very rarely are there any shelves or definite storage facilities.

Areas around the houses will be covered with coral gravel. The Ujilang people renew and add to this covering from time to time by scattering gravel collected from the ocean beach. This area is kept free of grass and trash.

Rainwater, collected from the roofs of buildings, will be the principal source of fresh water. Ujilang has several concrete cisterns, but most people have two or three 55-gal drums, fed from the roofs of their homes. One of the concrete cisterns has a 10,000-gal capacity and uses the roof of the church as a catchment. It is used by the general community, and probably a similar cistern would be built on Enewetak. The proposed plan for the Enewetak houses calls for a built-in cistern in each house, with a storage capacity sufficient for several weeks. Well water is brackish and not used at all when rainwater is plentiful; however, as rainwater stocks decline, well water will be used first to wash clothes, then for the daily bath, and only as a last resort for drinking or cooking. It should be noted that Enewetak receives somewhat less rainfall than Ujilang, and therefore well water might have to be used to a larger extent. However, this same lack of rainfall also is responsible for a more brackish well water on Enewetak, making it even less palatable. Well depths on Ujilang varied from 2.5 to 6 or 7 m, but several people who lived on Enewetak remembered the wells there as deeper than any on Ujilang (therefore estimate about 10 m). Medren Island presently has considerable area in the form of concrete slabs and metal roofing which could be used for catchment purposes. The airfield alone on Enewetak could probably supply the entire population with water, given a collection and distribution system. It should be possible to make up in area what is lacking in rainfall, at least for the southern islands of the Atoll.

Routine for Daily Activities*

A few activities are common to all members of the household. Families retire for the night between 10 and 11 p.m. Everyone sleeps inside the house on a woven pandanus-leaf sleeping mat spread on the floor. A typical mat is made up of a double thickness of leaves, about 75-100 cm wide by 150-180 cm long, and weighs about 1 kg. Double mats are also used, with the width and weight increased about a factor of two. Almost everyone arises between 6:30 and 7:30 a.m.

Two or three days a year the entire family will go on a one- or two-day picnic to one of the other islands. However, transportation is a real problem, and there was one girl, 14, who had never been off the main island of Ujilang.

Married women (essentially all women over 16-17 years of age) spend the whole day in or around the house attending small children, cleaning, washing clothes and cooking. The Marshallese are very concerned with personal cleanliness. Everyone bathes every day and washing clothes is a daily activity. Houses are swept several times a day, and the custom is to remove shoes or zories (if any) before entering the house. Clothes are washed outside, usually by teenage girls or older women. Many people have set aside a particular area for laundry by making a raised bed consisting of a framework of coconut logs filled with coral gravel. These beds are typically 2-3 m on a side and 1/2-1 m high. Clothes are washed in a pan (~50 cm diam) with soap powder, if available, by a combination of wringing, rubbing on flat rocks or plywood, and pounding with a stick. They are then rinsed and hung on a line to dry. This treatment is a little rough on the fabrics, but they are clean. Cooking and food preparation will be discussed in another section.

Men spend the morning hours in and around the houses, cleaning up outside the house, smoking, visiting with each other, and generally taking it easy. Afternoons are spent much the same way, although these days considerable time is spent in meetings regarding the return to Enewetak. If a breadfruit- or coconut-gathering trip is made away from the village, it will usually be early in the morning before the heat of the day. Similarly, a fishing trip near the village might be planned to take advantage of known fish movements. The only significant deviation from this routine occurs on Saturday, when the cooperative fishing

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*Tobin feels that the presence of the survey party had a strong influence on the daily habits of the people, especially the men. He says the Marshallese are naturally curious and tend to stay close to visitors. Also, the action and excitement were a welcome change from their usual routine. For these reasons, copra production and outer-island trips were probably curtailed. This points up the difficulty of gathering reliable information. The presence of the observers tends to affect that which is observed, but on the other hand, too much reliance on interviews runs the risk of bias from "cooperative answers." Again, the best picture is a composite from several sources. With regard to the survey party's effect on the people's routine, however, it should be mentioned that for at least several years after the resettlement of Enewetak, frequent and numerous visitors may be expected.

trip to other parts of the lagoon takes place. Fishing in general will be discussed in a separate section.

Children up to the age of about 3-6 years spend most of their time around the village close to or inside their houses, under the supervision of their mother and older children. Children from about 6 years up to about 10-15 years spend their time in school and playing around the village between the ocean and lagoon.

At least half of the children's free time is spent playing on the lagoon beach and in shallow water; the remainder is about evenly divided among the village, surrounding forest, and ocean beach. Girls from about 12 to 15 perform many of the arduous household tasks, such as grating coconut or preparing breadfruit. Boys of this same age climb the coconut and breadfruit trees to harvest green "drinking coconuts" or ripe breadfruit.

School was not in session in July; they observe a June-to-September recess. Children start first grade at about 6 years and are required to attend through the eighth grade. School hours are 8-12 a.m. and 1-3 p.m. The school is a one-room structure, and students sit on the floor. Subjects taught are English, mathematics, social studies, science, and physical education. Most eighth grade graduates can read and write Marshallese. If students wish to attend high school, they go to the district center at Majuro, and the official language is English. At about age 15, if they do not attend high school, children begin to assume more of the duties of adults.

Table 4 provides a rough estimate of the amount of time spent by men, women, and children in various locations. For dose-assessment calculations, hours per week is probably the best unit. Hours per day would carry a large standard deviation (~20-50%), while hours per month would be unnecessarily coarse, except for time spent off the main island. How these estimates would change for Enewetak is very difficult to predict. With the much larger and less protected lagoon there, transportation will have a strong influence. If reliable boats are available, the total time spent by men on the lagoon water and other islands would probably about double or triple, at the

Table 4. Time spent in various areas of the Ujilang Atoll.

	Time, hr/wk		
Location	Men	Women (children to age ~5)	Children (~5 to ~15)
Inside houses	60	60	60
Interior of island—outside	80	95	43
Lagoon beach	10	10	50
Lagoon water (boat)	5	0	7
Other islands	5	1	1
Ocean beach	3	2	7
Open sea	5	0	0

expense of time on the home island. Women's and children's time distribution would probably not change more than 10-20%, because their lives are more centered around the home and community. The table gives the time distribution of the residents of Ujilang who have lived there 26 years. It is probably typical of a completely rehabilitated Enewetak. After the cleanup, if the houses are completed, even the first year would be about as described.

Diet

At the time of the trip to Ujilang, no Trust Territory ship had called there for over two months. The people were subsisting on the local products, consisting of breadfruit, coconut, and fish. The survey party took 350 lb of flour, 150 lb of rice, 50 lb of sugar, and assorted canned goods to Ujilang; thus it was possible to observe the impact of imported food on the native diet. It could only be described as profound. There is little doubt that, given the opportunity, Marshallese consumption of imported foods would constitute at least 80% of their diet. The favorite imports, unanimously reported, are rice, flour, sugar, canned corned beef, and assorted canned fish, usually tuna, salmon, and mackerel. Marshallese who live on Majuro and Ebye (Kwajalein Atoll) and who, therefore, have money and access to "American" food, live almost entirely on imports, including such accessories as soft (and hard) drinks, beer, candy, cigarettes, and convenience foods, limited only by their ability to afford them. However, these people become hungry for the native diet (breadfruit, coconut, and fish), and a once-a-week Marshallese meal is traditional. However, the Marshallese foods are of limited availability due to population pressures. Thus an interesting picture emerges of the outer-island people desiring unavailable imported foods, while those in the population centers desire equally unavailable traditional foods. The lack of reliable inter-island transportation contributes greatly to this problem. Dose calculations based on the diet observed at Ujilang should provide good upper limits on ingestion of radionuclides at Enewetak, modified, of course, by a few factors such as the greater availability at Enewetak of some food sources (e.g., sea birds).

Cooking and eating are not big social events in Marshallese life. Food is usually cooked in the evening, some eaten then, and the rest during the next day. Families will sometimes eat together, but usually everyone eats whatever is available whenever he is hungry. When more cooked food is required, it is prepared then; thus cooking and general food preparation may take place at almost any time of the day, and usually is going on somewhere in the village all the time. On special occasions large meals will be prepared, and everyone, often the whole village, will eat together. This is about as close as the Marshallese come to the "American family dinner." A typical day's food consumption would be a light meal in the morning, usually a handful or two of food left over from the previous evening meal, perhaps a drinking coconut and some copra around the middle of the day, and then a larger meal of freshly cooked food in the evening. There were no plates or flatware in use on Ujilang;

everyone ate with his fingers from leaves of the breadfruit or coconut. In the case of large fish or meat, people would eat directly from the carcass, often passing it from person to person. Eating takes place outside the houses, and everyone sits on the ground.

A typical Marshallese "kitchen" has an area set aside for raw food preparation, a single-burner kerosene stove, an underground oven or um (rhymes with zoom), a fire pit with a grate for broiling or general cooking if there is no kerosene stove, and sometimes a pit for food storage. Again, everything is on the ground, and the cook sits or squats on the ground while cooking. Large pieces of coral serve to support pans and food baskets. Food is commonly gathered, as well as stored, in these baskets woven of coconut fronds. The kitchen is usually attached to the house by extending two walls and sometimes the roof; in other cases, the kitchen has its own roof. The fourth side is usually at least partially closed in, but rarely has a hinged door. The proposed houses to be built on Enewetak will have similar areas.

The um exists in two styles, shallow and deep. A shallow um is excavated in the coral to a depth of 10-20 cm, but is often not excavated at all. A fire is built on the rocks, and when only glowing coals remain, the food is wrapped in breadfruit leaves and laid on the coals. Everything is covered with more breadfruit leaves, then with sand and gravel, and finally with coconut fronds or burlap. Cooking time is about an hour. The deep um is excavated to 50-60 cm and is used in the same way, mostly for baking bread, which requires a higher temperature and longer baking time. Most people prefer a Coleman oven set on a kerosene stove, but these are rare. The food storage pit is excavated to a depth of about 50-75 cm (but not over an arm's length). These pits are used mostly to store preserved breadfruit, but may be used to store cooked leftovers. All food to be stored is wrapped in breadfruit leaves, and the pit is lined with either breadfruit or pandanus leaves.

Obviously the Marshallese kitchen is considerably more portable than the American version. Many fire pits and ums are located outside; in fact, they may be constructed and used at the food-gathering site. Kerosene stoves are valuable possessions which are kept under cover, although seldom in the house itself. There was one four-burner model occupying a place of honor in one Marshallese house. For broiling in an um, a fire is started with dry coconut frond; then either Messerschmidia wood, coconut shells or husk, or pandanus wood is added. Most other woods may be used, but coconut shell is preferred for the um because it produces good coals.

The important native foods on Ujilang, and presumably on Enewetak, are fish, coconut, breadfruit, and arrowroot. Pork and chicken are consumed in varying amounts, and water comsumption is highly dependent on the availability of tea and coffee. Fish, coconut, and breadfruit are eaten both raw and cooked in a variety of ways. Only cooked arrowroot is eaten. Table 5 represents an attempt to quantify the Marshallese diet on a daily basis and is based on information supplied by Dr. Mary Murai of the University

Table 5. Summary of Marshallese daily diet.[a]

Food item	At time of return, g/day: Men	Women	Children (older than 3-4 yr)	10 yr post return, g/day
Fish	600	600	400	600
Domestic meat[b] (pork, chicken)	60	60	35	60
Pandanus fruit	0	0	0	100 (200-400 for children)
Wild birds	100	100	60	10
Bird eggs	20	20	15	5
Arrowroot	0	0	0	40
Coconut	20	20	20	100
Green coconut milk	20	20	20(?)	300 (0-1500)
Ripe coconut milk	20	20	15	100
Coconut crabs	25	25	15	0-5
Clams (and other shellfish)	10	0	0	25
Garden vegetables	100	100	80	200
Breadfruit	0	0	0	200
Imports[c]	400-1000	200-1000	150-800	0-1600
Total	~1600	~1600	~1300	~1800

[a]Every entry in this table is subject to qualifications and should not be used without reading the accompanying text.

[b]Ranges from 0 to 250 g/day due to individual possession of swine and fowl.

[c]Flour, rice, sugar, tea, canned meats, and canned fish are by far the favorites. These will comprise from 0 to 80% of the diet, depending on availability.

of California (Berkeley), and on observations gathered during the 10 days on Ujilang. It should be emphasized that imported foods are highly favored by the Marshallese and will constitute anywhere from 0 to 80% (perhaps even 100% for short periods) of the daily diet. The critical factor influencing the quantity of imported food consumed is availability, which for the Ujilangese means transportation. The breakdown into men, women, and children is perhaps more misleading than informative, particularly for the women and children, because they are constantly exposed to food during the daily preparation and their intake is highly variable.

Pregnant women eat the regular diet, sometimes reducing their intake for weight-control purposes. Infants are nursed up to about 1-1½ years of age, when they are weaned onto the current diet with only a modification in food preparation. Certain foods may be mashed or cooked somewhat longer to make them more suitable for infants. The meat of the green coconut, which is naturally soft, and arrowroot paste are popular infant foods.

Pandanus is the lollipop of the Marshall Islands, much favored by children and to a certain extent by adults.* Fried breadfruit is a favorite snack food, especially of older women who may spend many afternoons eating fried breadfruit, smoking, visiting, and playing bingo. Averaged over a monthly basis, the numbers in Table 5 are probably good to ±50%, the "10-year postreturn" column is strictly a guess; much depends on what becomes of Enewetak. The diet will depend greatly on the extent of American (or Japanese) influence.

Because it is very difficult to express the Marshallese diet in grams per day, the following discussion of the various food items and their uses is given.

Seafood

Fish is certainly a favorite item in the Marshallese diet. Even if imported food is available, local fish remains high on the list of variety foods. If imported food is not available, fish probably supply the entire protein intake. The favorite fish at Ujilang, and those observed caught and eaten, approximately in order of abundance are: rabbitfish (Siganus), grouper (Epinephelus), convict surgeon (Hepatus), goatfish (Mulloidicthys), pompano (Hynnis), surgeonfish (Naso), bonito (Sarda?), squirrelfish (several varieties), ulua (Caranx), and yellowfin tuna (Neothunnus). Bonito, ulua, and tuna must be caught by trolling; therefore their importance in the diet depends strongly upon motorboat availability. All three are a favorite fish, particularly for sashimi (raw).

Almost any fish which is caught and cooked will also be eaten raw. The head of the smaller fish is considered a delicacy, and the heart and liver are also occasionally consumed. Fish which are to be cooked within a few minutes of being caught are seldom eviscerated. Fish eaten raw, and those which will be kept even an hour or so are eviscerated. Large fish, such as the tuna and jacks, are usually cleaned back at the village because the heart and liver are practically always cooked and eaten. The smaller reef fish are cleaned on the spot, often just with fingers and teeth. Fish are usually cooked with the skin and scales left on; the scales peel off easily after cooking, and most of the skin is usually discarded. However, whether or not the skin is eaten depends on both the fish and the diner. Sashimi is always skinned first.

The Marshallese are opportunists and will tend to eat what they catch; however, they know where and when their favorite fish are likely to be found and plan their trips accordingly. Their techniques are

*According to Tobin, pandanus is probably more important in the diet than this report indicates. The fact that it was out of season during the visit may have contributed to the impression that it is not widely consumed. Tobin states that it is a very nutritious food, and that its consumption should be encouraged by planting it in abundance on Enewetak. Perhaps the amounts given in Table 2 should be doubled or tripled for the 10-year postreturn consumption. Murai originally estimated 200 g/day without regard to age or sex.

also directed toward certain types of fish. The two principal factors which discriminate against certain fish in the diet are flavor and the occurrence of ciguatera or other forms of poison. Sharks are good examples of the flavor factor. The meat contains large quantities of urea, requiring laborious preparation which, when combined with the generally unpleasant disposition of these fish, serve to eliminate them from the diet. Moray eels, barracuda with three gill rakers, and one species of mullet are examples of fish which frequently contain ciguatera. The puffer fish and such obvious species as the stonefish and scorpion fish are also excluded from the diet.

Frying in oil or lard and broiling over coals are the principal methods of cooking fish, although boiling and baking in the um (particularly for large fish) are sometimes used. Cooked fish may be kept for several days by wrapping it in breadfruit leaves and covering it with coconut or pandanus fronds. It is reported that fish can be stored over longer periods by salting it raw and drying it in the sun. The Ujilangese make their own salt by evaporating ocean-side water in kettles over a fire. The preserved fish are rinsed in fresh water before they are eaten. Since fish are abundant, the daily intake depends mostly on personal preference. Many interviews indicated that the 600 g/day, wet weight, estimated by Murai and included in Table 5, is probably accurate to within 10-20%.

Tridacna and hippopus clams are about the only other seafood eaten in any significant quantity. Clams of edible size are not common at Ujilang (or Enewetak, for that matter), and most are consumed on the spot by the fisherman. The large adductor muscle is eaten raw, as well as the mantle, but dark parts are discarded. It is possible that some clam meat, particularly the mantle, finds its way into the diet of the women and children, but certainly not much. Sea turtles, spider snails, and helmet shell snails are also sometimes consumed, but again are only a small portion of the diet. Sea cucumber (Holothuria) and small crabs are not eaten. A variety of small snail (Littorina) is a delicacy, but the quantities consumed are insignificant.

Coconut

Until one has lived awhile with the Marshallese, it is impossible to realize what a useful tree the coconut palm is to these people. Essentially every part of it is used in at least one way. The leaves are used to make baskets, to thatch roofs, and for various handicrafts. The trunks are used for firewood and as logs for general building purposes. Coconut husks make good fire-building material, while the shells make good charcoal and are also used as cups and bowls. The sap from the blossom of a tree 4-5 years old is gathered and used as a syrup; it gives a pleasant coconut sweetness to several foods. This same sap may be fermented to produce an alcoholic drink; however, drinking is against the law for the Ujilang people. Small roots of the tree (~1-2 mm diam) can be bleached in the sun, dyed with the water extract of colored crepe paper, and woven into a variety of baskets. Hearts of palm are rarely eaten. The tree must be 4-5 years old before the top is cut off and the growing core is harvested. This yields about 4-5 kg of material and kills the tree.

The coconut itself is a dietary mainstay. A drinking nut, ni (pronounced "knee"), is full grown but totally green, and contains about 250-350 ml (grams) of liquid. The meat at this stage is only about 4-5 mm thick and, while firm, is covered with a gelatinous coating on the inside. Consumption of drinking nuts is highly variable. They are traditional at festive occasions and make an excellent "coffee-break" drink. Usually they are not used to quench thirst because water is preferred, but they are used more as the Marshallese version of soda pop. However, if water is not available, a working man might consume up to a dozen nuts or so a day. On Ujilang they are plentiful and there for the taking, which makes an accurate estimate of the consumption impossible. The meat of the drinking nuts, a popular baby food, is consumed only in small quantities by older children and adults.

Ripe coconuts, similar to those for sale in American stores, are consumed in a variety of ways, but mostly raw. Some of the liquid is used in cooking, and the meat, called "copra" by the Marshallese, may be eaten in pieces with fish, or grated and added to other foods. Favorite recipes include a mixture of grated coconut, wheat flour, water, and a little sugar which is baked in the um; a similar mixture containing baking powder which is deep-fried ("doughnut" in Marshallese); a mixture of breadfruit and grated coconut baked in the um; and grated coconut and coconut sap, mixed with steamed rice. All of the people interviewed said they ate about half a coconut per day. Since an average coconut yields about 200 g of copra, the figure of 100 g/day listed in Table 5 is fairly accurate. This also agrees well with Murai's estimate.

Commercial copra is prepared by spreading pieces of coconut meat on a grate about 2 m above an open fire. Coconut husks and shells are the favorite fuel, and complete drying requires about 24 hr. After drying, the copra is stored in burlap sacks to await a Trust Territory field ship. Copra-making was not in evidence on Ujilang because, the people said, it often spoiled before a ship would arrive. However, while the survey party was there, Smith Gideon built a copra-drying shed which he said would dry several hundred pounds at a time.*

There is a stage of the coconut between ripe and sprouted when it is not consumed. Once sprouted, the layer of meat is gone and the inside is filled with a pithy, yellowish mass called iu (pronounced ("you"), which is highly prized by the Marshallese. Iu may be eaten raw

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*According to Tobin, most copra is dried in the sun rather than over a fire, and official Trust Territory figures list the copra production of Ujilang as 51.6 tons ($5000) in fiscal 1971 and 110 tons ($11,000) in fiscal 1972. If these figures are reliable, it would seem that much more copra-making goes on than was evident during the survey party's visit. It is possible that copra is made on other islands, but the people generally said they did not make much copra. Certainly on the main island there did not appear to be an area large enough to sun-dry more than 100 tons of copra, even in a year. Current copra production is of little importance to dose-assessment calculations, but if copra is to be an important cash crop in the future, careful attention should be given to potential radionuclide levels.

or used like copra. In what is probably the favorite recipe for iu, it is grated together with copra and perhaps a little sugar, then slurried with ni to make a thick drink, a sort of Marshallese milkshake. On Majuro this mixture is frozen on sticks and sold like Popsicles.

Breadfruit is the third main component of the Marshallese native diet and was in season during the visit there. Three varieties exist, two of which must be cooked, and the third, somewhat less plentiful, can be eaten either cooked or raw. A typical breadfruit will be about 15 cm long, 10 cm in diameter, slightly ovoid, with a rough, light-green skin and orange flesh. The general appearance is that of a very large avocado. Average weight is 1100 g, with about 10% as peel and core. The variety eaten raw is smaller, weighs perhaps 700-800 g and contains about 100 g of seeds which look like small chestnuts. These seeds can be roasted and eaten. Breadfruit is cooked in several ways, much as we would cook potatoes. However, the skin is never eaten. The breadfruit may be peeled and cored, then cut up and boiled, or it may be baked whole with the skin on, either over coals or in the um. A favorite way, especially of older women, is to peel and core the breadfruit, then slice it perpendicularly to the long axis, salt lightly, and deep-fry. This produces a product resembling fried pineapple rings, but somewhat larger, and is a good snack food, a sort of Marshallese equivalent of potato chips. Once cooked, breadfruit can be covered and kept for several days.

Another method of preparing breadfruit is to peel and core about a dozen fruits and let them soak about 24 hr in a coconut-frond basket in the lagoon. They are then rinsed in fresh water and kneaded together on a rock or board until the product resembles orange-colored bread dough. This is then divided into "loaves" of a kilogram or so apiece, wrapped in breadfruit leaves, and stored underground in a pit as already described. It is said to keep several months this way, and may be used like fresh breadfruit after another rinse in fresh water. This product is usually mixed with grated coconut and baked in the um.

Arrowroot grows all over Ujilang and is the principal undergrowth in the coconut forest. In July, the tubers were small because the harvest season begins around November. The preparation of arrowroot has been described by Tobin and consists of digging, then washing and grating the tubers, and placing the pulp in a burlap sack or one woven of coconut roots. The sack is immersed in salt water, squeezed out by hand, and the milky extract, consisting of a fine suspension of starch, is collected. In an hour or so the starch coagulates and is washed several times by decantation with salt water, then fresh water. The starch is then spread in the sun to dry, ground lightly to break up lumps, and stored away where it will keep indefinitely. Arrowroot starch is not at all like wheat flour and is only used as a thickening agent in soups or stews. It resembles our familiar cornstarch. When questioned, the Ujilangese all stated a preference for wheat flour over arrowroot starch. Flour can be used as a thickener, as well as for other purposes. They said that given both, they would use up the flour first and then fall back on the arrowroot. From start to finish, arrowroot production is a long, tedious process, resulting in a product which has no flavor and limited usefulness.

Pandanus was just coming into season during the July trip. When questioned, most adults said that they eat hardly any pandanus. It is consumed mostly by the children. Tobin reports a method of sun-drying pandanus on coconut fronds; the Ujilangese acknowledged this, but claimed that they do not make it often. Pandanus is not abundant on Ujilang and probably will not be on Enewetak either.

About the only other native food consumed in any quantity on Ujilang was pork and, in even lesser amounts, chicken. The quantity of pork consumed varies greatly from family to family, because pigs are private property, and there is no obligation to share them. Some families have many pigs and may eat pork two or three times per week, replacing fish on a gram-for-gram basis, while other people have few or no pigs and hence eat little or no pork. Chickens are in the same category but are very scarce. The reason for this seems to be that the cats, originally imported to control the rats, did such a good job that they had to move on to the chickens. All animals are free-roaming and forage anywhere on the island.

Little need be said for other native foods. Coconut crabs and wild birds have been essentially wiped out on Ujilang but may be important at Enewetak, especially for the first year or two. The coconut crabs are highly prized for food. Their legs and claws are broken off and cooked immediately; then the crab is force-fed until the tail doubles in size, when it is used for soup. Almost all of the sea birds are eaten except the golden plover, which is believed to contain spirits of departed souls. The young birds just getting feathers are a favorite food item. Again, the Marshallese recipe is simple: catch the bird, wring its neck, and cook it over an open fire, entrails, feathers, and all. The liver and heart are eaten. Bird eggs are eaten but are not a favorite food item.

The only garden vegetables growing on Ujilang were two pumpkin vines, neither of which had any pumpkins, but one was in blossom. The lack of agriculture is explained first by the fact that there is practically no soil, just rocks, and second, that the pigs are free-roaming and fond of anything edible. The latter fact, when combined with the cat-chicken situation, provides a real insight into the Marshallese philosophy of life, "play it where it lies."

Methods of cooking imported foods have been described as they accompanied the native diet. Flour, in addition to the products mentioned, is also made into bread, baked in the um. Rice is exclusively boiled with the standard proportions of two parts of water to one of rice. Tea is drunk hot and is much preferred to coffee. In fact, the order of preference in beverages is tea, coffee, water, soft drinks, and ni. Sugar is added to several foods, and almost everyone uses sugar in tea and coffee. Canned meats such as corned beef, tuna, salmon, and mackerel are eaten with no more preparation than heating, and they replace fresh fish on a gram-for-gram basis.

Medicines and Remedies

This was the only area where there seemed to be a definite desire for secrecy. Apparently the Marshallese medicine, like the folk medicine in parts of the United States, is a family secret and not shared extensively, especially with outsiders. Part of this reticence may be due to the fact that the Marshallese realize the sophistication of American medicine and are afraid of ridicule. It was inferred that many of the Marshallese themselves did not have much faith in their medicine, but it was worth a try, particularly if the American version did not work or was unavailable. Held's article (op.cit.) contains some information regarding the local remedies of Rongelap. The reported uses of Messerschmidia and Scaevola were confirmed on Ujilang. The use of Messerschmidia is particularly important with regard to dose assessment, because leaves are used as a first-aid bandage and as a poultice to cover open wounds.

A few general remarks regarding health care should be made. Ujilang is the most remote of the Marshall Islands and as such, suffers even more than the others from a lack of readily available first aid, much less real medical care. The dispensary stock consisted of aspirin, tetracycline capsules, penicillin, dextrose solution, normal saline solution, and miscellaneous odds and ends of patent medicines. A Marshallese medical attendant was in charge. A kerosene refrigerator was operable but out of fuel, and there was no other medical equipment or furniture of any kind. In case of a medical emergency, the usual procedure is to divert a Trust Territory ship and take the victim to Majuro. Usually this means a minimum of three days' delay. The people all appeared very healthy and vigorous, and there seemed to be no evidence of malnutrition or illness. However, it was reported that all through the Marshall Islands a baby's first birthday is a big event and a cause for celebration.

Agricultural Considerations

Just what the level of agriculture will be in Enewetak is very difficult to say. Certainly the two staples, coconut and breadfruit, will be grown, especially on the islands of Medren, Japtan, and Engebi. Some pandanus and arrowroot will also be raised. The fact that no agriculture is practiced on Ujilang and the reasons why have already been mentioned. Whether things will be different at Enewetak remains to be seen. Many Ujilangese interviewed remembered that the Japanese raised a variety of vegetables as row crops on Engebi and Enewetak. These were irrigated with either cistern or well water containing human waste. No one knew whether vegetables could be grown on any other islands (probably Japtan) but, since irrigation is necessary, the availability of fresh water would be a crucial factor. The implication is that, given some effort and perhaps some fertilizer, a variety of crops could be grown. One Ujilangese, Balik by name, worked as a Trust Territory agriculturalist on Majuro for a year. He also lived on Enewetak at the time of the Japanese occupation and recalls their growing pumpkins, cucumbers, watermelons, potatoes, sweet potatoes, green onions, cabbage (bok choi), carrots, and maybe soybeans. Thus there is certainly a potential for augmenting the standard diet of coconut, breadfruit, and fish. It is reported by Tobin and confirmed by others that the Ujilangese are quite industrious and will probably grow at least some vegetables, but will probably not practice American-style truck farming.

Pigs and chickens will remain the only domestic animals raised for food; no one interviewed indicated otherwise. However, Tobin says that Muscovy ducks and turkeys do well in this part of the Marshalls. As on Ujilang, livestock will be allowed to forage on their own, although it would seem that for at least a few years after return, some sort of food supplement would be necessary. On Ujilang the pigs ate coconuts at all stages of ripeness, grass, the leaves of the trumpet morning glory (Ipomoea), fallen breadfruit, family garbage, and small crabs and snails from the lagoon beach. Presumably the chickens consume a similar diet. It would seem that on Enewetak the confining of either the animals or the vegetables would be beneficial.

Marine Resources at Enewetak

During conversations and fishing trips with Smith Gideon, Ujilang magistrate, in a two-week period at Enewetak Atoll in July 1973, some information on the food habits of the Ujilang people was gained which may be used to help estimate dose rates from food intake. In general, the data gathered concern the use of fish in the Ujilang diet and specifically include data on meals eaten during fishing trips while on Enewetak.

Generally, it can be stated that the Ujilang people are opportunists and will eat most types of fish which they happen to catch. However, certain fish are preferred and special efforts are made to

Table 6. Average wet weights of tissues from common edible nearshore fish at Enewetak Atoll.

Common name	Tissue	No. of fish	Average wet weight	Wet/dry
Goatfish	Eviscerated whole	61	145	3.4
Goatfish	Viscera	61	13	3.5
Goatfish	Muscle		45-50[a]	4.8[a]
Mullet	Muscle	32	57	3
Mullet	Eviscerated whole	32	167	3
Mullet	Viscera	32	44	2
Rabbitfish	Muscle	9	200	3.9
Convict surgeon	Eviscerated whole	47	54	3.5
	Viscera	47	10	5.3
	Muscle		15[b]	4.0[b]
Parrotfish	Muscle	17	144	4.9

[a]Estimated from similarity to size and body shape of mullet.

[b]Estimated.

capture the preferred species. Also, certain fish are avoided either because they are known to be poisonous (ciguatera), difficult to prepare, or simply because they are not as flavorable as other species.

One apparently favorite fish is the goatfish, either "Jo" (Mulloidichthys) or "Jome" (M. auriflamma). The whole fish is laid on a grill (if available) and roasted over a bed of hot coals for about 10 minutes. The skin is then peeled off and the flesh eaten. The head of the goatfish is considered a delicacy and is often offered to a guest as a courtesy. The soft parts (brain, eyes) of the head are eaten, but the bones and viscera are discarded. All organic waste from a meal is placed in the fire and burned. This is a garbage disposal method and serves to keep the fly population down. One goatfish or mullet (see Table 6 for average weight of fish) is a reasonable intake at one meal; however, some people may eat three goatfish. The remainder of the meal usually consists of one-third of a copra coconut and a drinking coconut.

Another apparent favorite is the rabbitfish, "bejrok" (Siganus). Rabbitfish of other species are also known as "mole" or "molle" and are referred to several times in Tobin's 1955 journal as a favorite fish of the Ujilang people. The rabbitfish are cooked in the same manner as the goatfish. In fact, it appears that most fish are cooked in this manner, except for occasions when the um is used. Only the flesh of the rabbitfish is eaten, and one fish is the usual intake for a meal. One-fourth of a copra-type coconut (the kind usually sold in the U.S., with the meat dry), coconut crab legs (100 g, wet), and a drinking coconut completed this meal as prepared at Enewetak.

Other fish which were captured on fishing trips and which are said to be eaten are mullet, convict surgeon, parrotfish, grouper, surgeonfish, and damselfish. These fish, along with the goatfish and rabbitfish, probably comprise the most common fish found in the nearshore water around the island of Enewetak, and hence will probably be the most common fish in the diet. Seven or eight convict surgeon, some copra, and a drinking coconut, or two to three convict surgeon, copra, rice, and a drinking coconut are typical meals.

There seems to be some conflicting opinion as to whether or not the Ujilang people eat mullet and parrotfish. Tobin, in one conversation, stated that the Ujilang people do not eat either mullet or parrotfish. However, Smith Gideon, when shown specimens of mullet and parrotfish, indicated that at least three different species of the smaller (<12 in.) mullet, both "ikare" (Chelon vaigiensis or Neomyxus chaptalii) and "jomou" (Mugil sp.), and three species of parrotfish are eaten on occasion. The conflicting opinions may be due to the fact that one genus of mullet, "iol" (Crenimugel sp.), is considered to be poisonous and therefore is not eaten. Furthermore, parrotfish from the northern end of the Enewetak Atoll are also considered to be poisonous and are not eaten. Parrotfish from the David to James area of the Atoll are eaten. In addition, the fact that other species of fish (goatfish and rabbitfish) are preferred may have led to the confusion on this point. However, it seems clear that the Ujilang people, on occasion, will eat both mullet and parrotfish.

Of the fish actually captured and shown to Smith, his preference in descending order seemed to be goatfish, rabbitfish, mullet, convict surgeon, and parrotfish, with grouper, surgeon and damselfish occupying indefinite intermediate positions between rabbitfish and parrotfish. These nearshore fish are captured by several methods, including use of thrownets, gillnets, and a surround technique by which the fish are driven into shallow water where they are hand-captured or dip-netted. Additional thrownets and gillnets, along with appropriate mending materials, might be considered as a part of the rehabilitation program for the Enewetak people.

A fish not actually captured but indicated to be very good to eat is the flying fish, "jojo" (Exocoetidae). These fish are captured at night by building a fire in a boat and attracting them to within a range where they may be netted. Some flying fish also fall into the boat during their flight toward the attracting light. Small hooks on a line are also used in a manner similar to the jigging of herring or smelt which bite on the bare hooks that simulate the planktonic organisms they feed on.

Other fish which reportedly are eaten are barracuda with four gill rakers, "nidwa," tunas, and other similar lagoon fish such as jacks, mackerel, and dolphin. Although larger sharks (probably gray sharks but not thresher or nurse sharks) are eaten, they probably are a minor portion of the diet due to the length of time required in the preparation of the flesh to make it edible. This lengthy preparation is due to the urea in the flesh which renders the fresh fish unpalatable: "a shark has a big smell."

In the preparation of shark flesh, the fish is boiled in hot water for about 10 minutes, after which the skin is removed. The flesh is then boiled for several hours, presumably until the smell goes away. Next, the boiled meat is fried or steamed (um) and then placed in the sun until it is dry. This process takes most of a day, but the finished product is considered good.

The capture of large lagoon fish requires boats and fairly heavy fishing lines, feathered jigs, and large hooks. Hence, the use of these fish in the diet is highly dependent on these items and is probably less than the utilization of the nearshore fish because of the present scarcity of adequate fishing gear and because the nearshore fish are so abundant and easily captured at most times. In general, at the present time, deepwater lagoon fish are probably not as abundant in the diet as they would be if more fishing gear were available to the people.

Other marine organisms which may be eaten include porpoise, tridacna clams, ("kabwur"), shore crabs, and large gastropods (en). Other smaller gastropods are also called en, but they are not eaten. These include spider snails and smaller Strombus species.

Porpoise are captured by surrounding them as they enter the wide pass or deep channel and herding them into shallow water. Herding is accomplished by banging rocks together underwater and splashing on the surface.

Three types of Tridacna are distinguished by the Enewetak people: (1) the large killer clam, Tridacna gigas; (2) a white-mantle, medium-sized clam; and (3) small clams with colored mantles which are embedded in the reef. All types are called kabwar. No information was obtained on how these clams are prepared, but it is known that other Marshallese people do not eat the kidney, due to its very bitter flavor, and it may be presumed that this is the case for the Enewetak people until different information is obtained.

Another organism which will certainly be eaten by the returning Enewetak people, unless advised to the contrary, is the coconut crab, "baru lip" (Birgus latro). The first step in preparing this crab is to knock the pincer legs and the largest walking legs off with a machete. The legs appear to break off near the body at a natural breaking point, which quickly heals over. By doing this the crabs can be easily contained without causing damage to themselves or to their captors. Also, crabs can be held alive like this for several weeks. The legs and the bodies of crabs not to be saved are then roasted over a bed of coals.

From discussions with Smith Gideon, I would conclude that the diet of the Ujilang people is very similar to diets of the Bikini people, the Rongelap people, and other northern island groups in the Marshall Islands. This is true because the basic foods are the same in all these areas. Breadfruit, pandanus, arrowroot, and coconut are the chief natural terrestrially grown vegetative foods, with imported rice and flour supplementing this portion of the diet to a degree which is very dependent upon the length of time from the visit of the last field-trip ship.

Fish, clams, and langousta from the lagoon and reef; birds and bird eggs from bird-nesting islands; domestic pigs and chickens raised on the village island; and imported meats (corned beef, sardines) provide the animal protein in the diet. Again, the proportions vary greatly with the availability of specific items; however, fish are indicated as being an important part of the diet at Ujilang and will probably be more important at Enewetak Atoll where the fish supply is greater.

It should be remembered that a diet determined for the Ujilang people over one short time period may differ greatly from a diet determined over another time period in a different season or at a different length of time from the last visit of a trade ship. I feel, therefore, that a composite diet, based on all available diet information for the Ujilang, Bikini, and Rongelap people, is the best information to be used in the calculation of dose rates from food intake.

III. Survey Execution

W. Nervik, Lawrence Livermore Laboratory, Livermore, California

SURVEY PLAN

After agreeing to conduct the radiological survey, the AEC assigned responsibility for the program coordination to its Division of Military Applications (DMA). Major General F. A. Camm, Asst. Gen. Mgr. for Military Applications, then directed the AEC Nevada Operations Office (NVOO) to execute the program, using the following specific instructions:

"As a result of commitments made by Ambassador Williams and initial agreements reached during an interagency meeting held on September 7, 1972, it is the overall AEC purpose to gain a sufficient understanding of the total radiological environment of Enewetak Atoll to permit judgements as to whether all or any part of the Atoll can safety be reinhabited and, if so, what steps toward cleanup should be taken beforehand and what postrehabilitation constraints must be imposed. It is necessary to thoroughly examine and evaluate radiological conditions on all islands of the Atoll and in the local marine environment prior to commencement of cleanup activities in order to obtain sufficient radiological intelligence to develop an appropriate cleanup program. Specifically, it is necessary:

1. To locate and identify contaminated and activated test debris,
2. To locate and evaluate any significant radiological hazards which may complicate cleanup activities, and
3. To identify sources of direct radiation and food-chain-to-man paths having radiological implications.

You are directed to plan, organize, and conduct a radiological field survey to develop sufficient data on the total radiological environment of Enewetak Atoll to permit the assessments on which the judgements described above can be made."

A number of factors strongly influenced the planning of the survey:

- Although a number of studies of Enewetak had been conducted previously, none provided either current or complete information on the radiological state of the Atoll. The Survey would therefore have to obtain data on all islands and all human dose pathways in sufficient detail and accuracy to permit reliable population dose estimates to be made for the future inhabitants.
- In September, 1972, the only field support facilities available at Enewetak were those operated by the U.S. Air Force, which then had custody of the Atoll. The base support resources were committed to certain military activities, but an open period in those activities permitted the scheduling of support to the AEC survey from mid October thru December 1972.
- Although Ambassador Williams had not promised the return of the Enewetak people to the Atoll at the end of 1973, his speech was widely interpreted to

mean just that, and therefore there was considerable pressure for the AEC radiological survey and dose assessment effort to be completed as quickly as possible.

- Given the size of the sampling program, the time constraints imposed by limited field support facilities, the large amount of radiochemical analytical work required, the complex dose assessments that were needed, and the growing hopes and expectations of an early resettlement, it was clear that no single technical organization was big enough to conduct this program by itself, nor were there many who could or would divert sizable numbers of highly qualified technical people from previous commitments on less than one month's notice.

With these factors influencing decisions, the Radiological Survey was organized in the following way:

- A Program Manager (Roger Ray) was assigned by NVOO to provide overall program responsibility, liaison and coordination among organizations operating in the field, and fiscal controls at the NVOO level.
- The Lawrence Livermore Laboratory (LLL) agreed to provide a Technical Director (Dr. Walter Nervik) for the program and to act as the focal point for technical activities associated with the program.
- Technical leadership for the various components of the program was assigned as follows:

  Aerial Photography and Radiation Survey (J. Doyle, EGG)
  Terrestrial Soil and Radiation Survey (P. Gudiksen, LLL, and O. D. T. Lynch, NVOO)
  External Dose Estimates (J. McLaughlin, HASL, P. Gudiksen, LLL, and D. Jones, LLL)
  Marine Survey (V. Noshkin, LLL, and V. Nelson, U. Wash.)
  Terrestrial Biota Survey (G. Potter and J. Koranda, LLL)
  Air Sampling (D. Wilson and B. Clegg, LLL)
  Radiological Support to the DOD
  Engineering Survey (O. D. T. Lynch, NVOO)
  Analysis Program (R. Hoff, LLL)
  Radiological Controls (O. D. T. Lynch, NVOO)
  Dose Assessments (D. Wilson, Y. Ng, and W. Robison, LLL)

- These leaders then completed plans for the field sampling, analysis, and interpretation portions of their component and identified individuals who would be doing the work. Because of the scope and unusual nature of this program, individuals from an exceptionally large number of organizations have been involved, including NVOO, LLL, National Environmental Research Center (EPA, Las Vegas), Laboratory for Radiation Ecology (LRE) (University of Washington), University of Hawaii Enewetak Marine Biological Laboratory (EMBL), Trust Territory of The Pacific Islands (TTPI), McClellan Central Laboratory (MCL), Laboratory for Environmental Studies (LFE), Eberline Instrument Co. (EIC), AEC Division of Operational Safety, AEC Division of Biomedical and Environmental Research, EG&G, Inc.

(EGG), AEC Health and Safety Laboratory (HASL), the Defense Nuclear Agency (DNA), Holmes and Narver (H and N), the U.S. Navy, U.S. Marine Corps, and the U.S. Air Force field support contractors.

Given the directive to proceed on September 7, 1972, the Survey plan was completed, reviewed, and approved on September 18. (A copy of the final Survey plan appears in Appendix I.) The Field Survey party departed CONUS in two contingents, one on October 13 and the second on October 15, and field operations were begun on October 16 with the Soil, Marine, Terrestrial Biota, Air Sampling, and Engineering Survey Components all conducting their activities simultaneously. This put a very definite strain on the marine transport equipment (four boats), but all operations were proceeding smoothly until October 21, when the Survey party received its first alert warning of the approach of Typhoon Olga, predicted to pass directly over Enewetak on October 24 with winds of 125 knots and gusts to 165 knots. Survey activities ceased with that alert, all equipment was made secure, and everyone on the Atoll was evacuated to Kwajalein on the evening of October 23. Upon return to Enewetak on October 25, the power plant was found inoperative, and we were advised that the island could not support the Survey Party. All Survey personnel were sent home until support facilities could be provided once again.

Operations were resumed on November 8 with the initiation of the aerial survey. In the interim period from October 25 to November 8, changes in the scheduling of the military programs at Enewetak provided further relief in the form of an extension of available field support. The AEC radiological field survey schedule was thus extended to mid February. The field effort actually terminated on February 14, 1973. In the following sections each component of the Survey is discussed in detail by those who were responsible for the effort.

AERIAL RADIOLOGICAL AND PHOTOGRAPHIC SURVEY

T. P. Stuart and R. Meibaum
EG&G, Inc., Las Vegas, Nevada

Introduction

An aerial radiological and photographic survey of Enewetak Atoll was performed by EG&G during a 16-day period between November 8 and 23, 1972. This work was done in order to characterize the terrain, including the entire reef, and to determine the gamma-radiation levels and the spatial distribution of radioactive isotopes which are residues from earlier nuclear explosive experiments. Much of the fission-product and activation residues from the nuclear explosives experiments during the period 1948 through 1958 have remained to contaminate many of the islands and sections of the adjoining reef. In addition to fission and activation products, there is plutonium metal scattered at some locations as a result of explosive experiments which did not achieve a fission yield. Primary contaminants observed from the aerial radiological measurements are ^{60}Co, ^{137}Cs, and ^{239}Pu.

The aerial radiological and photographic survey was carried out from a helicopter and covered all 39 islands of the Atoll. The photography covered four wavelength bands in the visible and near-infrared spectrum, and served to document the geographical features of the Atoll and serve as a basis for navigation in carrying out the radiological survey. The aerial radiological survey involved only gamma-ray measurements and included both gross gamma counts and energy spectral information in the 50-keV to 3-MeV range. The radiological measurements resulted in a determination of the spatial distribution of gamma-radiation exposure rate in μR/hr at one meter above the ground, as well as isotopic concentration for ^{60}Co, ^{137}Cs, and plutonium-related ^{241}Am. These measurements are presented as isopleth plots superimposed on aerial photographs of the islands. Correlations with ground-based radiation measurements and soil sample analysis are discussed in the subsection on Nuclear Instrumentation Systems and Methods.

The photographic data, together with the radiological survey results for the gamma-exposure rates and isotopic concentration for ^{60}Co, ^{137}Cs, and plutonium-related ^{241}Am, are presented in Appendix II. The next subsection of this report gives a description of the photographic instrumentation and methods, while the last subsection describes the nuclear instrumentation systems and methods.

Photographic Instrumentation and Methods

Multispectral Camera System

Hasselblad Camera System – The aerial photographs of the islands comprising the Enewetak Atoll were taken with a four-camera system consisting of 70-mm 500 EL Hasselblad cameras, equipped with 80-mm lenses. The four cameras were arranged along parallel optical paths and imaged identical ground images on the four image planes. The frame size was 55 × 55 mm.

Each of the four cameras recorded a different portion of the visible and near-infrared spectrum. The wavelength region recorded was controlled by the choice of film sensitivity and optical filter combinations. The four film and filter combinations used are shown in Figs. 7 through 10. The four wavelength regions recorded were:

Normal color	4000-7000 Å
Infrared color	5000-9000 Å
Panchromatic/ red filter	6000-7000 Å
Infrared black and white	7000-9000 Å

Camera Mounting – The four Hasselblad cameras were mounted on a rigid plate which subsequently was mounted to the floor of a CH-53 Sea Stallion helicopter, allowing the cameras to view the terrain through a large port in the floor. Since gyrostabilization or shock mounting of the cameras was not used, the system optical axis moved in concert with the aircraft attitude and pitch. The optical axis of the camera system was perpendicular to the floor of the aircraft, which was maintained reasonably level during photographic missions.

Operational Considerations – Photographic missions were flown at altitudes selected to image a single island on a single frame. On the longer islands, consecutive overlapping frames were taken to provide a mosaic of the individual island. Flight altitudes were selected to the nearest convenient 300-m (mean sea level) interval in order to simplify the flight plans and allow the acquisition of several islands on a single flight path. Once over the island, the cameras were triggered simultaneously by an operator looking through the floor of the aircraft. Flight altitudes ranged from 300 to 3000 meters.

In addition to the individual island photographs, complete coverage of the Atoll was acquired from an altitude of 3000 m. For this coverage the pilot was directed to fly the center of the visible portion of the Atoll while the camera system was triggered to record overlapping coverage.

The islands were photographed over a span of 8 days from November 12 to 20, 1972, and at diurnal periods between 0955 and 1624 hours, local time. The specific time of day of any photograph in the set presented in Appendix II is available.

<u>Quick-Look Photography</u> – The first missions flown on the island were for the purpose of acquiring photographic

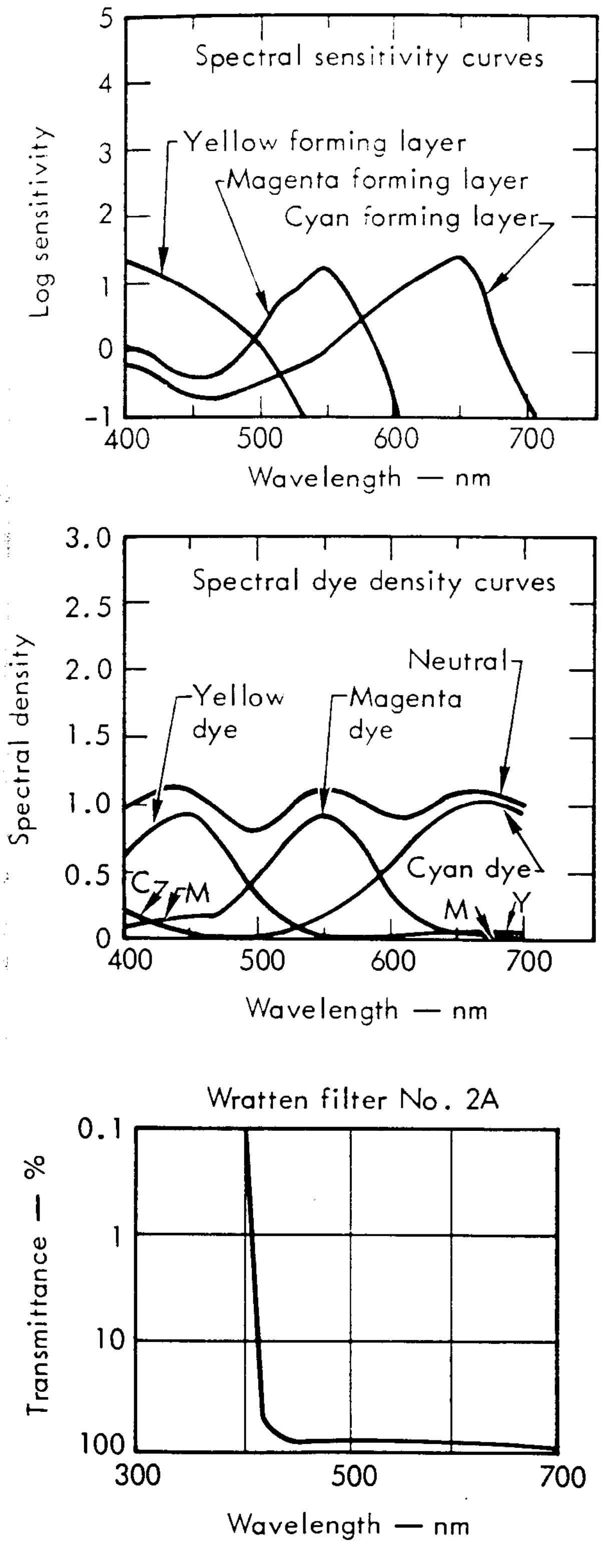

Fig. 7. Kodak Aerocolor Negative Film 2445. This film is a three-layer color film with sensitivity in the visible portion of the spectrum. This film is designed for processing to a color negative and does not have an integral color mask. In this form, the film is suitable for direct visual interpretation or can be readily printed to a positive print. The three layer sensitivities are to blue, green, and red. The film is normally used with a Wratten 2A haze filter, which reduces the recording of unwanted atmospheric haze on the film.

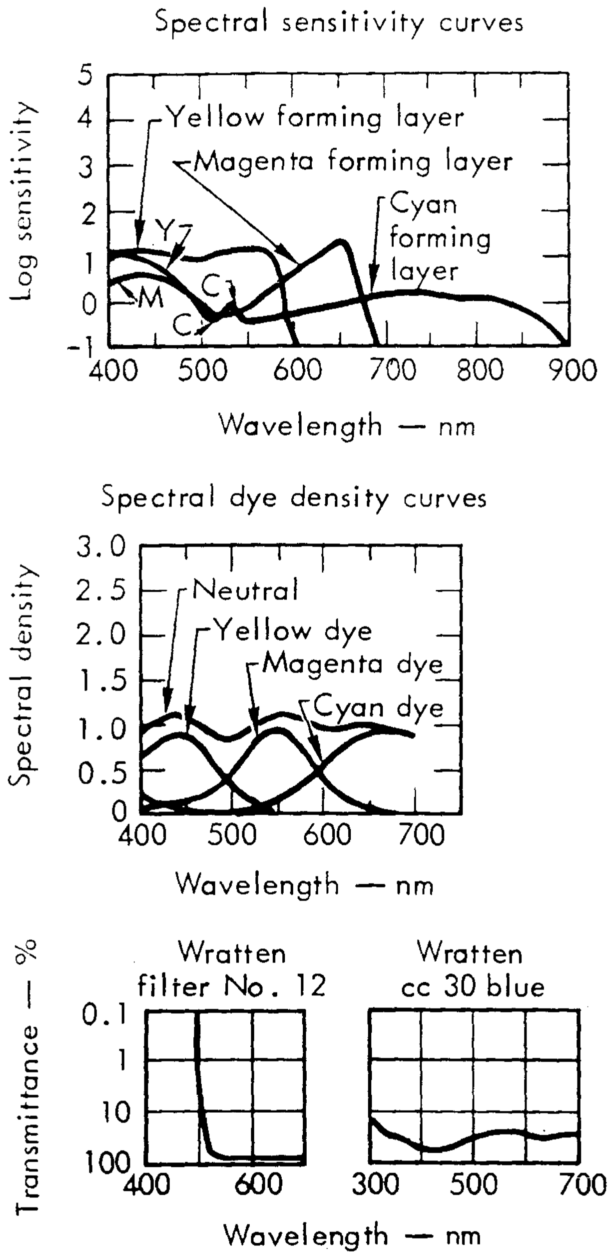

Fig. 8. Kodak Aerochrome Infrared Film 2443. This film is a false-color reversal film designed for use in aerial photography. It differs from ordinary color film in that the three layers are sensitive to green, red, and infrared radiation instead of the usual blue, green, and red. A Wratten 12 yellow filter is always used with this film to absorb blue light, to which all three layers are sensitive. The Wratten CC30 blue filter was used to correct the color balance of this particular emulsion batch and is not normally used with this film.

maps for use by the radiation monitoring personnel. This was accomplished by using the four-camera system equipped with a different film and filter combination than for the multispectral coverage. Kodak Plus-X Aerographic with a Wratten 12 filter was used to provide a photographic record in black and white that closely simulated the tonal relationship

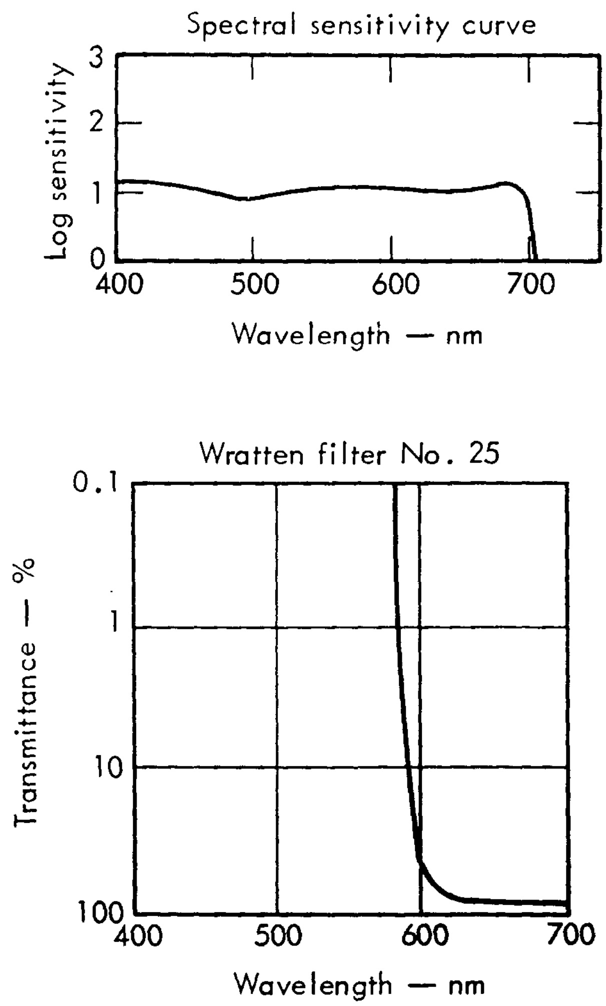

Fig. 9. Kodak Plux-X Aerographic Film 2402. This film is a panchromatic negative material that has extended red sensitivity. When used with a Wratten 25 filter which absorbs blue and green light, only those objects that have reflections in the red portion of the spectrum will be recorded.

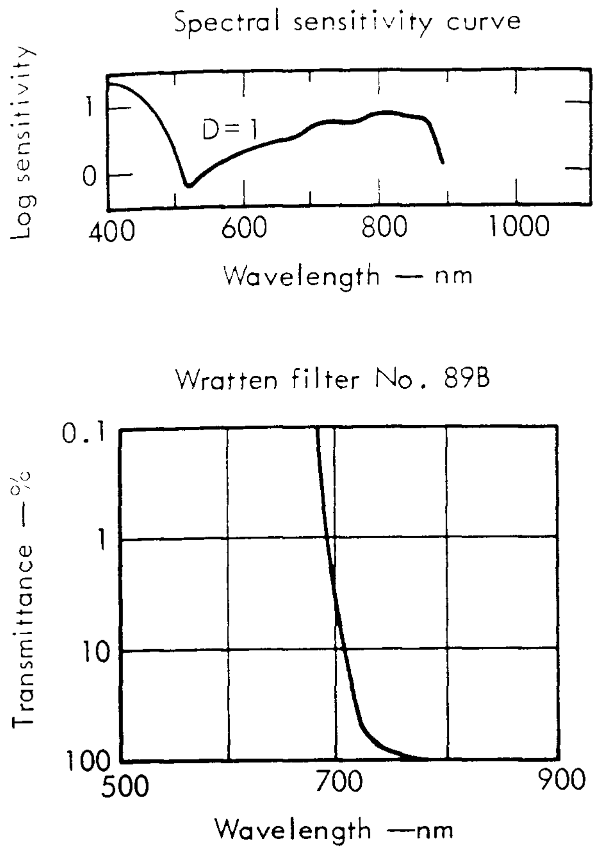

Fig. 10. Kodak Infrared Aerographic Film 2424. This film is a negative material which is sensitive to infrared radiation, as well as to the blue light of the visible spectrum. When used with a Wratten 89B filter, which absorbs all visible radiation, only the infrared radiation from the subject is recorded on the film.

that the human eye sees. The missions were flown similarly to the multispectral missions.

Photographic Processing and Printing

On-Island Processing and Printing— The imagery acquired during the quick-look photographic missions was processed and printed on the island, using the Eniwetok Marine Biology Laboratory. Conventional black-and-white developing and printing were accomplished to provide a 40 × 50-cm photographic map of each island.

Laboratory Processing and Printing – Exposed film from the multispectral camera system was processed in Las Vegas, Nevada. The two black-and-white films were processed by EG&G in a Versamat 5N. Both color-film records were processed commercially in a Kodak Color Versamat.

Photographic enlargements were made by EG&G from all records. The degree of enlargement varied for each island photograph because the island size was imaged to fit the print format with some water surrounding it.

Report Reproductions – The color lithographs in Appendix II were made from the normal color photographic record using four-color separation negatives prepared by EG&G. The color printing was done by EG&G on a model 1250 L&W Multilith press. Overprinting of titles and data was accomplished on the same press.

Interpretation and Utility of the Photographs

Multispectral Imagery Interpretation – The imagery acquired of each island consists of the four wavelength regions previously described, examples of which are shown in Figs. 11-14. These are film records recorded simultaneously over Japtan Island (DAVID). Each figure shows imagery from a different portion of the spectrum. Figure 11 shows normal wavelengths similar to those seen by the human eye, covering 4000 to 7000 Å. In Fig. 12 all of the colors seen are "false" with regard to human vision. In this picture, wavelengths between 5000 and 6000 Å (green wavelengths) are recorded as blue, wavelengths between 6000 and 7000 Å (red wavelengths) are recorded as green, and wavelengths between 7000 and 9000 Å (infrared wavelengths) are recorded as red.

Figure 13 is the black-and-white record on panchromatic film and exposed through a Wratten 25 red filter. On this imagery, only wavelengths between 6000 and 7000 Å are recorded. Figure 14 is the black-and-white record recorded on infrared film with a visible absorbing filter. On this imagery only infrared wavelengths between 7000 and 9000 Å are recorded.

While there are many facets to consider when interpreting multispectral photographs, a few general guidelines may be helpful. It is best to spread the four photographs for any one island out on a table when examining them so that the differences can be easily and quickly observed. The normal color record and the black-and-white (red filter) record both penetrate water depths well and show underwater terrain well. However, from the normal color record, it is difficult to determine where the water's edge is located. This can be easily determined by looking at the black-and-white (infrared film) record which shows all water areas as black. The differences between the appearance of the water areas on the normal color and the infrared color record are significant. The normal color record shows colors on the print as they would be seen by the eye. However, on the infrared color record, all the colors are "false." On this record the water still shows as a blue color, even though the film, when used with a yellow filter, has no sensitivity to blue wavelengths. The blue areas on the print are the direct result of green wavelengths reflected to the camera. In this "false-color" imagery, healthy vegetation and coral areas show as red. This indicates high reflectivity in the near-infrared region of the spectrum. The black-and-white (red filter) record shows green trees very dark and generally causes man-made objects such as concrete, asphalt, and buildings to stand out against the dark background. On the black-and-white (infrared film) record, green healthy trees which have a high reflectance in the infrared region appear very light, indicating again a high reflectance in the infrared region.

Other Interpretations of the Photography — A wealth of information is contained in the photographs. Using a detailed study of one or of a series of photographs and aided by suitable analysis techniques, the photographs could be used for the following:

- Determine the percentage of tree cover for any island.
- Establish vegetation types.
- Determine the waterline at the time of the photograph.
- Locate major areas of debris.
- Determine suitable boat landing areas.
- Determine relative water depths around the islands.

Additionally, because some islands were photographed with overlapping coverage, a stereo presentation is possible. This results in considerably more information about the terrain, surface cover, and man-made structures than is possible with a single photograph.

Fig. 11. Normal color aerial photograph of DAVID covering 4000 to 7000 Å.

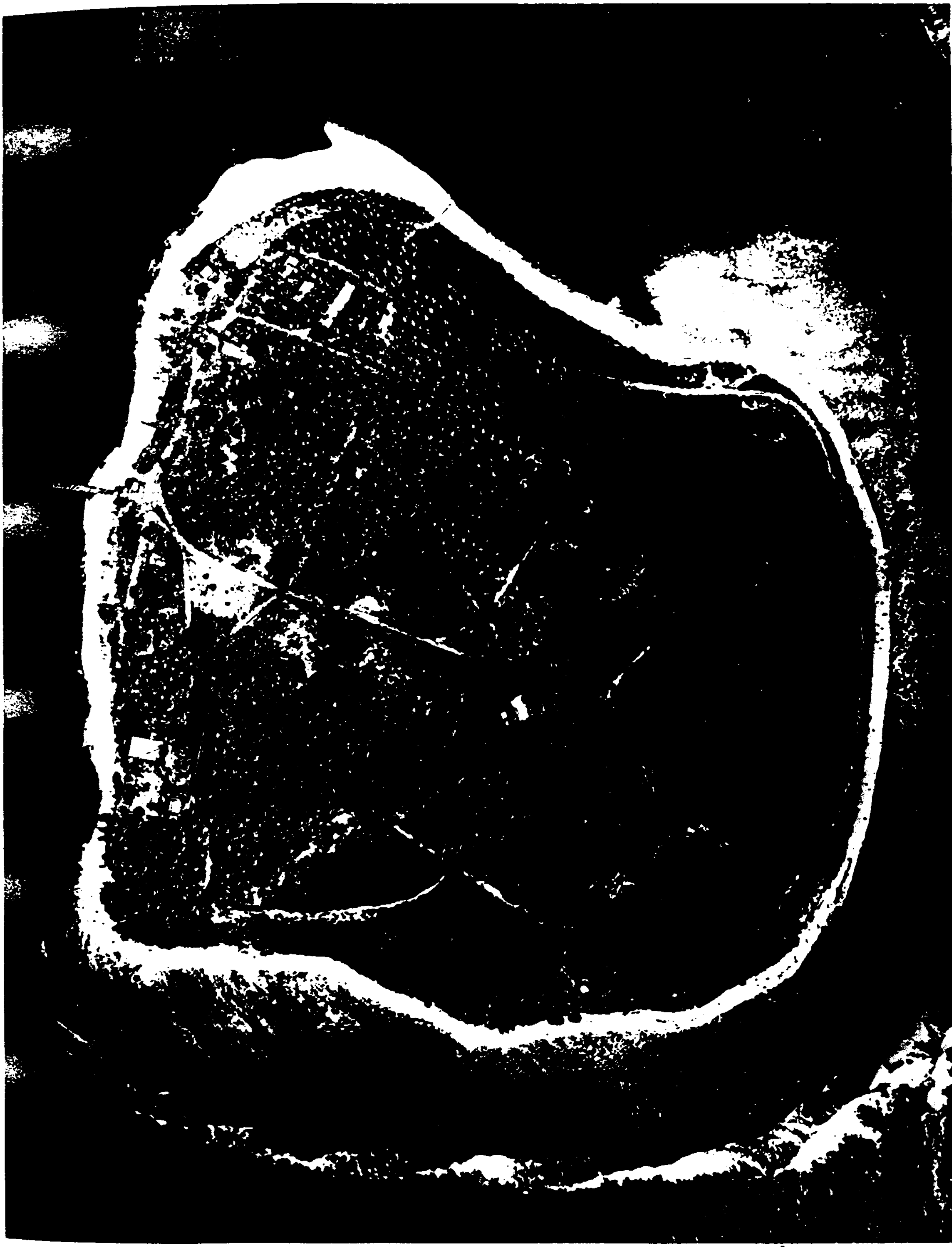

Fig. 12. False color aerial photograph of DAVID covering 5000 to 9000 Å.

Fig. 13. Aerial photograph of DAVID covering 6000 to 7000 Å.

Fig. 14. Aerial photograph of DAVID covering 7000 to 9000 Å.

Fig. 15. Single frame of high-altitude photographic coverage.

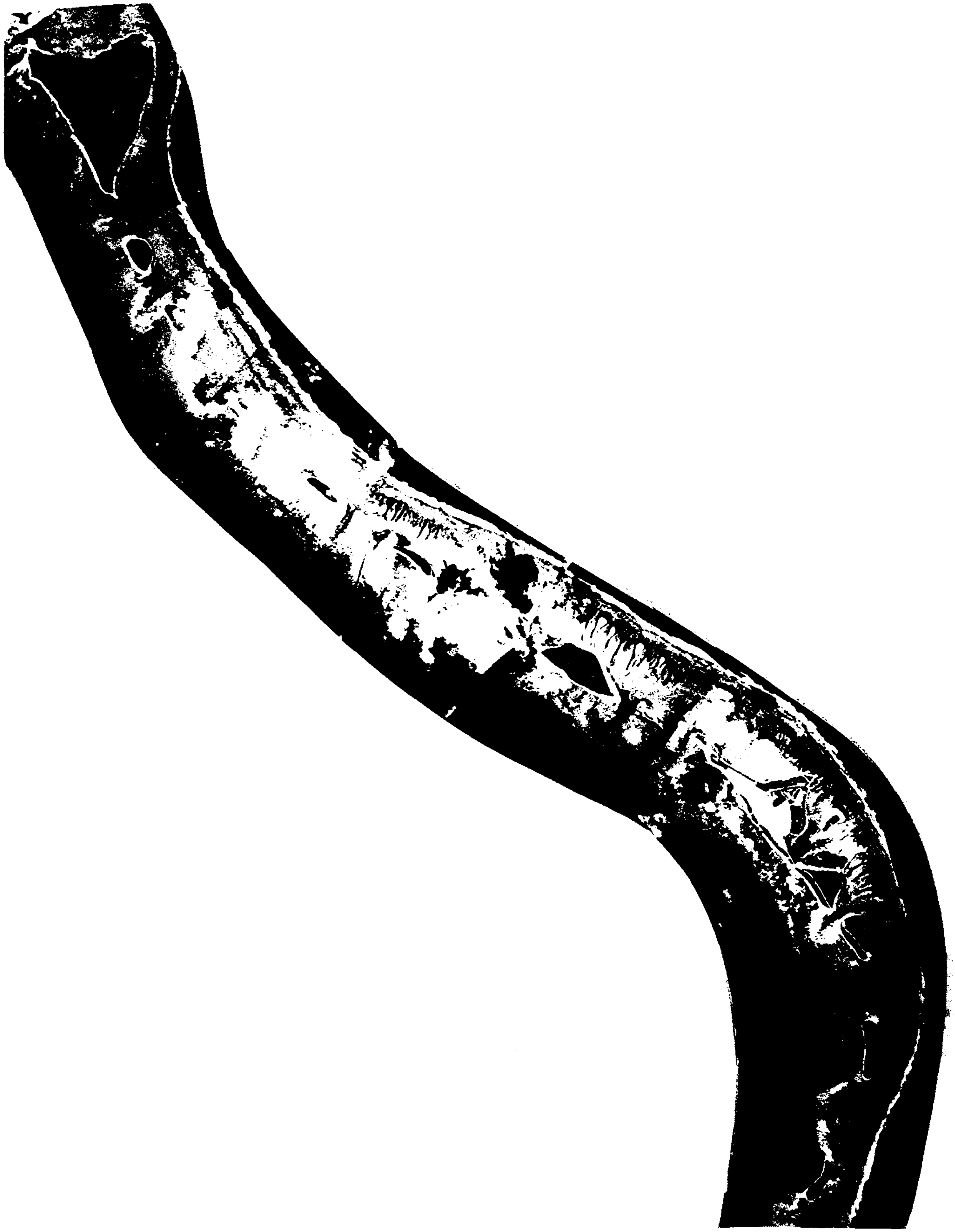

Fig. 16. Assembled mosaic from JANET to WILMA.

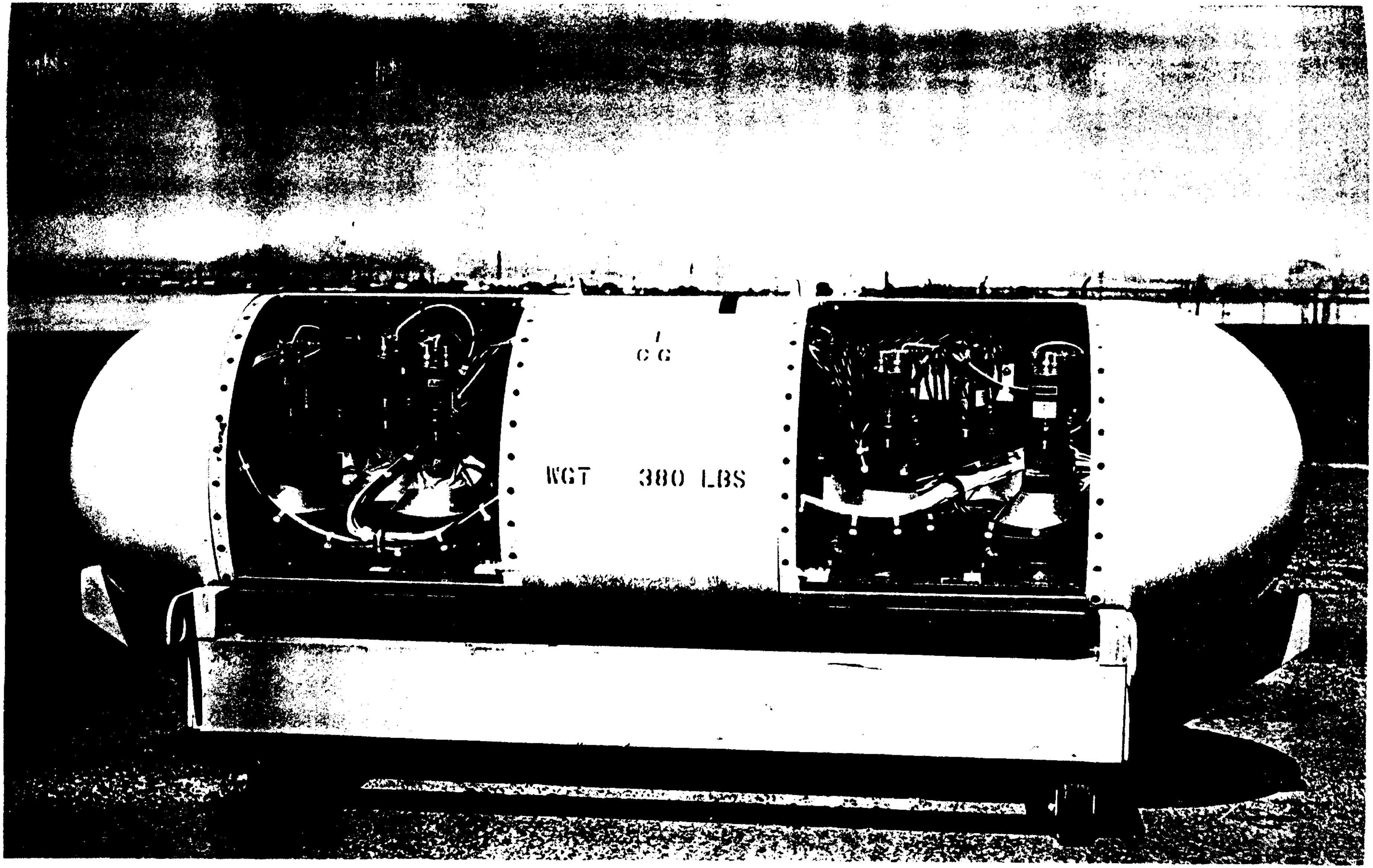

Fig. 17. Single array of NaI detectors.

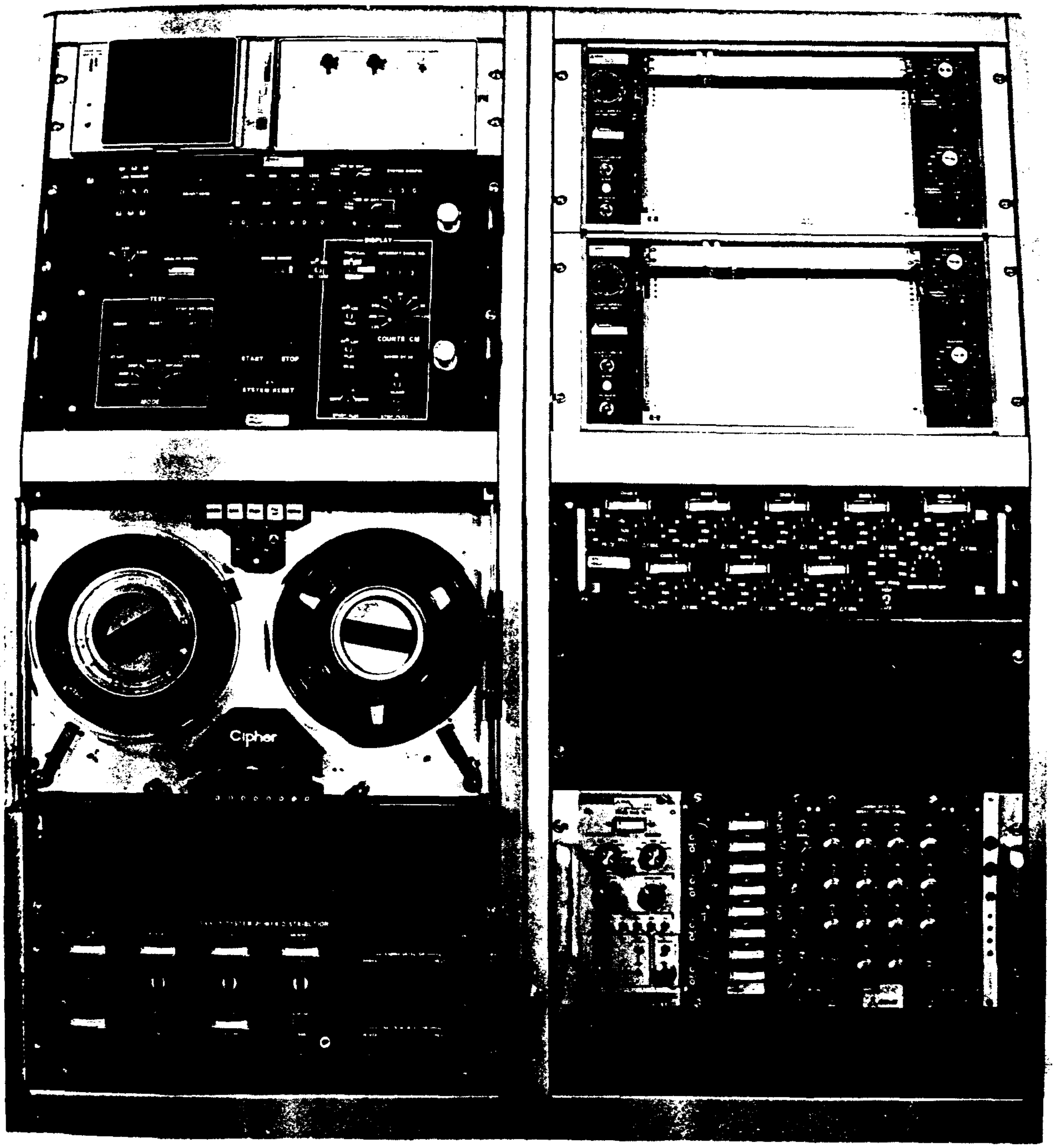

Fig. 18. Data recording system.

High-Altitude Mosaic – The entire Atoll was photographed with the Multispectral Camera System from an altitude of 3000 m over a period of several days for the purpose of making a mosaic. A single frame of the high-altitude coverage is shown in Fig. 15. From this altitude the relationship of the islands to one another, as well as the entire reef structure, can be clearly seen. A portion of the assembled mosaic extending from JANET to WILMA is shown in Fig. 16.

Nuclear Instrumentation Systems and Methods

Descriptions of Instrument Systems

Detectors – Gamma rays were detected in two arrays of twenty 12.7-cm diam × 5-cm thick NaI crystal spectrometers. Figure 17 shows one of these arrays. The output from the crystal photomultiplier-preamplifier combinations was summed and fed to the recording system.

Inertial Navigation System – Accurate position data are obtained from a Litton Inertial Navigation System, LTN-51. The actual flight coordinates (latitude and longitude) are recorded on magnetic tape. Special software, prepared by Litton to our specifications, allows these data to be recorded with a minimum detectable distance increment of 15 ft.

When these data are processed, the flight paths are overlaid on a photographic map of the survey area. The end points are matched with the known positions of the start and finish of each line. The position of the aircraft is then known at any point along the flight path with an uncertainty related to the flying time of ±1/2 sec. For a typical survey, conducted at an altitude of 100 ft above terrain and at a speed of 30 m/sec, this implies that the location of the aircraft is known with an uncertainty of ±15 m.

Recording System – Summed signals from the separate detectors were split and fed to (1) a 300-channel pulse-height analyzer and (2) a maximum of eight single-channel analyzers with adjustable upper and lower limits. These limits are set to monitor regions of the spectrum pertinent to isotopes of interest. Accumulation time for single-channel data was a minimum of 0.2 sec, while accumulation time for multichannel data was a minimum of 3 sec. Inertial-navigation position data and multi- and single-channel counts occurring in the above time intervals were recorded on magnetic tape. The recording system is shown in Fig. 18.

Data-Processing System – Magnetic tape was processed by a ground-based system, key components of which were two cipher data tape drives, a NOVA computer, and a Cal Comp plotter.

Helicopter – The NaI spectrometer pods and the data-recording system were carried inside a Marine CH53 helicopter. This arrangement resulted in the radiological measurements being made with the terrestrial gamma radiation traveling through the floor of the helicopter to reach the gamma spectrometers. This attenuation effect was taken into account by performing calibrations in a similar geometry. This is discussed in the subsection on Isotopic Concentration.

Operational Procedures

Survey Measurements – Due to the large difference in photopeak energies and resolution of the recording system, a separate survey was made for plutonium while data for ^{60}Co and ^{137}Cs concentrations were accumulated simultaneously. Plutonium was sensed via the 60-keV γ ray from ^{241}Am, a decay product of ^{241}Pu. Electronic gain was adjusted for those surveys so that the full-energy scale corresponded to a γ-ray energy of 300 keV. Typical spectra with and without ^{241}Am are shown in Fig. 19. Shaded areas in this figure define three single channels, the outer two of which were set to monitor changes in background levels. The central window monitors the 60-keV photopeak.

Electronic gain was set to cover a full scale of 3 MeV for the ^{60}Co and ^{137}Cs surveys. A typical spectrum is shown in Fig. 20. Shaded areas in this figure again define the single channels set up to monitor background and photopeak regions of the spectra. Gross counts (those between 50 keV and 3 MeV) were also recorded during the high-energy surveys.

A grid of lines spaced 150 ft apart was flown over each island at an altitude of 100 ft and an airspeed of ~70 knots. Flight lines were laid out on aerial photographs taken for navigation purposes. An on-top marker was recorded on the magnetic tape when a landmark near the shore was crossed at the start and finish of the flight line. Some individual detectors in the array were turned off, and flight lines were reflown when count rates were high enough to produce spectral distortion due to pulse pileup.

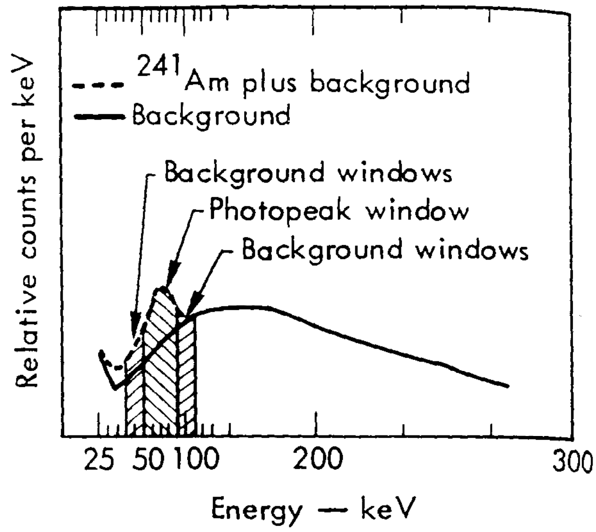

Fig. 19. Gamma spectra with and without the ^{241}Am contribution.

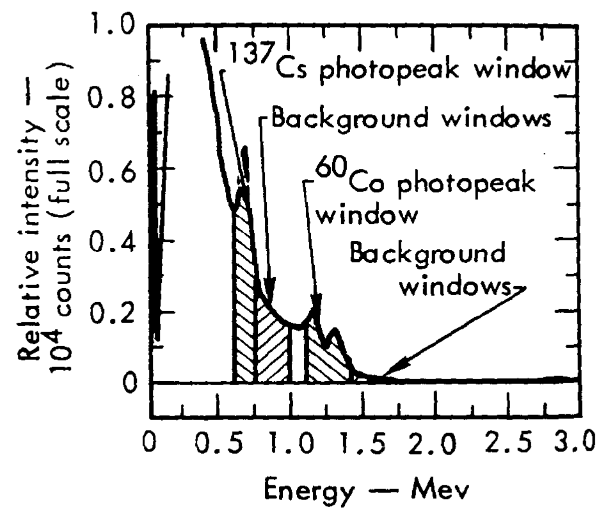

Fig. 20. High-energy gamma spectrum showing contributions from ^{60}Co and ^{137}Cs.

Data Processing – The data-processing system converts magnetic tape records to scalar field plots of aircraft position vs count-rate data. Symbols denoting the on-top markers are also printed on the plot. Lines are contracted and expanded in length so that the on-top markers coincide with the photographic landmarks used to annotate the tape.

Contours are drawn after all flight lines have been properly positioned on the photograph of the island.

Computer software has been developed to plot weighted sums of any combination of single-channel data accumulated during 1-sec time intervals. Multichannel data can be processed to give the same type of information, but with a minimum of 3-sec time intervals.

Instrumentation Calibration and Conversion Factors

This section describes the method used to convert aerially measured gamma-ray count rates to exposure rates one meter above the ground and to isotopic concentrations in the ground. Count rates in windows previously defined are used to derive isotopic concentrations. The isotopic concentrations can be converted to exposure rates one meter above the ground using previously derived data.*

General Expressions for Isotopic Concentration—Count rates in pulse-height windows centered on gamma-ray photopeaks of interest are composed of unscattered γ rays from the isotope of interest and background counts from (1) cosmic rays and natural activity in the aircraft and Atoll material and (2) possible contribution from higher-energy contaminants. Background is compensated when the data are processed by subtracting weighted combinations of count rates in appropriate windows. The assumption that only unscattered γ rays remain in the photopeak window after the background is subtracted allows simple expressions to be derived to relate aerial count rates to various source geometries. Good definition of the photopeaks lends credence to this approach.

Conversion factors are developed in the following paragraphs. Detector efficiency is defined in terms of an effective detector area at normal incidence. This area is calculated from gamma-ray count rates measured in helicopter hovers over point radioactive sources of known strength. The change in effective detector area with angle of incidence must be considered for sources distributed over the Atoll. Appropriate or limiting values for angular responses will be assumed according to γ-ray energy. Conversion factors result from eliminating effective detector area between expressions derived for count rates over a point calibration source and the distributed source of interest.

Detector efficiency (effective area) is determined by signal minus background count rates when hovering over ^{60}Co, ^{137}Cs, and ^{241}Am calibration sources of known strength. The photopeak window count rates, CR_p, when hovering directly over a calibration source can be written in terms of an effective detector area:

$$CR_P = \frac{sA}{4\pi d^2} \exp\left[-\left(\frac{d}{\lambda_a} + \frac{t}{\lambda_s}\right)\right], \quad (1)$$

where

d = distance between point source and the detector,

t = thickness of aircraft skin and floor,

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*H. L. Beck, J. DeCampo, and C. Gogolak, In Situ Ge(Li) and NaI(Tl) Gamma-Ray Spectroscopy, HASL, 258, p. 49, 1972.

s = source strength,

λ_a = γ-ray mean free path in air,

λ_s = γ-ray mean free path through aircraft structure,

and

A = effective detector area at normal incidence to the crystal face.

The derivation of the effective detector area includes consideration of the effect of photopeak window efficiency, and the possibility of subtraction of photopeak counts appearing in radiation background windows.

Equation (1) can be combined with an assumed detector angular response to derive expressions for the diameter of the circle that contains ground concentrations that are spatially close enough to the aircraft to contribute to the aerially measured count rates. The count rate when hovering to the side of a point source is:

$$CR_P' = \frac{SA\ f(\theta)}{4\pi(\ell^2 + d^2)} \exp\left[-\left(\frac{\sqrt{\ell^2 + d^2}}{\lambda_a} + \frac{t}{\lambda_s}\right)\right], \tag{2}$$

where

ℓ = lateral distance between source and detector,

and

$f(\theta)$ = detector angular response.

The diameter of the circle of influence is defined as twice the lateral distance between the source and detector when the signal is equal to half the value measured when the detector is directly over the source. The following equation defines the diameter, Δx, of the circle of influence:

$$\frac{1}{2} = \left[\frac{d^2}{\left(\frac{\Delta x}{2}\right)^2 + d^2}\right]\left[\frac{f(\theta)}{f(0)}\right] \exp\left\{\left[\frac{1}{\lambda_a} + \frac{t}{d\lambda_s}\right]\left[\sqrt{\left(\frac{\Delta x}{2}\right)^2 + d^2} - d\right]\right\}. \tag{3}$$

For a detector with isotropic angular response, this equation becomes:

$$\frac{1}{2} = \left[\frac{d^2}{\left(\frac{\Delta x}{2}\right)^2 + d^2}\right] \exp\left\{\left[\frac{1}{\lambda_a} + \frac{t}{d\lambda_s}\right]\left[\sqrt{\left(\frac{\Delta x}{2}\right)^2 + d^2} - d\right]\right\}. \tag{4}$$

For a detector with a cosine angular response, this equation becomes:

$$\frac{1}{2} = \left[\frac{d^2}{\left(\frac{\Delta x}{2}\right)^2 + d^2}\right]^{3/2} \exp\left\{\left[\frac{1}{\lambda_a} + \frac{t}{d\lambda_s}\right]\left[\sqrt{\left(\frac{\Delta x}{2}\right)^2 + d^2} - d\right]\right\}. \tag{5}$$

The diameters calculated from these equations apply to a stationary detector. A moving detector, accumulating data over discrete time intervals, will not be described by a circle of influence, but rather by a figure resembling an ellipse with the major axis along the direction of motion. The increase in length along this direction is equal to the product of data accumulation time and helicopter speed. This product is ~100 ft for all but the ^{241}Am data.

The form of the expression for count rate at altitude from a distributed source depends upon the vertical distribution of the source in the soil and the angular response of the detector. Due to incomplete knowledge of the form of the source distribution, an exponential decrease with depth will be assumed. It will be shown that factors for converting aerially measured count rates to one-meter-level exposure rates are insensitive to relaxation depth and, therefore, to form of distribution.

Due to the geometrical configuration of the NaI crystals and the detector array, the highest efficiency occurs for photons incident at 0° with respect to the normal to the crystal face. The hypothetical conditions, then, of isotropic angular response and cosine angular response (zero efficiency at 90° incidence) bracket the true angular response.

The differential count rate from a concentration at depth z uniformly distributed over a volume $2\pi r dr\, dz$ of atoll material is given by:

$$dCR = \left[\frac{\alpha\eta e^{-\alpha z} A}{4\pi(h^2 + r^2)}\right] \exp\left[-\frac{\sqrt{h^2 + r^2}}{h}\left(\frac{h}{\lambda_a} + \frac{t}{\lambda_s} + \frac{z}{\lambda_m}\right)\right] \times 2\pi r\, dr\, dz, \qquad (6)$$

where

α = reciprocal relaxation depth of contributing radionuclide,

η = total surface concentration or integral of volume concentration to ∞ depth,

h = height above ground,

and

λ_m = γ-ray mean free path in the Atoll material.

The above expression can be integrated over the ∞ half space defining the ground to give:

$$CR = \frac{\eta A\alpha}{2}\int_0^\infty E_1\left(\frac{h}{\lambda_a} + \frac{t}{\lambda_s} + \frac{z}{\lambda_m}\right) e^{-\alpha z}\, dz, \qquad (7)$$

where E_1 is an exponential integral of the first kind. The following equation results from eliminating A between Eqs. (1) and (7).

$$\eta = \left[\frac{S \exp\left[-\left(\frac{d}{\lambda_a} + \frac{t}{\lambda_s}\right)\right]}{2\pi d^2 \alpha \int_0^\infty e^{-\alpha z} E_1\left(\frac{h}{\lambda_a} + \frac{t}{\lambda_s} + \frac{z}{\lambda_m}\right) dz\, CR_p}\right] CR. \qquad (8)$$

The conversion factor in brackets contains known geometrical parameters, calibration source strengths, and measured count rates.

The expression corresponding to Eq. (6) for a cosine angular response includes an additional factor equal to $h/\sqrt{h^2 + r^2}$. The integral of this expression is:

$$CR = \frac{\eta A}{2}\alpha\int_0^\infty e^{-\alpha z} E_2\left(\frac{h}{\lambda_a} + \frac{t}{\lambda_s} + \frac{z}{\lambda_m}\right) dz. \qquad (9)$$

This equation is the same as Eq. (7) with the order of the exponential integral changed. The conversion factor corresponding to Eq. (8) is, therefore:

$$\eta = \left\{ \frac{S \exp\left[-\left(\frac{d}{\lambda_a} - \frac{t}{\lambda_s}\right)\right]}{2\pi d^2 \alpha \int_0^\infty e^{-\alpha z} E_2\left(\frac{h}{\lambda_a} - \frac{t}{\lambda_s} - \frac{z}{\lambda_m}\right) dz \; CR_P} \right\} CR. \quad (10)$$

Plutonium Concentrations

Plutonium is sensed via the 60-keV γ ray from ^{241}Am, which is a decay product of ^{241}Pu. The pulse-height spectrum from γ rays with energy greater than ~100 keV is linear in the energy range between 40 and 80 keV. Therefore, the background count rate in the 20-keV-wide signal window (50-70 keV) is assumed to be equal to the sum of two count rates from 10-keV-wide windows contiguous to both sides of the signal window.

Window count rates can be taken from multichannel data or from single-channel data. Multichannel data have been used, due to electronic problems and the presence of excessive count rates in the single-channel windows as set up for the plutonium survey. Spatial resolution along the direction of flight is degraded by use of the multichannel data, which have a 3-sec data accumulation time. Part of the expected 300-ft degradation is removed by the manner in which the data are processed. The diameter of the circle of influence is 135 ft, as calculated from Eq. (5).

Due to the presence of the cadmium shielding on the sides of the crystals, the count rate for low-energy photons is proportional to the cosine of the angle of incidence with respect to the normal to the crystal faces. The appropriate conversion factor is therefore given by Eq. (10). The conversion factor as calculated from this equation with an assumed relaxation depth of 10 cm is shown in Table 7.

Cobalt-60 Concentrations

Background counts in the ^{60}Co photopeak window (1.095 to 1.395 MeV) are assumed to be proportional to aircraft

Table 7. Photopeak window conversion factors.

		Conversion factor			
		Concentration, $\frac{\mu Ci}{m^2}\frac{sec}{cnt}$			
Radionuclide	Relaxation depth in Atoll material, cm	Isotropic angular response of detector array	Cosine angular response of detector array	Average of previous two columns	Exposure rate at 1 m as calculated from previous column, $\frac{\mu R}{hr}\frac{sec}{cnt}$
^{241}Am	10		66×10^{-4}		
^{137}Cs	1	8.5×10^{-4}	15.2×10^{-4}	11.8×10^{-4}	74×10^{-4}
	Average[a]			20.9×10^{-4}	72×10^{-4}
	10	23.2×10^{-4}	36.6×10^{-4}	30.0×10^{-4}	70×10^{-4}
^{60}Co	1	4.6×10^{-4}	7.2×10^{-4}	5.9×10^{-4}	155×10^{-4}
	Average[a]			10.6×10^{-4}	152×10^{-4}
	10	11.2×10^{-4}	19.4×10^{-4}	15.3×10^{-4}	150×10^{-4}

[a]Average value for two relaxation depths.

background, cosmic rays, and contributions from natural background emitters, all in the energy interval between 1.395 and 3.00 MeV. The ratio is determined by flights at 100 ft over water, which should contain negligible amounts of ^{60}Co. Data are processed to continuously subtract this background from the photopeak window count rate.

Table 7 compares the factors [(calculated from Eqs. (8) and (10)] for converting the resulting count rate to ground concentration for two relaxation depths. The conversion factor shown in the fifth column is the average of values from the two previous columns. This average represents the best value presently available. Experiments with ^{137}Cs sources have shown the average to be accurate to within a few percent.

The diameter of the circle of influence lies between 145 and 180 ft, as calculated from Eqs. (4) and (5).

Cesium-137 Concentrations

The background count rate in the ^{137}Cs photopeak window (0.6 to 0.75 MeV) is assumed to be composed of two parts. One of these is proportional to aircraft background, cosmic rays, and contributions from natural background emitters in the energy interval between 1.395 and 3 MeV. The second background component, which is proportional to the ^{60}Co contribution to the ^{137}Cs window, was determined from spectral shape when ^{60}Co was present with negligible amounts of ^{137}Cs. Backgrounds of both types were subtracted during data processing by summing appropriately weighted single-channel count rates. Table 7 compares the factors [(calculated from Eqs. (8) and (10)] for converting the resulting count rate to ground concentration for two relaxation depths. Other experiments have shown that the true detector angular response is such that the average conversion factors in the fifth column are accurate to within a few percent.

The diameter of the circle of influence lies between 145 and 180 ft, as calculated from Eqs. (4) and (5).

Exposure Rates – Factors for converting ^{60}Co and ^{137}Cs photopeak count rates to 1-meter-level dose rates have been calculated by combining data in the fifth column of Table 7 with data from H. L. Beck et al. The result of this combination is given in the last column of the same table. The average value between extremes in angular response is used because experiments show that this average is good to a few percent, at least for ^{137}Cs sources. The same averaging process is used for ^{60}Co sources, although similar measurements have not been made.

Note that the factor for converting aerially measured count rates to dose rate is insensitive to large variations in relaxation depth. In most cases the two assumed relaxation depths bracket those measured in soil-sample analyses.

Comparison with Ground Data

Aerial data were processed to give 20% increments between contour levels for the islands of JANET, ALICE, BELLE, and DAISY. The sum of Co and Cs contributions to dose rates (using the conversion factors listed in the last column of Table 7) is compared with LiF thermoluminescent dosimetry (TLD) measurements at 37 locations in the chapter on external dose estimates. Dose rates averaged over these locations were 11% lower for the aerial measurements than for the standard TLD measurements. Two special TLD badges, shielded against β rays, gave a 10% lower exposure rate than the standard unshielded badges at the same location. The aerial measurements do not sense β rays because of the mass of air and structure between the source and NaI. Therefore, the aerial measurements for γ rays only are in excellent agreement with the γ-ray contribution to the TLD measurements. The aerial data have not been normalized to the unshielded TLD data.

It should be mentioned that the excellent agreement between the aerial data and the TLD data is well within the uncertainties in the aerial measurements. In particular, an error of a few feet in the 50-ft hover altitude over the calibration sources would introduce a 10% error in the conversion factor. Oscillations about the point directly over the source effectively increase the average slant range. Use of an excessively small slant range falsely increases quoted concentrations.

The total mass of aircraft structure between the detectors and sources was not known. In particular, the mass of reinforcing material between the two outside plates of the aircraft floor was not known and was excluded in the attenuation calculations. The presence of additional mass lowers the distributed source count rate relative to the count rate from the point calibration source. Neglect of this additional mass has the effect of falsely decreasing quoted concentrations. The two types of errors described above occur in opposite directions and are expected to be partially self-compensating.

Explanation of Contour Maps

^{60}Co and ^{137}Cs Separately – Contour maps were generated for e island on the basis of photopeak wir count rates for ^{60}Co and ^{137}Cs sep All other types of background were tracted so that the only counts rem: were due to the separate isotopes. were processed so that letter symb denoted a range of values for count in the photopeak windows. The fiftl seventh columns in Table 8 relate t contour letter symbols (correspond window count rates) to the dose rat delivered by each isotope. This re ship is established from values in t last column of Table 7. Table 8 al: lates letter symbols to soil concent averaged over the two extremes as: for relaxation depths. The two extı and the average conversion factor a given in the fifth column of Table 7. contours are superimposed on gray of the islands (the "m" series of fig in Appendix II); ^{137}Cs contours are imposed on green prints of the islar (the "k" series of figures in Append

These contours were used to tabı an estimated average dose rate ove: island. Results are shown in Table

Average Dose Rates From Gr Counts – Contours superimposed on greenish-gold prints (the "b" series figures in Appendix II) were constru from counts in the energy interval b 50 keV and 3 MeV. An average con factor must be established to relate counts to concentration, since this interval senses both ^{60}Co and ^{137}C: This average conversion factor is a

Table 8. Contour map key for use with figures in Appendix II.

Symbol	^{241}Am concentration (assumed 10-cm relaxation depth)		^{137}Cs		^{60}Co		
	Total $\mu Ci/m^2$	pCi/g averaged over top 10 cm	Concentration, $\mu Ci/m^2 \pm 50\%$ for 1 cm < relaxation depth < 10 cm	Exposure rate, $\mu R/hr$	Concentration, $\mu Ci/m^2 \pm 50\%$ for 1 cm < relaxation depth < 10 cm	Exposure rate, $\mu R/hr$	Gross count exposure rate, $\mu R/hr$
A^{--}			0-0.1	0-0.34			
A^{-}			0.1-0.2	0.34-0.68	0-0.04	0-0.59	
A	21-30	-13	0.2-0.4	0.68-1.36	0.04-0.08	0.59-1.14	0-1.0
B	30-45	13-19	0.4-0.6	1.36-2.0	0.08-0.12	1.14-1.7	1.0-1.5
C	45-66	19-28	0.6-0.8	2.0-2.7	0.12-0.16	1.70-2.3	1.5-2.0
D	66-100	28-42	0.8-1.6	2.7-5.4	0.16-0.32	2.3-4.6	2.0-4
E	100-145	42-61	1.6-3.1	5.4-11	0.32-0.64	4.6-9.2	4-8
F	145-210	61-89	3.1-6.2	11-22	0.64-1.3	9.2-18	8-16
G	210-300	89-130	6.2-12	22-44	1.3-2.5	18-36	16-33
H	300-450	130-190	12-25	44-88	2.5-5.0	36-72	33-66
I			25-50	88-170	5-10	72-140	66-130
J			50-100	170-340	10-20	140-290	130-260
K			100-200	340-700	20-40	290-580	260-520
L			200-400	700-1400	40-80	580-1200	520-1050

to be half the sum of the separate conversion factors for ^{137}Cs and ^{60}Co. The two separate factors are calculated by multiplying photopeak conversion factors in the sixth column of Table 7 by the ratio of photopeak counts to gross counts in spectra taken at 100 ft over islands that contain predominantly one or the other isotope. Uncertainty as to whether the contaminant is ^{60}Co or ^{137}Cs introduces errors of ±10% in the exposure rates derived from gross counts.

The seventh column of Table 8 relates the contour letter symbols to exposure rates for these figures.

Count rates produced by aircraft background and cosmic rays have not been subtracted before application of the conversion factor. The contours, therefore, assume that the conversion factor multiplied by gross count rates over uncontaminated Atoll material equals the dose rate at the 3-ft level at the same location. The primary contributor in these areas, cosmic rays, are estimated to produce ~3 $\mu R/hr$ at the 3 ft level. The product of gross counts and conversion factor is 0.9 $\mu R/hr$. Therefore, the fractional error is small for dose rates greater than 20 $\mu R/hr$ and consistent with errors inherent in the average conversion factor concept.

^{241}Am Concentration – The island of YVONNE has been contoured for ^{241}Am concentration. Data were processed so that contour letter symbols denoted a range of counts remaining in the photopeak window after the two contiguous background windows had been subtracted. This letter symbol and range of count rates was related to concentration according to Eq. (10). A 10-cm relaxation depth

Table 114. Summary of average exposure rates for islands in Enewetak Atoll.

Island	Average exposure rate, μR/hr at 1 m[a]			
	^{137}Cs	^{60}Co	Total γ (0-3 MeV)	Range[b]
ALICE	42	36	81	4-170
BELLE	61	50	115	5-200
CLARA	20	19	42	5-100
DAISY	6.8	14.4	21.3	5-140
EDNA	2.8	2.4	6	5-8
IRENE	14	63	80	3-560
JANET	25	13	40	2-150
KATE	11	7	19	3-22
LUCY	6	7	14	1-20
PERCY	2	2	5	2-11
MARY	5.5	4	10	2-12
NANCY	6	5	12	1-50
OLIVE	6.5	4.5	11	1-15
PEARL	12	45	70	1-400
RUBY	2	12	14	1-42
SALLY	3.5	3	7	3-110
TILDA	4	2	6	2-11
URSULA	3	1.8	5	1-7
VERA	2.8	2	5	1-6
WILMA	1	1	2	1-3
YVONNE	5.6	22.4	33	1-750
SAM	<0.3 (0.20)	<0.6 (0.11)	10.9	0-1
TOM	<0.3 (0.18)	<0.6 (0.13)	<0.9	0-1
URIAH	<0.3 (0.06)	<0.6 (0.43)	<0.9	0-1
VAN	<0.3 (0.08)	<0.6 (0.25)	<0.9	0-1
ALVIN	N. D. (0.06)	<0.6 (0.25)	<0.9	0-1
BRUCE	0.4 (0.22)	0.8 (0.34)	1.2	0-1
CLYDE	<0.3 (0.04)	<0.6 (0.11)	<0.9	0-1
DAVID	N. D. (0.21)	N. D. (0.10)	<0.9	0-5
REX	<0.3 (0.28)	<0.6 (0.25)	<0.9	0-1
ELMER	N. D. (0.19)	N. D. (0.12)	<0.09	0-2
WALT	<0.3 (0.08)	<0.6 (0.10)	<0.9	0-1
FRED	N. D. (0.14)	N. D. (0.12)	<0.9	0-1
GLENN	0.4 (0.33)	<0.6 (0.20)	<0.9	0-1
HENRY	<0.3 (0.14)	<0.6 (0.20)	<0.9	0-1
IRWIN	<0.3 (0.08)	<0.6 (0.46)	<0.9	0-1
JAMES	<0.3 (0.05)	2.8	3.0	0-5
KEITH	<0.3 (0.15)	<0.6 (0.49)	<0.9	0-2
LEROY	2.8	4.8	7.6	3-8

[a]Average dose rates given are derived from aerial survey data. On islands where activity levels are at the lower limit of sensitivity of the aerial survey equipment, dose rates derived from the soil sample data are given in parentheses.

[b]As measured with the Baird-Atomic instrument.

was assumed as an average of those measured in soil sample analyses. The resulting conversion factor is given in the fourth column of Table 7. The second column of Table 8 relates contour symbols to ^{241}Am concentrations as calculated with this conversion factor. The third column of Table 8 lists the corresponding volume concentrations averaged over the top 10 cm.

Concentrations above our minimum detectable level in ^{241}Am were not present in sufficient quantity to justify plotting exposure rate or material concentration distributions for other islands. The minimum detectable level is controlled by statistical variations in the background count rate from cosmic rays, ^{137}Cs, and ^{60}Co. The minimum detectable level, thus, changes from island to island and from point to point within a particular island. Soil samples may show concentrations that are not detectable from the air due to high background count rates or to the presence of dense vegetation, which severely attenuates the 60-keV γ rays from ^{241}Am.

TERRESTRIAL SOIL SURVEY

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Soil Survey Plan

The Enewetak soil survey, described in this section, had as its objective a thorough evaluation of the present radiological conditions of all islands of the Atoll. Planning of the soil survey was based upon extensive investigations of the historical aspects of the weapons-testing program, the most recent information gathered during previous radiological surveys of Bikini Atoll, and preliminary surveys of Enewetak Atoll in July 1971 and May 1972.

Laboratories which conducted the experiments provided reports containing data on the original nuclear devices. Actual test information, fallout patterns, radiological safety reports, etc., came from AEC sources. Construction drawings and information on modifications to the topography were made available by the testing support contractor, Holmes and Narver, Inc. (H&N). Other organizations, including those which conducted environmental studies during and after the testing program, supplied their findings. In addition, a wealth of information was available in old reports, records, documents, etc., stored in archives.

Examination of reports from the Lawrence Livermore Laboratory (LLL) and Los Alamos Scientific Laboratory (LASL) enabled us to identify radionuclides most likely to be present, based upon the composition of the nuclear devices and associated experiments. These radionuclides are listed on Table 10. The quantities of of "environmental" materials such as structural steel, concrete, wiring, pipe, etc., were also determined for purposes of estimating the types of contaminated debris that should have remained after a shot.

The Test Manager's operations reports contained fallout patterns for nearly every event. From these reports, in a crude effort to estimate residual conditions, the Atoll's islands were graded as

Table 10. Radionuclides expected in Enewetak Atoll soil.

Radio-nuclide	Source	Radio-nuclide	Source
^{241}Am	Unburned weapon fuel	^{147}Pm	Fission product
^{240}Pu	Unburned weapon fuel	^{137}Cs	Fission product
^{239}Pu	Unburned weapon fuel	^{125}Sb	Fission product
^{238}Pu	Unburned weapon fuel	^{102}Rh	Activation product
^{238}U	Unburned weapon fuel	^{90}Sr	Fission product
^{235}U	Unburned weapon fuel	^{63}Ni	Activation product
^{207}Bi	Activation product	^{60}Co	Activation product
^{155}Eu	Fission product	^{55}Fe	Activation product
^{154}Eu	Fission product	^{14}C	Activation product
^{152}Eu	Activation product	^{3}H	Activation product and fuel
^{151}Sm	Fission product		

a function of the reported fallout contamination corrected to H + 1 hr past detonation. The resulting gradation is shown in Table 11.

Radiological safety reports written during and after the test operations indicated several acute radiological problems which were subsequently corrected, such as serious alpha contamination, radioactive debris, etc. Unfortunately, these reports failed to provide sufficient detail to determine, in all cases, the eventual fate of the radioactivity itself—whether it was disposed of in land, lagoon, or sea, for instance, and how thoroughly.

Interviews with test personnel produced additional information, although somewhat contradictory at times. However, these interviews did confirm that burial and relocation of high-level radioactive contaminated debris was attempted frequently in many places. Verification of these burial activities by documentation has been very difficult and only partially successful. This information, however, indicates that radioactive debris probably is buried only on islands that had surface ground zeros. A list, shown in Table 12, has been made of suspected or known burial sites, the locations of which are shown in Figs. 21-24.

Two preliminary radiological surveys, conducted in July 1971 and May 1972, confirmed suspected conditions on most of the islands and provided approximate but valuable estimates of the range of radioactivity levels to be expected.

The July 1971 survey was severely limited in time and scope. Even though visits were only made to six islands—IRENE, JANET, SALLY, TILDA, URSULA, and YVONNE—the following information was obtained:

- Many of the islands were still radioactively contaminated.
- Much of the Atoll was heavily revegetated and difficult to traverse.
- There were no obvious indicators (signs, posts, fences, etc.) of buried radioactivity in clear sight.

Table 11. Ranking of islands in Enewetak Atoll according to fallout contamination at H + 1 hr.

Island code name	Local name	Total R/hr	Total events[a]	Total SGZ
YVONNE	Runit	62,849	24	8
RUBY	Eberiru	10,643	16	2
EDNA	Sanildefenso	9,533	16	0
IRENE	Bogon	6,184	24	1
HELEN[b]	Bogairikk	5,277	23	0
PEARL	Rujoru	4,329	13	1
DAISY	Cochiti	3,554	20	0
JANET	Engebi	3,501	26	3
ALICE	Bogallua	3,383	28	0
BELLE	Bogombogo	3,382	25	0
CLARA	Ruchi	3,154	24	0
MARY	Bokonaarappu	2,785	18	0
SALLY	Aomon	1,981	16	3
LUCY	Kirinian	1,776	10	0
KATE	Muzin	1,753	11	0
OLIVE	Aitsu	1,252	12	0
NANCY	Yeiri	1,251	7	0
TILDA	Biijiri	774	17	0
URSULA	Rojoa	651	12	0
CORAL HEAD (MACK)	—	452	10	0
WILMA	Piiraai	294	13	0
VERA	Aaraanbiru	270	11	0
LEROY	Rigili	235	13	0
KEITH	Giriinien	31	3	0
JAMES	Ribaion	23	3	0
IRWIN	Pokon	19	3	0
HENRY	Mui	13	3	0
GLENN	Igurin	11	3	0
ELMER	Parry	2.6	5	0
FRED	Enewetak	2.6	4	0
BRUCE	Aniyaanii	1.5	4	0
DAVID	Japtan (Muti)	1	3	0
TOM	—	0	1	0
SAM	—	0	—	0
URIAH	—	0	1	0
VAN	—	0	1	0
ALVIN	Chinieero	0	2	0
CLYDE	Chinimi	0	1	0
REX	Jieroru	0	1	0

[a]This includes the events that produced contamination by fallout or surface ground zero location.

[b]Presently part of IRENE.

Table 12. Suspected or known burial sites for radioactive debris.

Island	Contamination	Quantity	Location	Confidence	Source[a]
IRENE	Soil	Large	Unknown/central island	Fair	1
JANET	Activated metal	Large	Around SGZ's	Fair	2
PEARL	Activated metal	Unknown	Around SGZ	Suspected	2
RUBY[b]	Soil/activated metal	Unknown	Old SGZ	Positive, high	3
SALLY	Debris	Unknown	Western SGZ area	Suspected	1
	Pu debris	Unknown	KICKAPOO SGZ	Absolute	3
	Pu debris	Unknown	Western SGZ area	Absolute	3
	Pu debris	Unknown	Causeway, SALLY/ TILDA	Absolute	3
YVONNE	Pu debris	Large	FIG/QUINCE SGZ-lagoon side	Absolute	4
	Pu debris	Unknown	Disposal area—location unknown	Positive, high	4
	Activated metal	Unknown	Anywhere—exact locations unknown	Absolute	5
	Contaminated debris	Unknown	West of CACTUS crater	Suspected	6
	Contaminated debris	Unknown	ERIE SGZ	Positive, high	7
	Contaminated soil	Unknown	North of HARDTACK Sta. 1310	Positive, high	8

[a]Sources

1. Interview.
2. Assumption.
3. H&N Drawing GS-6270, April 9, 1957, and FS-6287, April 18, 1957.
4. Task Group 7.5 Rad-Safe Support, HARDTACK, Phase I, OTD-58-3, April 1959.
5. Survey, 1971, 1972.
6. Completion Report, Operation HARDTACK, PHASE I
7. H&N Drawing 25-002-G7, January 20, 1958.
8. H&N Drawings 25-002-C3, 4, 5, January 20, 1958.

[b]That portion remaining attached to SALLY by a causeway.

- There was significant contaminated radioactive debris on YVONNE (Runit Island) at the CACTUS crater lip and also a plutonium-contaminated soil outcropping on the oceanside beach, mid-island
- There appeared to be a definite pattern to the exposure rates encountered, with the higher rates observed on the northern half of the Atoll.

As a result of this survey, the AEC's 1972 Bikini radiological survey was extended to cover Enewetak Atoll in a very limited reconnaissance effort during May of that year. Of the 43 islands of the Atoll, 18 were visited in May 1972. These, in addition to three other islands visited in the July 1971 effort, made available recent data regarding soil activity levels and radiation exposure rates on 21 islands, slightly less than half of the total number of islands within the Atoll. The results of this survey also verified the Atoll-wide pattern of contamination suggested by the 1971 survey and the ranking of islands according to fallout levels.

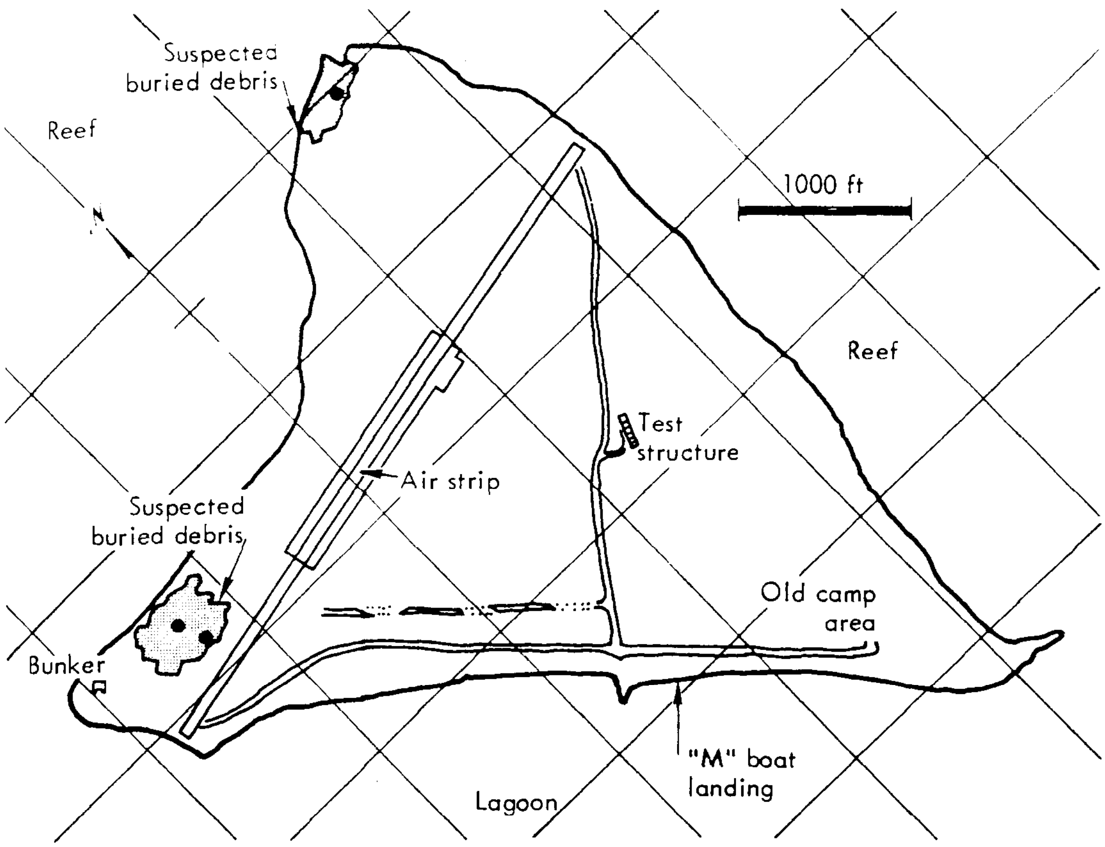

Fig. 21. Suspected or known radioactive material burial sites, JANET.

Since a cleanup effort would require preliminary cost estimates for the disposal of contaminated soil, the sampling plan was designed to provide data that could be used to estimate, at least in a gross manner, the volume of contaminated soil on those islands where it was thought to exist or had a high probability for existence.

The Atoll was stratified into groups of islands, individual islands, or specific areas of islands, according to what was known or suspected about the radiological condition of the area and the type of survey information that was desired. Since ^{239}Pu is an isotope whose distribution at Enewetak is of particular concern, estimates of its abundance were also used in the stratification process. A summary of this stratification, and the reasons for each stratification effort are indicated below, by phase, group, island, and fraction of island, as appropriate. Figure 25 shows the location of islands in each classification.

Phase I Islands

These islands, all of those on roughly the southern half of the Atoll, from all indications are relatively clean in comparison with the remainder. None of these islands included any surface ground zeros. All, with the exception of LEROY, received little fallout from the nuclear tests. LEROY is included because of its location and the fact that its fallout dosage was small compared to islands on the northern half of the Atoll.

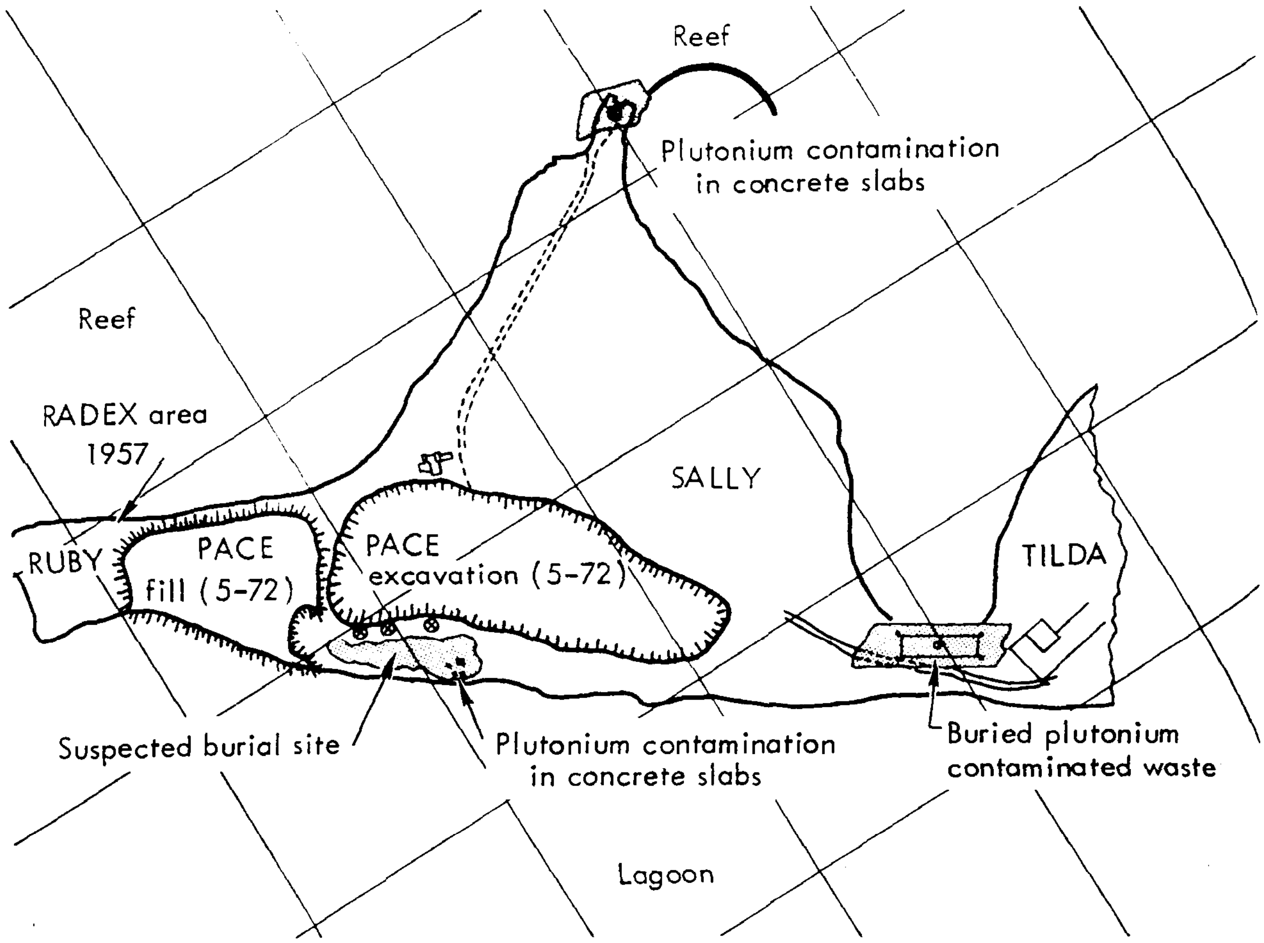

Fig. 22. Suspected or known radioactive material burial sites, SALLY.

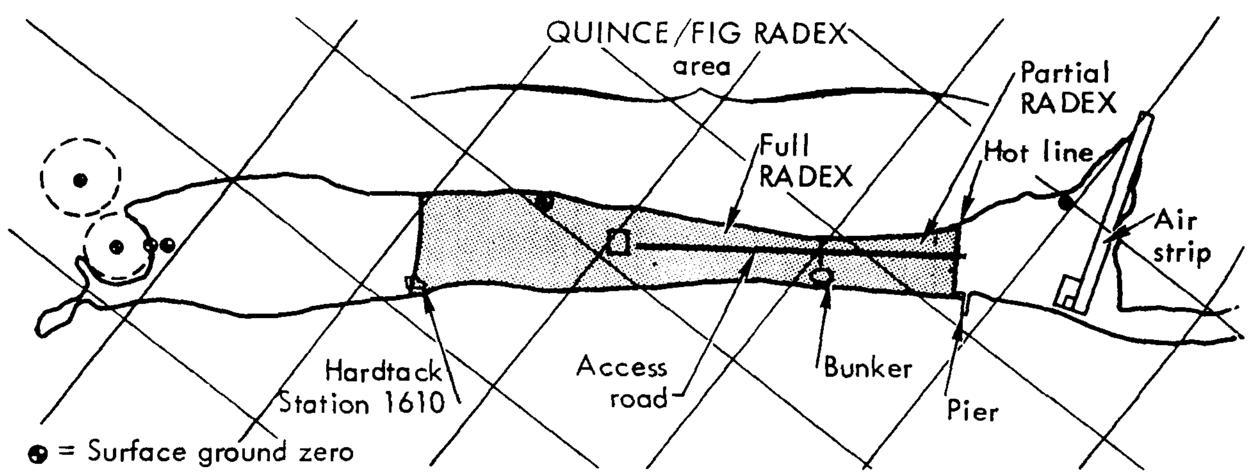

Fig. 23. QUINCE and FIG decontamination operations RADEX area, established 1958, YVONNE.

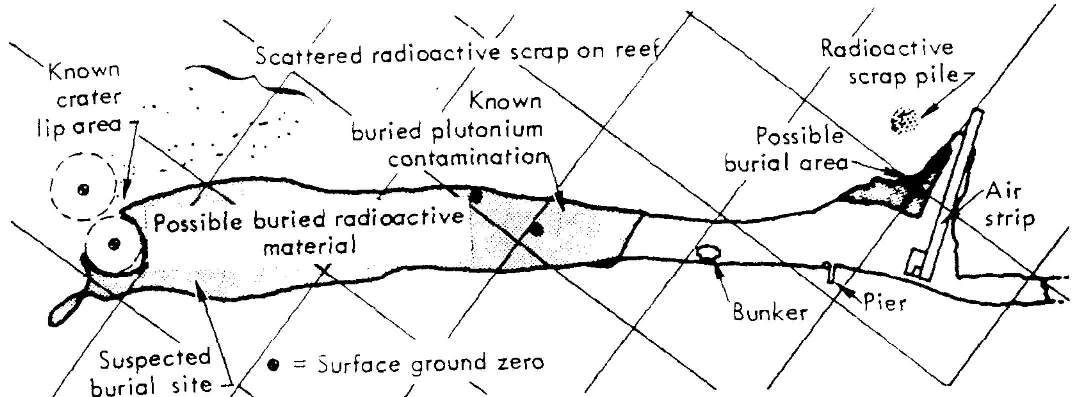

Fig. 24. Suspected or known radioactive material burial sites, YVONNE.

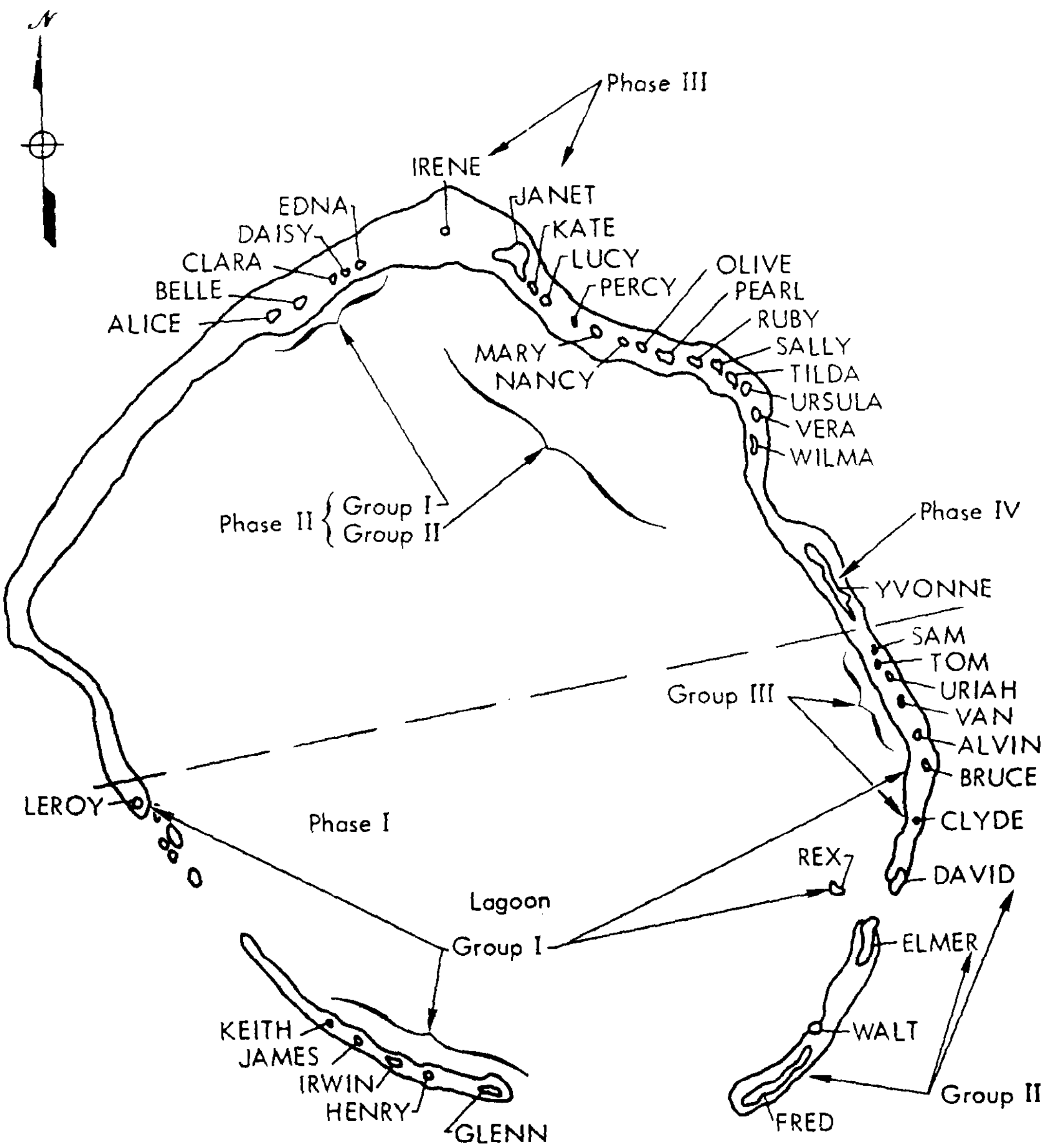

Fig. 25. Stratification of Enewetak Atoll for soil sampling program.

The average contamination of the Phase I islands was about 10 R/hr at H + 1 hr (see Table 11). FRED and ELMER were the sites of the main camps and airfields, and DAVID was used as a rest area.

The islands of Phase I were divided into the following three groups for soil-sampling purposes:

Phase I—Group I

BRUCE (Aniyaanii)	IRWIN (Pokon)
REX (Jieroru)	JAMES (Ribaion)
GLENN (Igurin)	KEITH (Giriinien)
HENRY (Mui)	LEROY (Rigili)

Phase I—Group II

DAVID (Japtan)	FRED (Enewetak)
ELMER (Parry)	

Phase I—Group III

SAM	WALT	ALVIN (Chinicero)
TOM	VAN	CLYDE (Chinimi)
URIAH		

Those in Group I are relatively large islands with fairly heavy vegetation; those in Group II are southern islands which are very likely to be inhabited continuously by the Enewetak people after they return; and those in Group III are sandbars or very small islands with relatively little vegetation or likelihood of heavy use.

Phase II Islands

The Phase II islands were termed to be "lightly contaminated," based upon the historical background, ranking of islands by fallout levels, and previous surveys. The term "lightly contaminated" is, of course, only a relative one. The islands were expected to be significantly more contaminated than any of the Phase I islands. Using the gamma exposure rates measured on ALICE through EDNA during previous surveys, and the positions of these islands relative to the islands with ground zeros, two groups of islands were developed: Phase II, Group I, those islands which had been visited and for which some radiological information was available, and Phase II, Group II, islands which have not been visited recently (except for limited sampling on TILDA and URSULA), but from all indications were likely to be similar in fallout level and exposure rate to the Phase II, Group I islands. These two Phase II groups consisted of the following islands:

Phase II—Group I
(visited during previous surveys)

ALICE (Bogallua)	DAISY (Lidilbut)
BELLE (Bogombogo)	EDNA (Sanildefonso)
CLARA (Eybbiyae)	

Phase II—Group II
(not visited during previous surveys)

KATE (Muzin)	TILDA (Biijiri)[a]
MARY (Bokonaarappu)	WILMA (Piiraai)
PEARL (Rujoru)	PERCY
VERA (Aaraanbiru)	OLIVE (Aitsu)
LUCY (Kirinian)	URSULA (Rojoa)[a]
NANCY (Yeiri)	

[a]Visited July 1971.

Soil samples were available from the May 1972 survey for the islands of ALICE, BELLE, CLARA, DAISY, and EDNA. These samples were very limited in number, and, unfortunately, were combined for each island during collection. However, they did indicate that the islands were contaminated, and there appeared to be some difference between the lagoon and the ocean sides of the islands. Plutonium-239 activities in soil on these islands were relatively high for the Atoll, ranging from about 17 pCi/g on EDNA to a maximum of 129 pCi/g on BELLE. A crude mean of 50 pCi/g was assumed for planning purposes for this chain of islands (ALICE through EDNA).

As a general rule, the number of samples to be collected on a particular island by this survey was proportional to the expected mean activity of ^{239}Pu in the soil on that island. The mean value of 50 pCi/g, listed above, was assumed to be applicable to all Phase II islands. However, the islands that had not been previously visited received an increased sample allocation because of the large uncertainty in their mean activity values.

Phase III Islands

These islands were designated with the relative term "moderately contaminated." Four islands and a tiny new islet are included in this phase: IRENE (Bogon), JANET (Engebi), RUBY (Eberiru), SALLY (Aomon), and what we chose to call SALLY'S CHILD, a small islet on the reef apparently formed by the deposition of sand and debris from the region between SALLY and TILDA.

All of these islands in Phase III were the sites of surface ground zeros. The historical search indicated that there had been considerable impact to the islands from close-in fallout, and some had or were expected to have burial grounds for contaminated debris.

IRENE (Bogon) is a medium-sized island whose single nuclear test left a sizable crater. Exposure rates of the order of 50-100 μR/hr were observed in the 1971 survey effort. The accumulated H + 1 hr fallout level was about 6184 R/hr from a total of 24 nuclear tests, sound indication of both fallout and probable buried contamination over much of the island's area.

JANET (Engebi) is the second largest island on the Atoll and was the site of three early nuclear tests. Weapons test structures may be found in numerous locations. The island was the site of a large base camp. It was also a primary site of native habitation and would possibly be so again.

Both SALLY and RUBY were the sites of multiple SGZ's. Buried contamination was expected, but not necessarily located prior to the survey effort. An additional complication, that of Project PACE excavation, affected the utility and the execution of a meaningful soils effort. Large areas of SALLY were excavated by PACE, some adjacent to SGZ's and suspected burial sites. In addition, the excavated material had been deposited on the remaining surface areas of SALLY and between SALLY and what remains of RUBY. Because of this situation, an attempt was made early in the survey to delete these islands from the effort, since PACE was then active and any earth-moving or other land modifications conducted by them would negate any soil-survey results before they could be reported. However, while the survey was in progress, PACE ceased all activities on the Atoll, at which time it was deemed prudent to include the undisturbed portions of these islands in the survey efforts.

Phase IV Island

Only one island, YVONNE (Runit) was classified in the Phase IV, "severely contaminated" category. This island, at the top of the list in accumulated fallout, with a total H + 1 hr fallout of 62,849 R/hr is the site of eight SGZ's. The island is the most disturbed testing location on the Atoll. Record searches produce many conflicting reports of the disposal of radioactive materials on or near the island. These records all show considerable construction and reconstruction activity. "Old-timers" indicate that the island was actually plowed in the search for experimental packages dispersed during several nuclear tests. The island is known to have significant amounts of activated or contaminated scrap and of plutonium-contaminated soil.

Every recent survey effort from July 1971 through the several cursory surveys conducted late in 1972 and early in 1973 confirms the indication that the northern half of the island is a heterogeneous conglomeration of radioactive debris. On the northern half of the island, soil samples collected at one location are not necessarily representative of those obtained at other locations within the immediate area.

It was obvious that a random-sampling approach to such a situation was inappropriate. Therefore, a sampling pattern based upon prior knowledge of known surface activity levels, ground-zero locations, construction activities, suspected burial areas, etc., was adopted. In essence, the plan included sampling the area in the vicinity of the QUINCE ground zero to a depth of 120 cm on an approximate 200-ft grid system, and every 200 ft along a line up the center of the island to the Cactus crater at the north end. It was felt that this approach would be adequate to reveal the extent of seriously contaminated areas in sufficient detail to enable cleanup estimates to be made.

The southern portion of the island (the area south of the bunker) also has a surface ground zero. However, most of the area was subjected to fallout from the nearby tests and could be sampled by a random approach similar to that used on Phase III islands.

Soil-Sampling Philosophy

A random-sampling technique was chosen as the primary method for determining soil-sample locations. The actual number of samples that were collected on a particular island was a function of parameters such as total accumulated fallout, number of ground-zero locations, amount of construction activities, and the likelihood of habitation. In general, the sampling frequency increased with contamination level; it was lowest on the Phase I islands and highest on Phase IV. Table 13 lists the actual number of sample locations on an island-by-island basis.

Selection of Sample Locations

The random selection of sampling locations was performed in the following manner. A map of each island was divided into relatively small rectangular areas. The grid spacing was generally 50 ft in order to get several thousand squares on the map of a large island. Each of these grid squares was numbered, except for those that would be impossible to sample, such as concrete pads, coral reef, runways, paved roads, etc. The sample

Table 13. Number of sample locations on each island.

Stratification	Island	Approx area, 10^5 ft^2	Assumed mean ^{239}Pu activity, pCi/g	No. of sample locations: Surface, 0-15 cm	No. of sample locations: Profiles
Phase I Group I	BRUCE	9	1	10	3
	REX	2	1	4	3
	GLENN	25	1	28	4
	HENRY	13	1	14	3
	IRWIN	7.5	1	9	3
	JAMES	4.8	1	6	3
	KEITH	11	1	12	3
	LEROY	7	1	8	3
Phase I Group II	DAVID	48	1	53	7
	ELMER	80	1	80	10
	FRED	140	1	64	8
Phase I Group III	SAM	0.25	1	4	1
	TOM	0.25	1	4	1
	URIAH	0.89	1	2	2
	WALT	1.74	1	4	1
	VAN	1.39	1	5	1
	ALVIN	0.61	1	4	1
	CLYDE	1.01	1	3	1
Phase II Group I	ALICE	10	50	22	4
	BELLE	20	50	33	4
	CLARA	2	50	9	3
	DAISY	6	50	15	4
	EDNA	0.3	50	6	2
Phase II Group II	KATE	8	50	22	2
	LUCY	10.5	50	22	4
	PERCY	1	50	5	1
	MARY	6	50	22	3
	NANCY	9	50	22	4
	OLIVE	14	50	23	4
	PEARL	27	50	45	4
	TILDA	15	50	33	5
	URSULA	12	50	27	4
	VERA	10	50	22	3
	WILMA	7	50	22	3
Phase III	IRENE	20	100	20	14
	JANET	120	50	132	12
	SALLY (including SALLY's CHILD)	37	50 (west end) 10 (elsewhere)	34	9
Phase IV	YVONNE (south)	18	50	51	9
•	YVONNE (north)	25	Highly variable	0	46

locations were chosen for each island by using random-number tables,* with an excess of 10% chosen to allow for additional locations which could not be sampled due to unforeseen coral outcroppings, concrete pads, beach erosion, etc. These locations were then replotted on the work maps, drawings, or photographs that were used in the field. Both surface and profile locations were determined in this manner.

The exact location of the sample collection was to be the center of the area chosen by the grid and random-number technique. It was realized that the determination of such a point with any great precision or accuracy in the field was technically difficult in most cases, even though large-scale photographs taken during the aerial radiological survey were used by the field parties. It was most important, however, that the individual collecting the sample make every reasonable effort to locate the position as closely as possible. In particular, the sample was to come from within a 10 × 10-ft area, defined as the center area for the grid point. In the field the sampling site was to be chosen by pacing from a known reference point or other field direction. If there were some obstacle to sampling at this specified location (which had not been eliminated prior to the random-selection process), then that fact was recorded in the field and no samples collected at that point. In this way, bias due to a collector choosing the easiest location to sample, such as a clearing rather than within a dense thicket, was minimized. This protocol was followed rigidly and did, in fact, result in some collection groups going to great effort cutting through jungle and arriving at the designated location, only to find it to be on a large pad of concrete or outcropping of coral. On JANET each sampling point was located accurately by an engineering survey team fielded for that purpose. This additional effort was expended because of the island's large size, dense vegetation cover, and probable rehabitation.

During November 1972 an aerial radiation survey was made of all islands within the Atoll which identified "hot spots" on a number of islands. Soil samples were taken in all of these locations independently of the random-sampling process.

Execution of Soil-Sampling Program

The soil survey was conducted over a period of 8 weeks by roughly 18 people. The islands surveyed ranged from small, bare sandbars to large (31-acre), densely vegetated islands, often infested with wasps and spiders. With the exception of FRED (Enewetak Island), the islands of the Atoll were accessible only by boat. Only five of the islands had usable personnel piers (FRED, ELMER, DAVID, YVONNE, and URSULA). All other islands had to be reached by using a small rubber dinghy or landing craft. Depending on the weather, tides, and location on the Atoll, these landings had to be made in up to Force 4 (11-16 knots) trade winds through surf of various conditions onto sandy beaches or coral reefs.

*Handbook of Mathematical Functions, USDC, NBS Applied Mathematics Series 55 (U.S. Government Printing Office, Washington, D.C., 1965), pp. 991-995.

Vegetation on the islands ranged from none on small sandbars to sparse on several islands to very dense on most of the islands to be surveyed. The survey parties had to cut into the dense jungle to reach sample locations, clear areas to make collections, and locate themselves with sufficient precision to carry out the random selection aspects of the program.

The samples were taken from a wide range of soil conditions. Soil texture ranged from soft coral sand to rough coral aggregates. These, in turn, were interlaced with plant roots and scrap metal junk. The possibility of encountering World War II ordnance was a constant threat on several islands, particularly JANET, where a U.S. Army EOD team assisted in the soils collection effort.

Soil profiles observed on most of the islets consisted of a surface layer of vegetative litter of varied thickness, followed by a somewhat thicker layer of dark coral soil containing some root structure, and other organic material. This layer also varied in thickness; it was thicker on undisturbed islands and thinner or absent on disturbed islands. This second layer was usually followed by the basic coral sand structure of the island, which prevailed down to the hard coral limestone bedrock. Buried horizons were found at almost any depth.

Soil-Sampling Techniques

Two types of soil samples were taken during the survey—"surface" and "profile."

At "surface" sampling locations, two samples were taken; one a 30-cm^2 × 15-cm-deep core, and the second a composite of two 30-cm^2 × 5-cm-deep cores.

Special tools were used to assure uniformity of sampling and ease of collection. The shallow core (5 cm) was obtained with a "cookie-cutter" type tool. The sampler was a section of hardened steel pipe exactly 5 cm deep, with an internal cross-sectional area of 30 cm^2. A handle on top assisted in pushing the tool down into the soil to its depth. The surrounding soil was then scraped away and a cutting tool (a flat piece of steel) was inserted beneath the tool, cutting the sample free. Excess debris was blown or wiped off the cutter surface, and the sample was bagged and numbered.

The deep core (15 cm) was obtained with a similar device, a hardened steel pipe with 1-cm increments marked on the side to a depth of 15 cm. The pipe, 30 cm^2 in cross section, was driven into the soil. The surrounding soil was then removed, the cutter inserted, and the sample treated in the same manner as the shallow core.

"Profile" samples were obtained using another special tool designed by Wayne Bliss of the Environmental Protection Agency. This consisted of a drawer-like sample collector, with the back of the drawer absent, which was inserted into the side wall of a trench dug to a total profile depth. The drawer was 10 × 10 cm on top and 5 cm deep. After the drawer was inserted into the soil, a cutter (large putty knife) was inserted as the back of the drawer, freeing the sample. The sample was then removed, bagged, and numbered.

The next sample was taken immediately below the previous one, continuing down the groove thus formed until the bottom of the profile was reached.

The trenches used to collect the profiles were dug by hand on most islands. On those islands where deep (greater than 120 cm) profiles were required, a backhoe was landed and used to dig the trenches.

Profile samples were taken at nominal depth increments of: 0 to 2, 2 to 5, 5 to 10, 10 to 15, 15 to 25, and 25 to 35 cm and at 10-cm increments to total depth. If soil horizons were encountered, an attempt was made to choose the interface lines as additional increments.

Each soil sample collected was placed in a plastic bag; the bag was numbered and placed inside of another plastic bag. The double-bagged sample was then placed in a field pack with other samples and transported to the shore, where all samples were placed in large plastic bags for transport back to FRED via rubber boat and larger craft.

Upon arrival at FRED, the samples were taken to a sample-processing area for short-term storage, sample-control processes, and bag checks to assure rebagging of those samples whose bags had been damaged in transport. Each sample was then gamma-scanned in the field counting laboratory, and placed in storage until it could be shipped to the continental U. S. laboratory.

Results and Discussion

The soil-sampling locations on each island are shown in the "f" overlay figures of Appendix II. Each location has an identifying number for reference purposes. These locations were chosen primarily by a random-selection technique with a few sites chosen to study specific areas of interest such as hot spots, decontamination areas, surfac ground zeros, etc. The average activ ties of ^{239}Pu, ^{90}Sr, ^{137}Cs, and ^{60}Co, exhibited by the core samples collecte to a depth of 15 cm, are shown in the ' "j," "l," and "n" overlays of Appendix I These activities, expressed in picocur per gram of dry soil, are displayed at the geographical locations where the re spective samples were collected. For those who desire to convert these data into activities per unit area, one may u an approximate dry soil density of 1.5 g cm^3. No attempt was made to measur *in situ* densities. The meaning of the r sulting deposition values, however, is subject to some interpretation since on must realize that an appreciable fractic of the total activity may be situated bel the sampling depth, as shown in the pro file figures for each island. In these figures the activities of ^{239}Pu, ^{90}Sr, ^{137}Cs, and ^{60}Co are plotted as a functic of depth for the corresponding profile locations. Additionally, the complete records of all radionuclides are reproduced on microfiche at the end of Appendix II.

In general, the activities shown in th figures, when properly grouped, approx mate lognormal distributions. This ma be illustrated by grouping the activity levels measured in the 15-cm deep core samples collected on JANET into equal class intervals and plotting the resulting frequency distribution curve shown in Fig. 26. Instead of being symmetric about the maximum as a normal distribu tion, one observes a long "tail" which includes a significant proportion of relatively high activity levels. This distribu tion can be transformed into the more

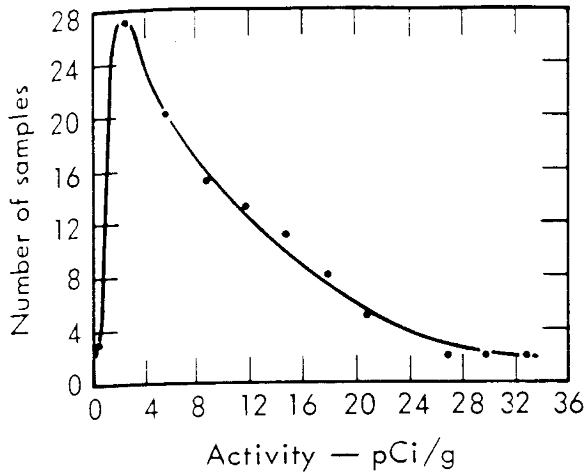

Fig. 26. Frequency distribution of ^{239}Pu activities in surface samples collected on JANET.

familiar normal (Gaussian) distribution by plotting the frequency distribution of the logarithms of the individual data points. This transformation permits the use of the usual statistical parameters for describing the population. By using a log probability grid, with a logarithmic vertical scale and a horizontal scale marked in cumulative percent, these parameters may be obtained with a minimum number of data points. As an illustration, Fig. 27 shows the ^{239}Pu activities used to construct Fig. 26, plotted as a function of cumulative frequency on this grid. The plot is approximately linear, indicating an essentially lognormal distribution. The convenience of using this type of plot may be demonstrated readily by the fact that two important parameters—the geometric mean and geometric standard deviation—may be obtained from the plot. The geometric mean is the equivalent of the median for a lognormal distribution. Therefore, the geometric mean (hereafter referred to as the mean) is the activity level corresponding to the 50% intercept on the log probability plot. Thus, the mean of the ^{239}Pu activities shown in Fig. 27 is 8.5 pCi/g. The geometric standard deviation (hereafter referred to as the standard deviation) represents a quantitative measure of the dispersion or variability of the activity levels. One standard deviation corresponds to the interval between the mean and the 84% quantile or, because of symmetry, the interval between the mean and the 16% quantile. Thus, one standard deviation on both sides of the mean contains 68% (84 less 16%) of the population values. One may readily observe that a set of data which has a relatively small variability will exhibit a frequency distribution curve of narrow width, and that the slope of the straight line on the log probability plot will be less than that for a more variable set of data, since the slope of the line is a direct measure of the standard deviation. The standard deviation may be calculated by dividing the activity corresponding to the 84% quantile by the mean activity. Thus, from Fig. 27 one may compute the standard deviation to be 25/8.5 or 2.9, with the result that 68% of the ^{239}Pu activities have values between 2.9 and 25 pCi/g (8.5/2.9 and 8.5 × 2.9).

A careful review of the activities exhibited by samples collected on any particular island in the northern part of the Atoll shows a reasonably direct correlation with the amount of vegetation present in the area surrounding the sampling locations. This is not surprising in view of the protection that a heavy vegetative cover can provide to minimize the effects of weathering processes (e.g., wind and rain erosion) that may serve to transport the surface activity to other areas of the

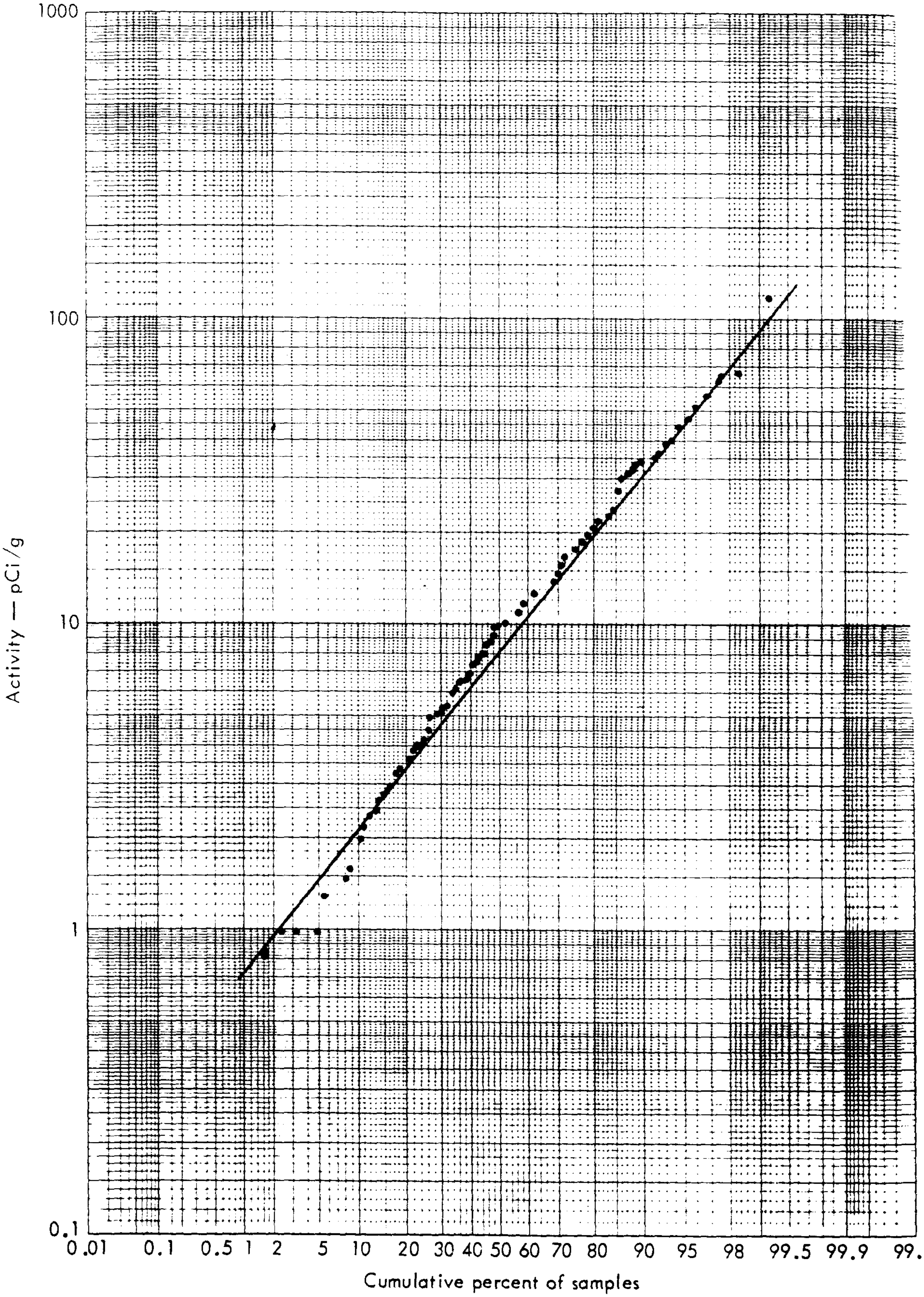

Fig. 27. Distribution of ^{239}Pu activities in surface samples collected on JANET.

Atoll. This correlation of activity with vegetative cover was also observed at Bikini. Thus, a particular island may show the following distinct areas having significantly different radiological conditions: Densely vegetated areas exhibiting the highest activities; sparsely vegetated areas showing intermediate activity levels; and beach areas displaying the lowest activities. This pattern is occasionally perturbed in "hot-spot" areas where ground-zero locations existed, as well as in areas that have been subjected to extensive construction activities.

The ^{239}Pu, ^{90}Sr, ^{137}Cs, and ^{60}Co activities shown in the figures in Appendix II were plotted separately on log probability paper on an island-by-island basis. Islands situated in the southern part of the Atoll were combined into groups because to their radiological similarities and low activity levels. Whenever appropriate, an island was divided into "dense vegetation," light vegetation," and "beach" categories, and if significant radiological differences were noted, a mean value and the standard deviation were obtained for each distinct area on the island. In those cases where the differences in the mean values were less than a factor of two, all of the measurements for a particular radionuclide were combined, and the mean and standard deviations were obtained for the entire island, excluding the beach areas. In most situations, the standard deviations were fairly constant, ranging largely between 1.5 and 2.5, indicating that the degree of variability of the measurements from one island to the next was small.

The distributions of activity with soil depth obtained for the profile samples show many variations. However, in spite of these variations, some general comments may be made. Excluding beaches and areas subjected to extensive construction activity, the radioactivity generally decreases with depth in some highly variable and nonlinear fashion. Frequently, the activity decreases rapidly within the first few centimeters and then more slowly with increasing depth. A relaxation length of 3-5 cm (the depth at which the activity is e^{-1} or 37% of the surface activity) is commonly observed within the top 5-8 cm. Below this depth the relaxation length frequently increases to 10 cm or more. Profile samples collected on or near the beaches display a different depth distribution. Surface activities are usually considerably lower than island interior values, and the distributions are essentially uniform or may even increase with depth.

Radionuclides other than ^{239}Pu, ^{90}Sr, ^{137}Cs, and ^{60}Co appeared in the gamma-ray spectra. A convenient way to evaluate these activity levels is presented in Table 14, which gives the median activity ratios of $^{241}Am/^{239}Pu$, $^{238}Pu/^{239}Pu$, $^{125}Sb/^{137}Cs$, and $^{155}Eu/^{137}Cs$ for each island situated within the northern portion of the Atoll. Inspection of the data indicates that the median activity ratios of $^{241}Am/^{239}Pu$, $^{238}Pu/^{239}Pu$, and $^{125}Sb/^{137}Cs$ are essentially constant, with approximate values of 0.40, 0.10, and 0.07, respectively. $^{155}Eu/^{137}Cs$ values exhibit a reasonably constant value of 0.20, except for DAISY, EDNA, and IRENE, where the values rise to a maximum of 2.5.

The following is a description of the current radiological conditions of the

Table 14. Median activity ratios of pertinent radionuclides measured in soil samples

Island	$^{241}Am/^{239}Pu$	$^{238}Pu/^{239}Pu$ [a]	$^{155}Eu/^{137}Cs$	$^{125}Sb/^{137}Cs$
ALICE	0.39	0.10	0.12	0.05
BELLE	0.33	0.11	0.15	0.07
CLARA	0.26	0.14	0.15	0.04
DAISY	0.36	–	0.72	0.09
EDNA	0.35	0.06	0.81	0.03
IRENE	0.19	–	2.5	0.15
JANET	0.38	–	0.11	0.03
KATE	0.42	-	0.22	0.06
LUCY	0.43	-	0.27	0.07
PERCY	0.41	–	–	0.17
MARY	0.38	–	0.22	0.06
NANCY	0.49	–	0.23	0.08
OLIVE	0.38	–	0.30	0.08
PEARL	0.25	–	0.48	0.08
RUBY	0.11	–	2.6	0.31
SALLY	0.28	–	0.18	0.07
TILDA	0.51	–	0.20	0.08
URSULA	0.41	–	0.14	0.07
VERA	0.44	–	0.17	0.05
WILMA	0.40	–	0.11	0.09

[a] ^{238}Pu activities were measured only in a few samples.

islands within the Atoll. For discussion purposes each island situated within the northern part of the Atoll is treated separately, while those within the southern part of the Atoll are treated in groups because of their radiological similarities. In addition, the mean values and range of observed activities listed for the northern islands do not include the activities of samples collected on the beaches, since it was felt that these low values might unduly distort the description of the islands' radiological condition. This was not considered to be true of islands within the southern part of the Atoll. The activities listed in the discussions were obtained from the surface samples collected to a depth of 15 cm.

For ease of comparison, the data for the northern islands are summarized in Table 15 and for the southern islands in Table 16.

Northern Portion of Atoll (ALICE-YVONNE)

ALICE—This island is densely vegetated over its entire surface. The mean and range of observed activities exhibited by the surface samples for the following radionuclides are:

Radionuclide	Activity, pCi/g	
	Mean	Range
^{90}Sr	80	14-430
^{137}Cs	36	5.6-141
^{239}Pu	12	3.9-68
^{60}Co	5.9	1.4-33

The radioactivity seems to be fairly homogeneously distributed throughout the island, even though considerable construction activities, such as the building of an airstrip along the center of the island and large-scale earth grading at

Table 15. Enewetak soil data, "northern islands" (pCi/g in top 15 cm).

		^{90}Sr		^{137}Cs		^{239}Pu		^{60}Co	
		Mean	Range	Mean	Range	Mean	Range	Mean	Range
ALICE		80	14-430	36	5.6-141	12	3.9-68	5.9	1.4-33
BELLE	Dense	123	14-670	48	14-170	26	7.2-130	10	3.1-30
	Sparse	44	35-130	8.6	3.3-44	11	5.8-26	4.6	2.4-9.6
CLARA		65	13-310	26	5.6-110	22	3.5-88	6.4	0.91-20
DAISY	Dense	190	100-380	11	3.4-33	41	22-98	11	6.4-26
	Sparse	32	16-120	3.8	0.86-9.0	15	3.8-33	0.85	0.37-7.4
EDNA		46	30-220	4.2	2.7-6.4	18	13-24	0.43	0.33-0.63
IRENE		30	5.9-570	3.2	0.22-41	11	2.4-280	5.4	0.12-520
JANET		44	1.6-630	16	0.57-180	8.5	0.08-170	1.9	0.02-33
KATE	Dense	67	37-200	24	18-37	17	8.6-50	2.7	1.6-5.8
	Sparse	11	1.6-49	4.8	1.8-16	2.3	0.17-14	0.46	0.03-3.5
LUCY		32	10-83	11	2.2-25	7.7	2.4-22	1.5	0.26-3.8
MARY		29	11-140	9.9	5.6-26	8.0	2.0-35	1.5	0.74-4.8
NANCY		36	16-110	12	6.0-28	9.1	2.3-28	1.6	0.56-5.3
PERCY		13	3.6-73	0.94	0.12-17	3.5	1.5-23	0.47	0.08-2.9
OLIVE	Dense	22	4.6-70	8.5	3.5-28	7.7	2.2-30	1.5	0.65-4.1
	Sparse	4.5	2.0-11	0.16	0.07-11	2.8	1.9-4.1	0.11	0.05-0.31
PEARL	Hot spot	62	35-140	19	7.4-55	51	15-530	12	3.6-70
	Remainder	17	3.2-61	7.6	1.2-34	11	0.85-100	4.1	0.49-49
RUBY		12	7.1-63	1.4	0.71-7.2	7.3	3.0-24	0.93	0.29-16
SALLY		8.4	0.87-140	3.0	0.03-30	4.3	0.21-130	0.54	0.05-69
TILDA	Dense	27	17-54	8.4	3.5-20	7.6	1.4-17	1.2	0.61-1.9
	Sparse	8.7	2.2-47	1.0	0.04-5.3	2.5	1.1-34	0.37	0.21-1.7
URSULA		6.8	2.0-19	1.7	0.13-7.8	1.3	0.26-7.3	0.31	0.05-1.7
VERA		6.3	1.1-68	2.0	0.03-12	2.5	0.60-25	0.30	0.02-2.2
WILMA		3.3	0.26-13	1.3	0.31-7.2	1.1	0.1-5.3	0.12	0.01-0.7
Southern YVONNE		1.7	0.09-20	0.40	0.02-3.6	3.2	0.02-50	0.64	0.01-20
Northern Beaches		6.4	1.2-30	0.30	0.03-9.0	2.7	0.34-18	0.13	0.03-1.6

YVONNE - Because of the complex distribution of activities on Northern YVONNE no single mean value for an isotope can be used for the island as a whole without being misleading. Readers should consult the YVONNE discussion in this section and the detailed data in Appendix II for information pertinent to their interests.

Table 16. Enewetak soil data, southern islands (pCi g in top 15 cm).

	^{90}Sr		^{137}Cs		^{239}Pu		^{60}Co	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Group A (DAVID, ELMER, FRED)	0.41	0.02-4.8	0.21	0.01-2.1	0.04	0.004-0.31	0.03	0.01-0.15
Group B (All others except LEROY)[a]	0.52	0.03-3.9	0.14	0.004-1.8	0.07	0.004-1.1	0.06	0.007-63
Group C (LEROY)	11	1.6-34	3.2	0.5-10	0.63	0.02-2.0	0.58	0.04-5.0

[a]SAM, TOM, URIAH, VAN, ALVIN, BRUCE, CLYDE, REX, WALT, GLENN, HENRY, IRWIN, JAMES and KEITH.

the northeastern end, took place during the weapons-testing period. This relative homogeneity is also supported by the results of the aerial survey.

The activities as a function of depth, obtained from Locations 24, 26, and 100 within the island's interior, follow the general rule of a rapid decrease in activity within the first few centimeters of the surface (relaxation lengths of 3-5 cm) and then level off to become almost homogeneous (as demonstrated at Location 100). Profile samples collected at Locations 23 and 25, which are on or near the beaches, display essentially homogeneous activity distributions.

BELLE—As clearly indicated by the photographs, this island is so heavily vegetated that it was almost impossible to penetrate. The only exception is the northeast corner of the island, which is relatively open with sparse vegetation. Most of the soil samples were collected within the densely vegetated areas, with a few obtained within the sparsely vegetated northeast corner. The following activities resulted:

Radionuclide	Activity, pCi/g Mean	Range
Areas of dense vegetation		
^{90}Sr	123	14-670
^{137}Cs	48	14-170
^{239}Pu	26	7.2-130
^{60}Co	10	3.1-30
Areas of sparse vegetation		
^{90}Sr	44	35-130
^{137}Cs	8.6	3.3-44
^{239}Pu	11	5.8-26
^{60}Co	4.6	2.4-9.6

The mean activities exhibited by the samples from the northeast corner are roughly a factor of three smaller than those from the remainder of the island. Since only a few samples were collected within the corner area, the factor of three may or may not reflect the true difference in the mean values. The aerial survey results do not reflect this difference.

The depth distributions indicate fairly rapid decrease of activity with depth. The activities are highest at Locations 35 and 100 in the interior of the island and considerably lower at Locations 36 and 37, which are situated near the beaches.

CLARA — This is a small, narrow island with reasonably dense vegetation. Thirteen locations were sampled on the island, and the results of the analyses are:

Radionuclides	Activity, pCi/g Mean	Range
^{90}Sr	65	13-310
^{137}Cs	26	5.6-110
^{239}Pu	22	3.5-88
^{60}Co	6.4	0.91-20

These activities are somewhat lower than those measured on ALICE and BELLE. Since the radiological contamination by the weapons tests to CLARA is essentially the same as that for ALICE and BELLE, the lower residual activities are probably due to increased weathering processes.

All of the profile sampling locations are situated within the interior of the island, and the results from these locations show properties similar to those observed for samples collected within the interiors of ALICE and BELLE.

DAISY — The southern (lagoon) and eastern sides of this island consist primarily of a very sparsely vegetated area, and the northwest portion contains considerably denser vegetation. The mean and range of the observed activities in the soil from these two areas are:

Radio-nuclide	Activity, pCi/g Mean	Range
Areas of dense vegetation		
^{90}Sr	190	100-380
^{137}Cs	11	3.4-33
^{239}Pu	41	22-98
^{60}Co	11	6.4-26
Areas of sparse vegetation		
^{90}Sr	32	16-120
^{137}Cs	3.8	0.86-9.0
^{239}Pu	15	3.8-33
^{60}Co	0.85	0.37-7.4

Thus, one observes large differences between the mean values exhibited by samples collected within the densely and sparsely vegetated areas. The highest activity levels were measured in samples obtained slightly toward the northwestern (leeward) side of the island, which is in excellent agreement with the exposure rate contours produced by aerial survey measurements.

The depth distributions measured at Locations 16, 17, and 18 display similar slopes. At Location 100, situated in the midst of the most densely vegetated area, the depth distribution shows a rapid decrease in activity within the top 5 cm (relaxation lengths of 2-4 cm) and then assumes a much slower rate of decrease with depth similar to those at Locations 16, 17, and 18. A homogeneous distribution was measured at Location 19, as would be expected because of its close proximity to the beach.

EDNA — This tiny island really consists of a sandbar with a little vegetation on it. The activities obtained from the eight sampling locations are:

Radionuclide	Activity, pCi/g Mean	Range
^{90}Sr	46	30-220
^{239}Pu	18	13-24
^{137}Cs	4.2	2.7-6.4
^{60}Co	0.43	0.33-0.63

These mean activities are lower than those measured on ALICE, BELLE, CLARA, or DAISY, even though the radiological contamination of EDNA from the weapons tests is a factor of three greater than those given to the other islands in the group. This is, of course, most probably due to the enhanced wind and wave action operating on this tiny island which has diluted and transported the activity. The homogeneous depth distribution at Locations 7 and 8 tends to bear this out.

IRENE — This island played a central role in the weapons-testing program. Highlights of its role include the detonation of the SEMINOLE event, which created a large water-filled crater within the island's central region; its proximity to the MIKE and KOA thermonuclear events, which significantly altered its physical characteristics; and extensive construction activities which involved the erection of test structures and the movement of large amounts of earth. Thus, one would expect the radiological situation on this island to be exceedingly complex and this was certainly borne out by the survey. The geographical distributions of the surface activities are relatively heterogeneous. Elevated ^{239}Pu, ^{90}Sr, and ^{60}Co activities appear immediately east and north of the crater; however, ^{137}Cs seems to be most abundant within the central portions of the present land mass. Because of the complex situation, no attempt was made to divide the island into areas of distinct radiological conditions. The activities of various radionuclides distributed over the island to a depth of 15 cm (including the beaches) are:

Radionuclide	Activity, pCi/g Mean	Range
^{90}Sr	30	5.9-570
^{239}Pu	11	2.4-280
^{60}Co	5.4	0.12-520
^{137}Cs	3.2	0.22-41

Profile samples were collected at numerous places throughout the island. The resulting depth distributions of activity also reveal the complexity of the situation. After a careful review of the distributions, one may identify several areas that show ^{239}Pu activities of about 100 pCi/g to depths as much as one meter beneath the surface. The approximate geographical distribution of these areas is shown in Fig. 28.

JANET — This is the largest island within the northern part of the Atoll. Three nuclear devices were detonated on the island. An enormous amount of construction activity associated with the weapons program and World War II operations took place, as indicated by the significant quantities of radioactive and nonradioactive scrap scattered around the island (refer to Engineering Survey data), the bunkers, test structures, and mounds of soil. In addition, an airstrip was constructed along the northern side

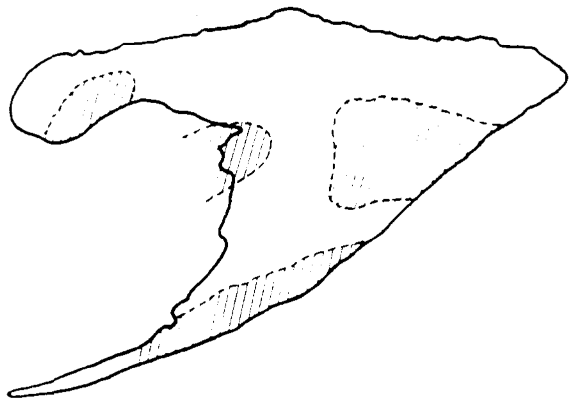

Fig. 28. The shading denotes areas that show elevated levels of subsurface ^{239}Pu contamination, IRENE.

of the island. A major fraction of the island's surface is covered with dense vegetation; however, other areas, especially along the northern side, are more sparsely vegetated. Even these are covered with some sort of ground cover.

The island was sampled extensively during this survey, partly because of its past history, but principally because it is the most likely site in the northern part of the Atoll for habitation by the returning native population. Surprisingly, in view of man's past activities on the island, the soil radioactivities measured in all of the 15-cm-deep surface samples (excluding beach samples) closely follow a lognormal distribution (as demonstrated in Fig. 27), even though they were collected throughout the island from areas of widely differing vegetation densities. The standard geometric deviations, on the other hand, were somewhat greater than usual (2.8-3.0), indicating increased variability in the measurements in relation to similar measurements made on the other islands. The pertinent activities exhibited by these surface samples are:

Radionuclide	Activity, pCi/g) Mean	Range
^{90}Sr	44	1.6-630
^{137}Cs	16	0.57-180
^{239}Pu	8.5	0.08-170
^{60}Co	1.9	0.02-33

The geographical distribution of ^{90}Sr, ^{137}Cs, and ^{239}Pu do not show any particular systematic pattern, but elevated ^{60}Co levels are observed preferentially within the northeast corner of the island. The area is primarily north of the airstrip, with a long finger extending south across the airstrip and halfway across the island. The mean activity within this area is about a factor of 2-3 greater than that shown above. These elevated activities are probably due to a surface ground zero situated within the open area near the beach, on the northeast corner of the island.

The depth distributions of activity were measured at 12 locations on the island to depths as great as 180 cm. As one would expect, considerable variability exists between the individual distributions. However, some common features do exist. Most of the distributions display a relatively rapid decrease in activity within the top few centimeters (relaxation lengths typically 3-10 cm) and subsequent leveling off in activity with increasing depth. Significant deviations from this behavior, however, are observed at several sites. At Location 147, the distributions reveal a layer of contaminated material situated between 50 and 90 cm below the surface. A similar feature, on a smaller scale, was also noted at Location 140. In addition, the depth distribution at Location 143 is essentially homogeneous to a depth of 50 cm below the surface.

KATE—This island contains relatively open, sparsely vegetated areas over a considerable portion of its interior and along the lagoon and north sides. The remainder of the island is covered with a dense vegetation cover. The activities of interest with respect to these areas are:

Radionuclide	Activity, pCi/G Mean	Range
Areas of dense vegetation		
^{90}Sr	67	3.7-200
^{137}Cs	24	18-37
^{239}Pu	17	8.6-50
^{60}Co	2.7	1.6-5.8
Areas of sparse vegetation		
^{90}Sr	11	1.6-49
^{137}Cs	4.8	1.8-16
^{239}Pu	2.3	0.17-14
^{60}Co	0.46	0.03-3.5

Again, considerable differences are noted in the mean values corresponding to the sparse and dense vegetated areas. The depth distributions of activity do not show grossly dissimilar characteristics from those obtained from more pristine areas, but they may not be entirely due to environmental factors since earth grading and building construction took place on this island during the weapons-testing program.

LUCY—This island is heavily vegetated over most of its surface, with somewhat lighter vegetation occurring on its southern end. Since only a few soil samples were obtained from this lightly vegetated area, it was necessary to treat this island as a single entity. The iso-exposure contours developed from the aerial survey measurements, however, reflect lower exposure rates over the lightly vegetated area. The mean and range of activities observed in soil samples collected on this island are:

Radionuclide	Activity, pCi/g Mean	Range
^{90}Sr	32	10-83
^{137}Cs	11	2.2-25
^{239}Pu	7.7	2.4-22
^{60}Co	1.5	0.26-3.8

The profile samples generally reflect a sharp decrease in activity within the top 10 cm (relaxation lengths of about 5 cm) and a leveling off below this depth.

MARY—The distribution of radioactivity seems fairly homogeneously distributed throughout the island, with no significant correlation between activity levels and the degree of vegetation in the vicinity of the sampling locations. The mean and range of activities observed over the entire island, excluding the beaches, are:

Radionuclide	Activity, pCi/g Mean	Range
^{90}Sr	29	11-140
^{137}Cs	9.9	5.6-26
^{239}Pu	8.0	2.0-35
^{60}Co	1.5	0.74-4.8

Relatively minor construction activity did take place on this island during the testing period. The effects of this may be reflected in the somewhat homogeneous depth distributions observed.

NANCY — This island is essentially covered with dense vegetation over its entire surface. The radioactivity seems to be fairly homogeneously distributed throughout the island. The activities of the pertinent radionuclides are:

Radionuclide	Activity, pCi/g	
	Mean	Range
^{90}Sr	36	16-110
^{137}Cs	12	6.0-28
^{239}Pu	9.1	2.3-28
^{60}Co	1.6	0.56-5.3

The depth distributions display the familiar rapid decrease of activity immediately below the surface (relaxation lengths of 3-5 cm) at Locations 23, 24, and 25 situated within the island's interior. The distribution at Location 22 is essentially homogeneous, as would be expected because of its location on the beach.

PERCY — This island is a small sandbar with no vegetation on it. Samples obtained from six sampling locations show the following activities:

Radionuclide	Activity, pCi/g	
	Mean	Range
^{90}Sr	13	3.6-73
^{137}Cs	0.94	0.12-17
^{239}Pu	3.5	1.5-23
^{60}Co	0.47	0.08-2.9

The depth distribution obtained from a single profile indicates that the maximum activity is situated 3-8 cm below the surface. This may have resulted from weathering processes that have diluted the surface activity levels.

OLIVE — This island contains dense vegetation over most of its surface, with the exception of a relatively sparsely vegetated area toward the south end. The sampling locations were divided into two groups: (1) those within the sparsely vegetated area on the south end and several locations situated on the edge between the vegetated area and the beach, and (2) those within the remainder of the island, where the vegetative cover is reasonably dense. The activities of interest in regard to these areas are:

Radionuclide	Activity, pCi/g	
	Mean	Range
Areas of dense vegetation		
^{90}Sr	22	4.6-70
^{137}Cs	8.5	3.5-28
^{239}Pu	7.7	2.2-30
^{60}Co	1.5	0.65-4.1
Areas of sparse vegetation		
^{90}Sr	4.5	2.0-11
^{137}Cs	0.16	0.07-11
^{239}Pu	2.8	1.9-4.1
^{60}Co	0.11	0.05-0.31

The unusually large difference in the mean values of the two groups of data is probably due to the fact that (1) samples collected on or near the edge of the sparsely vegetated area to some degree reflect the low activities on the beach, and that (2) a significant portion of the samples representing the densely vegetated interior were collected in an area somewhat toward the ocean side. According to the aerial survey measurements, the latter area had a slightly higher radiation level than the rest of the island.

The depth distributions obtained within the interior of the island, Locations 24, 25, and 26, are quite similar. Relaxation lengths of about 5 cm are typical. The distribution measured at Location 27 is essentially homogeneous as expected.

PEARL — Since this island contains a surface ground zero, the radiological analysis was based entirely upon the measured soil activities without regard to the degree of vegetation. A review of the data reveals a "hot spot" centered around Locations 5, 6, 9, 10, and 11. This is in reasonable agreement with the aerial survey measurements, except for the exact geographical location of the hot spot. The mean and range of observed activities for the hot spot and the remainder of the island are:

Radionuclide	Activity, pCi/g	
	Mean	Range
Hot spot		
^{90}Sr	62	35-140
^{137}Cs	19	7.4-55
^{239}Pu	51	15-530
^{60}Co	12	3.6-70
Remainder of island		
^{90}Sr	17	3.2-61
^{137}Cs	7.6	1.2-34
^{239}Pu	11	0.85-100
^{60}Co	4.1	0.49-49

The depth distributions measured at various locations throughout the island show relaxation lengths, of the order 5 cm, except at Location 48 (near the southeast end), where the soil activiti seem to be much more homogeneous w depth.

RUBY — This is a tiny island situated immediately north of SALLY. The activities obtained from five samp locations are:

Radionuclide	Activity, pCi/g	
	Mean	Rang
^{90}Sr	12	7.1-6
^{137}Cs	1.4	0.71-7
^{239}Pu	7.3	3.0-2
^{60}Co	0.93	0.29-1

The profile samples collected at Location 2 indicate a homogeneous distribution of activity with depth.

SALLY — This island was the site of several surface detonations. In addition, the PACE Project had excavated extensive areas throughout the island during the past year. Since some of these excavations centered around the surface ground zeros and possible buri sites, it was difficult to devise a meaningful and realistic soil survey. Therefore, a decision was made to include only the undisturbed areas in the sampling plan. The results of this effo should not be regarded as a definitive statement of the radiological conditions this island, but only as an indication of the activity levels that may be encounte The pertinent activities obtained from t samples collected within the undisturbe areas on SALLY and SALLY'S CHILD are:

Radionuclides	Activity, pCi/g	
	Mean	Range
^{90}Sr	8.4	0.87-140
^{137}Cs	3.0	0.03-30
^{239}Pu	4.3	0.21-130
^{60}Co	0.54	0.05-69

The maximum activities, listed above, were all obtained from a sample collected at Location 30 on the beach at the northern tip of SALLY. These activities are approximately a hundred times greater than expected. Since these elevated levels were not recognized until after the completion of the field portion of the survey, no additional samples were collected to define the extent of the contamination.

The profile samples collected at Locations 34 and 35 indicate increasing activities to a depth of 60-150 cm below the surface, while the distribution at Location 200 is essentially homogeneous to a depth of 40 cm. These unusual distributions may have resulted from mechanical mixing of the soils due to construction activities during the weapons-testing period or, more likely, due to the Project PACE excavations. The depth distributions measured at the remaining sites throughout SALLY and SALLY'S CHILD show the more conventional rapid decrease in activity with depth through the first 10-20 cm with a gradual leveling off in the rate of decrease below 20 cm.

TILDA — The activity that is distributed throughout this island resulted primarily from the devices detonated on SALLY, the adjacent island to the north. This activity seems to be distributed fairly homogeneously throughout the island; however, a direct correlation may again be made with the density of vegetation present. The island is divided more or less centrally by an old airstrip. Inspection of the aerial photographs of the island reveals that the area north of the airstrip and on the lagoon (west) side of the north-south road is much less densely vegetated than the remainder of the island situated between the airstrip and the road. The following activities reflect this difference in vegetation:

Radio-nuclide	Activity, pCi/g	
	Mean	Range
Areas of dense vegetation		
^{90}Sr	27	17-54
^{137}Cs	8.4	3.5-20
^{239}Pu	7.6	1.4-17
^{60}Co	1.2	0.61-1.9
Areas of sparse vegetation		
^{90}Sr	8.7	2.2-47
^{137}Cs	1.0	0.04-5.3
^{239}Pu	2.5	1.1-34
^{60}Co	0.37	0.21-1.7

Thus, the mean values vary by factors of nearly three or more between these two areas. This variation is also observed in the aerial survey measurements.

The depth distributions of activity seem to vary considerably throughout the island. The distribution measured at Location 35 reveals a maximum activity value at 10-15 cm below the surface, possibly due to road construction. On the other hand, the profiles obtained at Locations 34 and 36 display the usual rapid decrease in activity within the first few centimeters (relaxation lengths of 3-5 cm), while the activity at Location 38 falls off almost exponentially with a relaxation length of roughly 20 cm.

URSULA—The activities measured on this island were quite low with respect to those measured on the more northern islands. Possibly due to these low activities, no correlation was observed between activity and the degree of vegetation. The mean and range of activities measured in the surface samples collected over the entire island are:

Radionuclides	Activity, pCi/g Mean	Range
^{90}Sr	6.8	2.0-19
^{137}Cs	1.7	0.13-7.8
^{239}Pu	1.3	0.26-7.3
^{60}Co	0.31	0.05-1.7

The depth distribution at Location 29, an interior site, shows the typical decrease in activity with depth; however, the distributions measured at Locations 28 and 31 reveal higher activities beneath the surface. This may be due to their proximity to the beaches.

VERA—The radiological contamination of this island from the weapons tests is relatively minor. Consequently, the activities measured in the surface samples collected on this very densely vegetated island are correspondingly low. The pertinent activities are:

Radionuclides	Activity, pCi/g Mean	Range
^{90}Sr	6.3	1.1-68
^{137}Cs	2.0	0.03-12
^{239}Pu	2.5	0.60-25
^{60}Co	0.30	0.02-2.2

The depth distributions at Location 24 display relaxation lengths of 2-5 cm, while those at Locations 23 and 25 are more like 10-15 cm.

WILMA—Since the radiological contamination of this island was similar to that for VERA, one would expect roughly the same activity levels. This was borne out by the following data obtained from the surface samples collected.

Radionuclide	Activity, pCi/g Mean	Range
^{90}Sr	3.3	0.26-13
^{137}Cs	1.3	0.31-7.2
^{239}Pu	1.1	0.1-5.3
^{60}Co	0.12	0.01-0.7

The profile samples collected at several sites throughout the island display similar depth distributions, with relaxation lengths of 10-15 cm being the general rule.

Beaches—Since the activities of the samples collected on the beaches are appreciably lower than those measured in samples from the islands' interiors, and since these activities do not vary greatly from one island to another, it is convenient for discussion purposes to combine the beach activities obtained from all of the islands in the northern part of the Atoll, except for IRENE, EDNA, RUBY, and PERCY. The results are:

Radionuclides	Activity, pCi/g Mean	Range
^{90}Sr	6.4	1.2-30
^{137}Cs	0.30	0.03-9.0
^{239}Pu	2.7	0.34-18
^{60}Co	0.13	0.03-1.6

YVONNE—Yvonne received the most severe radiological dose of any island within the Atoll. Eight nuclear tests were conducted on the island, and the close-in fallout patterns from an additional 16 events intersected various parts of the island. This fallout history, plus construction and decontamination activities conducted during and after the testing period, have produced a rather heterogeneous and unusual radiological situation on the island.

To facilitate the soil survey, the island was divided into two sections: (1) the southern section consisting of the area south of the bunker complex (approximate center of YVONNE C photograph), and (2) the area situated north of the bunker (YVONNE A and B photographs). This division was based upon a review of historical records, data obtained from the aerial survey, and data from previous ground surveys. Indications were that these two sections were quite distinct in their radiological characteristics; it was expected that the southern section would be only slightly contaminated, while the northern section would probably reveal elevated activity levels with high geographical variability.

Southern YVONNE—A review of the activities measured in the soil samples collected on this section of the island indicates that the geographical distribution of activity within the top 15 cm is rather uniform; however, somewhat higher values appear preferentially within the area immediately north of the runway (see YVONNE figures in Appendix II). The geometric mean and the range of activities of selected radionuclides measured within the top 15-cm layer are:

Radionuclides	Activity, pCi/g	
	Mean	Range
^{90}Sr	1.7	0.09-20
^{137}Cs	0.40	0.02-3.6
^{239}Pu	3.2	0.02-50
^{60}Co	0.64	0.01-20

The distributions of activity with depth at Locations 33 and 34 show some irregular variations with depth but generally indicate reasonably homogeneous characteristics. The distributions at Locations 35 and 37, on the other hand, indicate fairly rapid decreases in activities with depth. This may be contrasted with those at Location 61, where the activities actually increase with depth by about a factor of five over those measured at the surface.

Northern YVONNE—The complexity of the radiological conditions on this section of the island was produced by several nuclear events. Most notable of these is the QUINCE event (see Fig. 23 for approximate SGZ location), which failed to produce a fission yield, with the result that the plutonium within the device was merely dispersed by the high explosives. Some effort was expended shortly after the event to decontaminate the area by soil removal and the placement of clean soil over the decontaminated area. In spite of this decontamination effort, considerable plutonium was still left behind. Subsequently, a second nuclear device was detonated over the same area. Recent radiation surveys reveal that the area is heterogeneously contaminated with ^{239}Pu particles of various sizes. Radiation surveys were conducted to evaluate the frequency and geographical distribution of the plutonium-bearing fragments situated on or near the surface within the QUINCE area. The surveys were executed by traversing the area on a 10-ft grid pattern with a Fidler instrument and carefully searching the area for relative "hot spots," or localized high Fidler readings. The Fidler, consisting of a thin NaI detector connected to a rate meter, is a field instrument designed to detect low-energy gamma radiation emitted by the ^{241}Am associated with the plutonium. The surveys uncovered roughly 60 "hot spots" scattered throughout the area in a highly random fashion. On Fig. B.23.1a (YVONNE B) the area in which "hot spots" have been found is bounded roughly by a line across the island 1 cm from the right-hand border of the figure and a line across the island 2 cm from the left-hand border, the full width of the island. One must be quite cautious in interpreting the meaning of a high Fidler reading since the instrument responds to low-energy scattered radiation produced by high-energy gamma emitters, as well as gamma rays associated with ^{241}Am. In addition, the instrument's response is a function of the amount of radioactive material, as well as its depth of burial. Thus, the "hot spots" found on YVONNE are local concentrations of radioactivity which, because of the history of the area, are probably, but not certainly, plutonium.

Soil samples were taken on a number of "hot spot" locations and progressively divided into "hot" and "cold" halves on the basis of Fidler readings, resulting in the isolation of milligram-size pieces of plutonium metal. The "cold" fractions were not amenable to further physical separation of plutonium; they gave Fidler readings but appeared to have plutonium uniformly dispersed through the soil volume.

In addition to the plutonium contamination, the northern tip of YVONNE was the site of several nuclear detonations; the most notable were the CACTUS and LA CROSSE events, which produced large craters now filled with water. The throw-out material from these events, according to the aerial survey results, presently display the highest gamma exposure rates on the Atoll [see Fig. B.22.1b (YVONNE A)].

With this situation in mind, the sampling plan illustrated in Figs. B.22.1f and B.23.1f was developed. In essence, the plan included sampling the QUINCE area to a depth of 120 cm on a systematic grid pattern, as well as every 200 ft along a line running up the center of the island to the CACTUS crater. The program also included sampling along a cross section leading from the crater to the lagoon side of the island. It was realized that this program could not address the complete distribution of the large plutonium fragments within the QUINCE area, but would only reveal the general contamination levels in the soil.

The following discussion of the radiological conditions is simplified for the sake of brevity and clarity. For a detailed analysis of the situation, the reader is referred to the original data shown in YVONNE figures in Appendix II. Analytical data for each of the profile sampling locations is also presented in the

YVONNE A and B sections of Appendix II. To aid in visualizing the three-dimensional distribution of plutonium on the northern half of YVONNE, the plutonium profile data have been plotted in Figs. 29-37, each of which represents a section either across the island or through a portion of its length.

A careful review of the ^{239}Pu activities measured in soil samples collected within this area reveals that a significant fraction of the activity is situated along the ocean side of the island between Locations 104 and 117. Within this area, the activities generally exceed 100 pCi/g to depths of 30 cm or more. These relatively high contamination levels appear to penetrate furthest inland along the Location 112-116 cross section, as evidenced by activity levels of greater than 100 pCi/g to depths of 50 cm at Location 113 and 10 cm at Location 114. Elevated ^{239}Pu activities are also observed to a lesser extent along the lagoon side of the island. Activities exceeding 100 pCi/g were measured to depths of 20 cm within a narrow strip situated along Locations 111, 116, 120, and 125. An additional area of interest may be noted at depths of 60-90 cm beneath the surface within the island's interior. A strip, estimated to be as much as 100-200 ft wide, may be delineated at Locations 110 and intersecting Locations 114 and 115. The ^{239}Pu activities generally exceed 10 pCi/g within the strip, with an observed maximum of value of 70 pCi/g.

The ^{239}Pu activities measured in the samples collected along the line running up the center of the island to the CACTUS crater are significantly lower than those measured within the QUINCE area. For instance, activities exceeding 100 pCi/g were measured only on the surface at Location 134. Except for minor variations, the ^{239}Pu activities range from

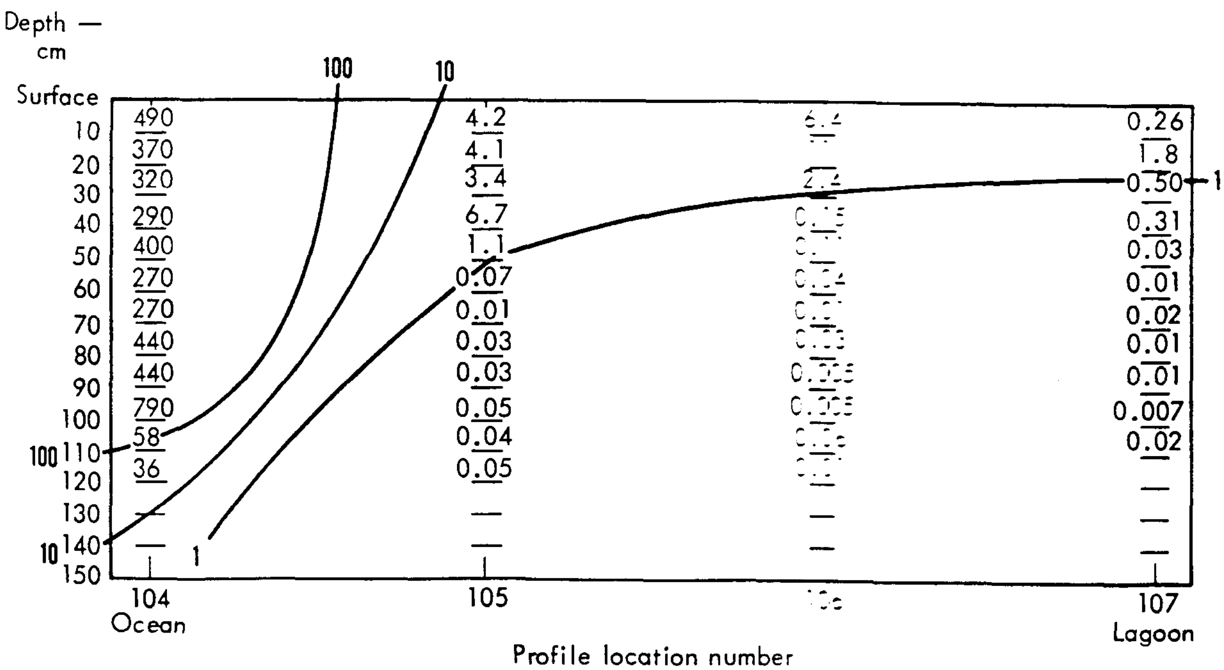

Fig. 29. Plutonium profile data, Locations 104-107, YVONNE.

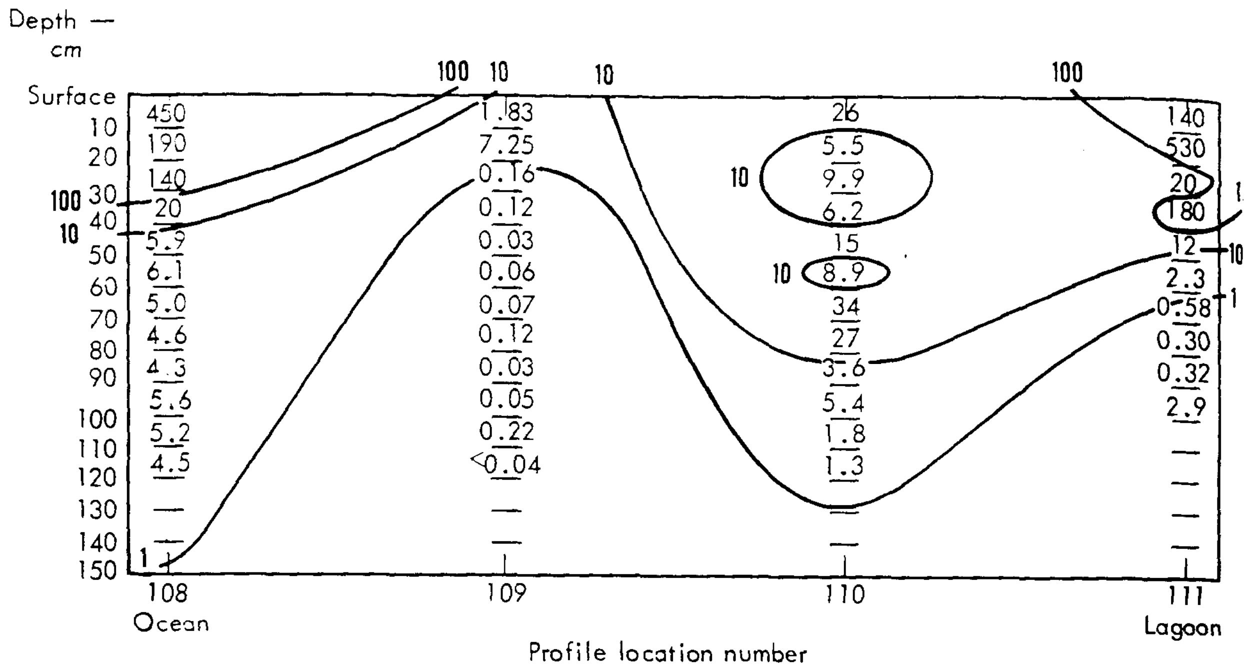

Fig. 30. Plutonium profile data, Locations 108-111, YVONNE.

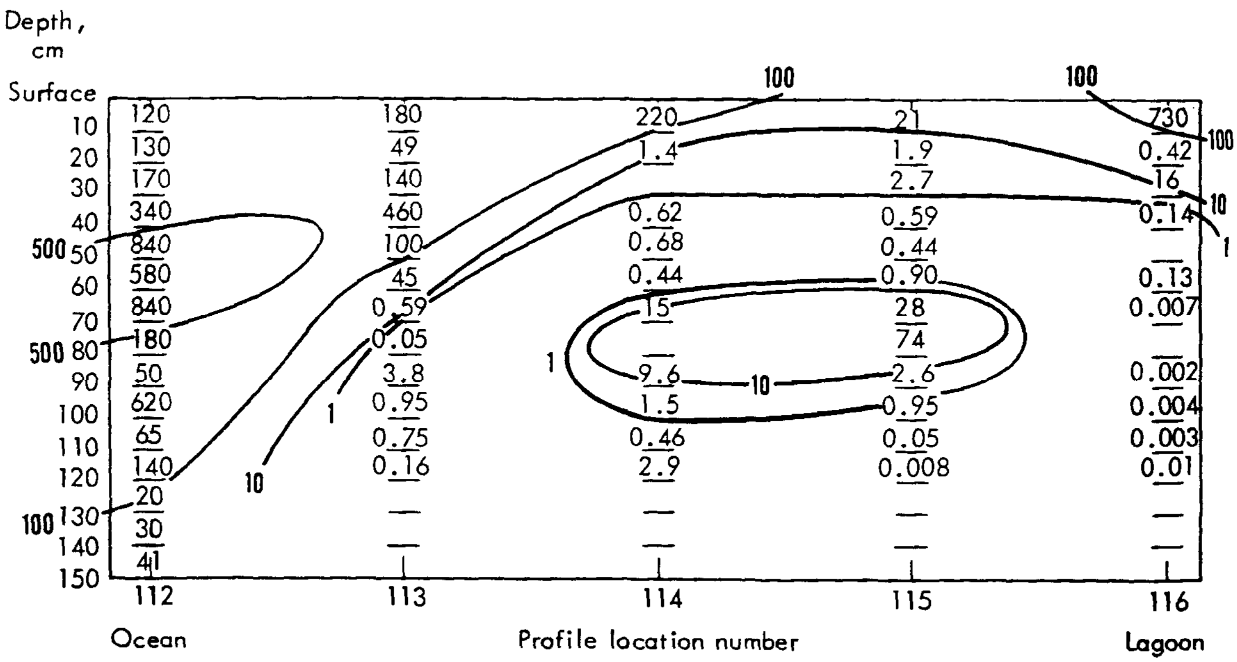

Fig. 31. Plutonium profile data, Locations 112-116, YVONNE.

5 to 30 pCi/g within the top 30 cm between Locations 132 and 142. Slightly higher activities, however, were measured at Locations 143, 144, and 146, along the CACTUS crater-to-lagoon cross section, where activities range typically between 10 and 150 pCi/g.

With the exception of the CACTUS crater area, the activities of ^{90}Sr, ^{137}Cs, and ^{60}Co seem to be fairly evenly distributed

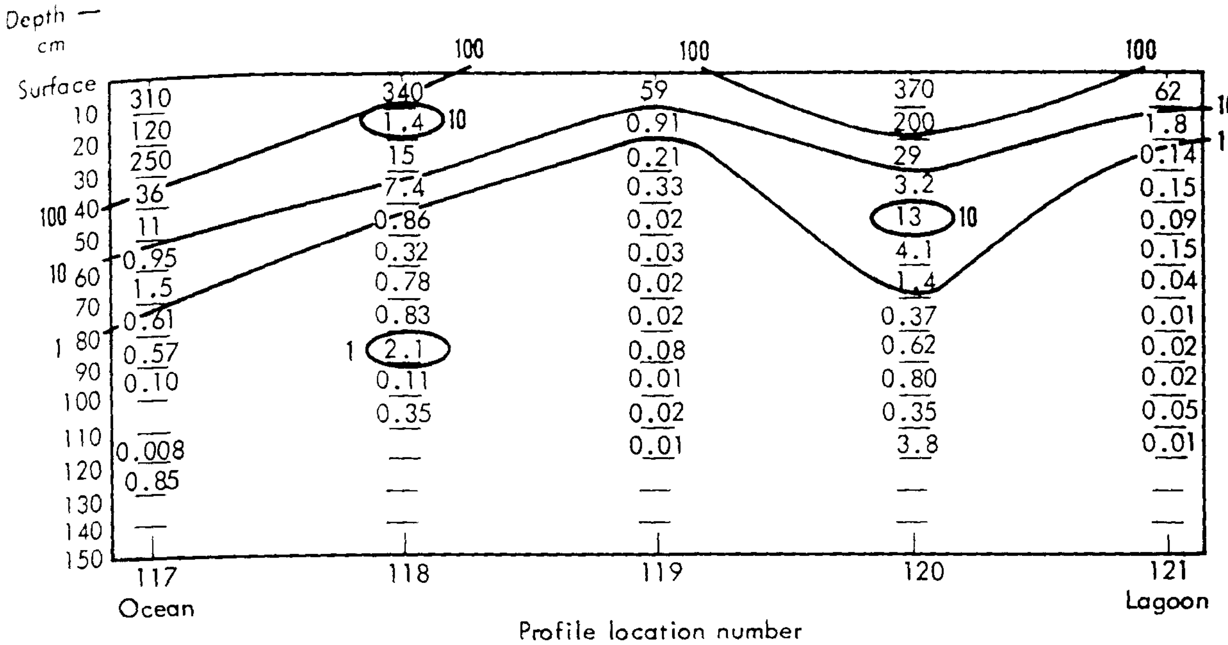

Fig. 32. Plutonium profile data, Locations 117-121, YVONNE.

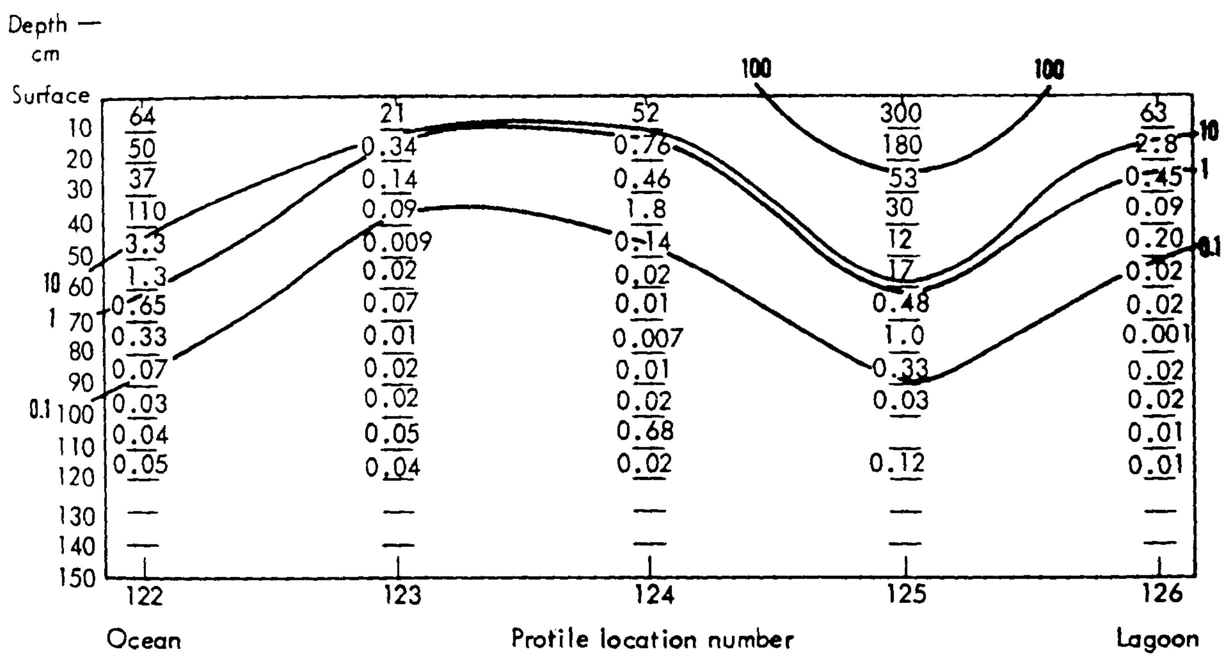

Fig. 33. Plutonium profile data, Locations 122-126, YVONNE.

throughout northern YVONNE. Generally, the ^{90}Sr activities range between 1 and 5 pCi/g within the top 50 cm and less than 1 pCi/g beneath this depth. The activities of ^{137}Cs and ^{60}Co are similar in magnitude and usually range between 0.1 and 2 pCi/g.

Within the CACTUS crater area, the mean surface activities of ^{90}Sr, ^{137}Cs, and ^{60}Co are generally an order of

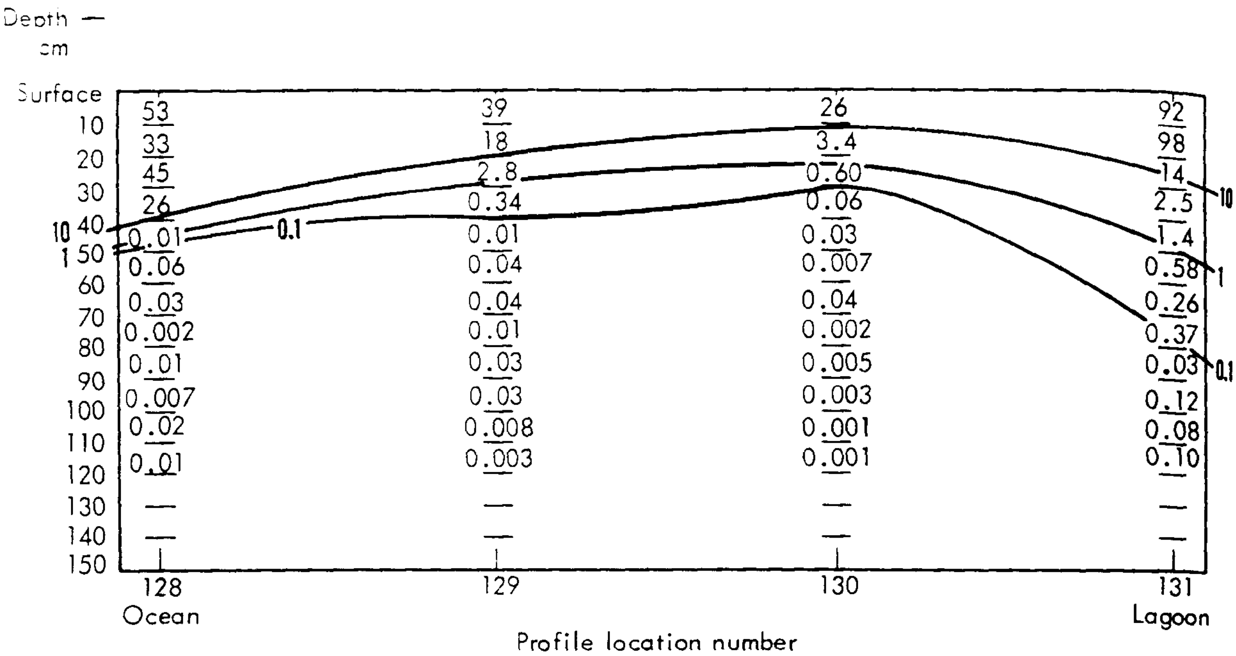

Fig. 34. Plutonium profile data, Locations 128-131, YVONNE.

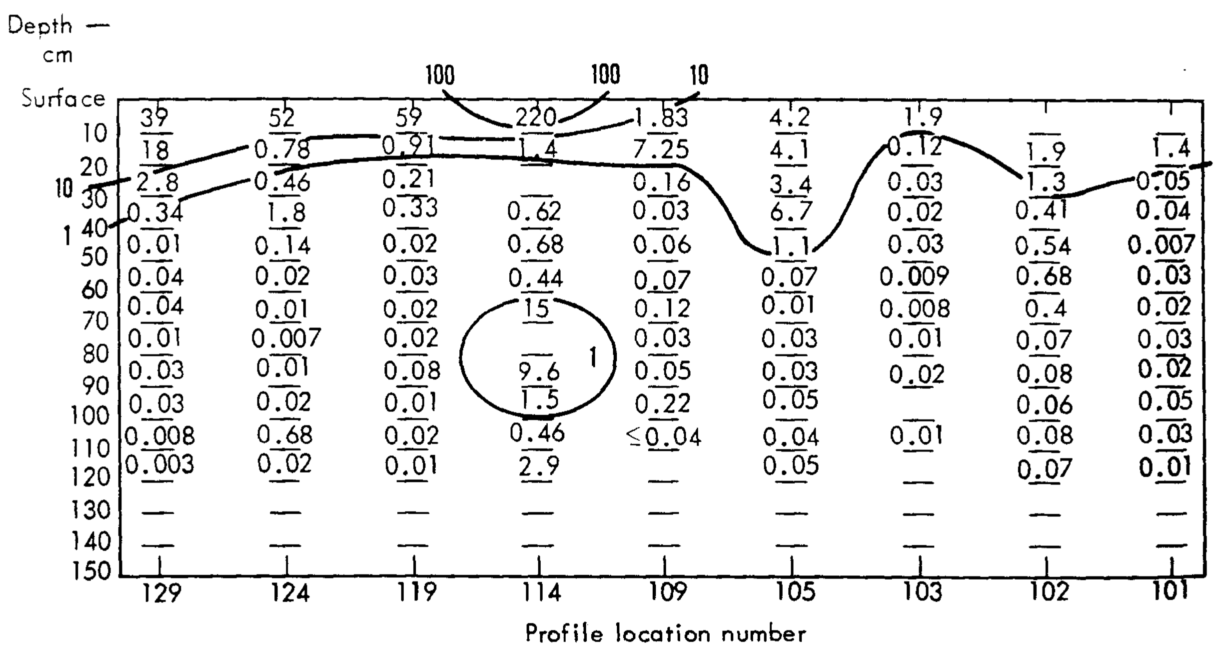

Fig. 35. Plutonium profile data, Locations 101-103, 105, 109, 114, 119, 124, and 129, YVONNE.

magnitude greater than those measured throughout the remainder of Northern YVONNE. Even though the geographical distributions of these radionuclides are highly variable, they do show somewhat similar characteristics. For instance, if one proceeds outward on the two sample radials leading from Location 142, on the crater lip, one encounters an approximate tenfold increase in activity levels (averaged

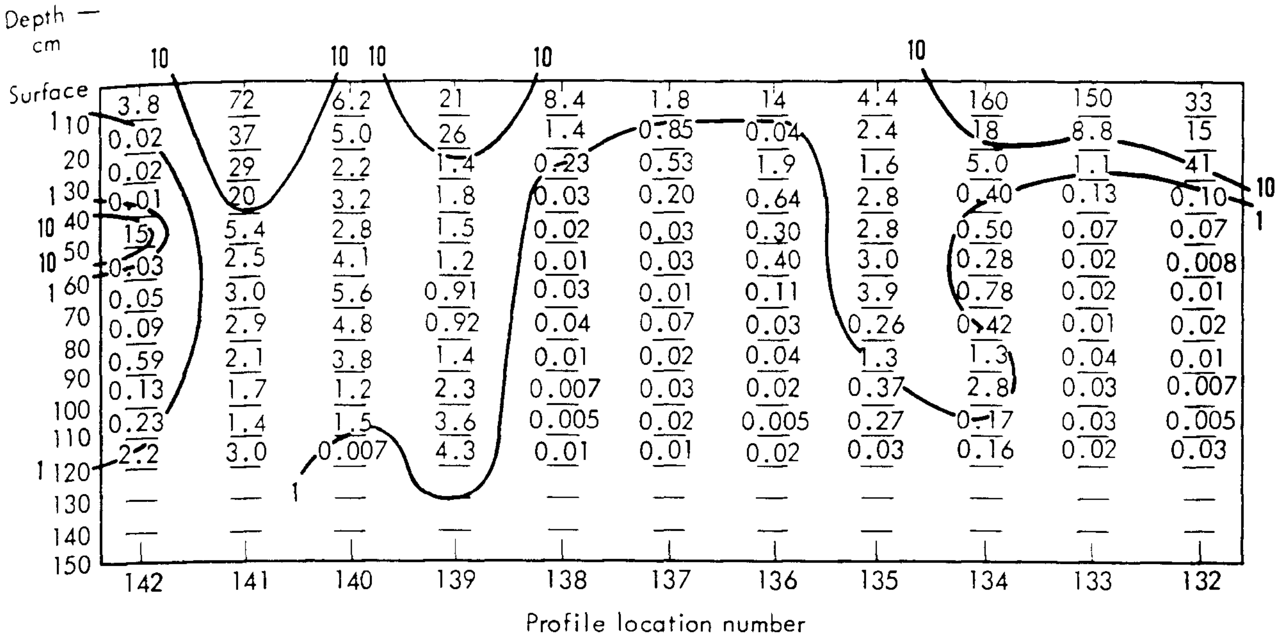

Fig. 36. Plutonium profile data, Locations 132-142, YVONNE.

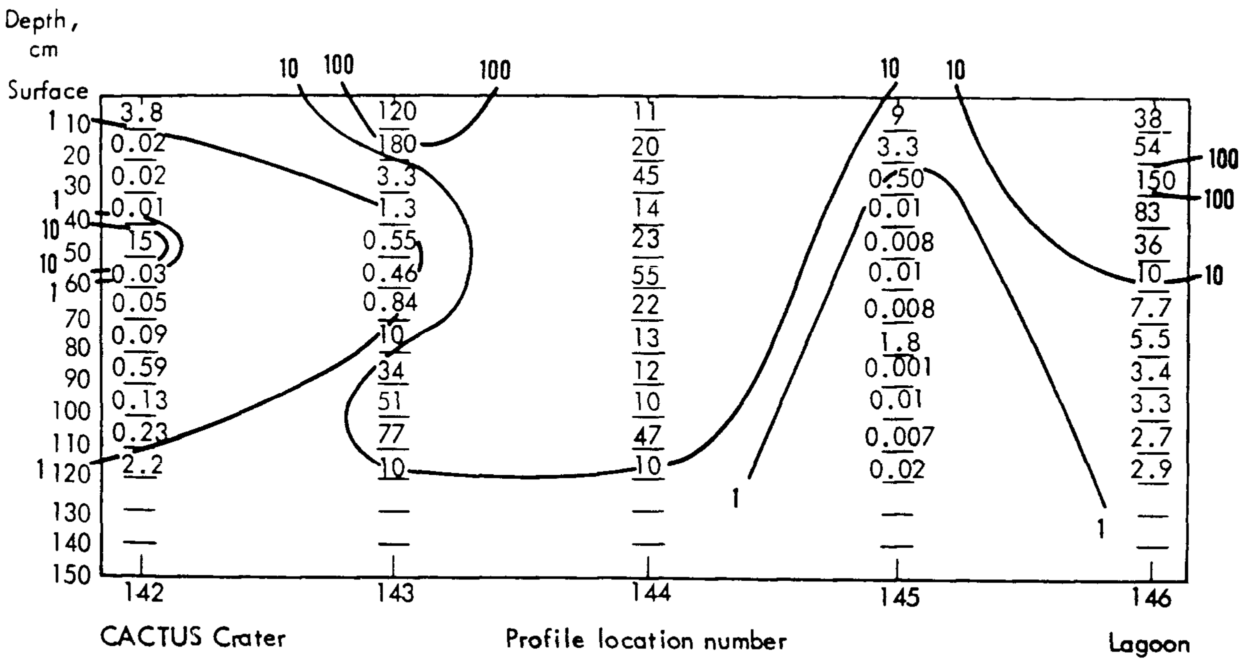

Fig. 37. Plutonium profile data, Locations 142-146, YVONNE.

over 120 cm depth) in the vicinity of Locations 141-140 and Locations 143-144. These activities fall off, however, as one proceeds to Locations 139 and 145.

Southern Portion of Atoll (SAM-LEROY)

For discussion purposes, the islands within this portion of the Atoll have been divided into three groups. Group A includes DAVID, ELMER, and FRED because of their importance as likely sites for habitation by the returning native population. These islands are no different, radiologically speaking, from the remainder of the islands in this part of the Atoll. Group B consists of all of the remaining islands except LEROY, including: SAM, TOM, URIAH, VAN, ALVIN, BRUCE, CLYDE, REX, WALT, GLENN, HENRY, IRWIN, JAMES, and KEITH. LEROY is placed in Group C because its radiological conditions are slightly different from those of the other islands.

Group A — The scientific and military headquarters were situated on ELMER and FRED during the weapons-testing period. DAVID was used mostly for communications and recreational purposes. Relative to the northern islands, radiological contamination of these islands was small. Any observed elevated levels of contamination probably would have resulted from special operations such as equipment decontamination, radiochemical processing, etc. Special samples were collected in those areas suspected of containing contamination from these operations; however, no elevated levels were noted. The mean and range of activities observed on these islands are:

Radionuclide	Activity, pCi/g	
	Mean	Range
^{90}Sr	0.41	0.02-4.8
^{137}Cs	0.21	0.01-2.1
^{239}Pu	0.04	0.004-0.31
^{60}Co	0.03	0.01-0.15

The depth distributions generally display a slight decrease in activity immediately below the surface and then become essentially homogeneous with increasing depth.

Group B — Most of the islands in this group are small in area; in fact, SAM, TOM, URIAH, VAN, ALVIN, CLYDE, and WALT are hardly more than small sandbars with some vegetation on them. The mean and range of observed activities obtained from the 15-cm-deep surface samples, including those collected on the beaches, are:

Radionuclide	Activity pCi/g	
	Mean	Range
^{90}Sr	0.52	0.03-3.9
^{137}Cs	0.14	0.004-1.8
^{239}Pu	0.07	0.004-1.1
^{60}Co	0.06	0.007-63

The distributions of activity with depth display similar characteristics throughout these islands. In areas of dense vegetation, the activities within the top 20 cm decrease relatively slowly with relaxation lengths of about 8 cm. On the other hand, profile samples collected in open or sparsely vegetated areas exhibited essentially homogeneous distributions.

Group C — LEROY was situated within the fallout patterns from several events that took place on the eastern and northern sides of the Atoll. This, of course, was reflected by the elevated activities measured in soil samples from this island. Furthermore, the island's dense vegetation probably tends to inhibit dilution of the activities by environmental processes. The activities obtained from the 15-cm-deep surface samples are:

Radionuclide	Activity pCi/g	
	Mean	Range
^{90}Sr	11	1.6-34
^{137}Cs	3.2	0.5-10
^{239}Pu	0.63	0.02-2.0
^{60}Co	0.58	0.04-5.0

These mean activities are roughly ten times greater than those observed on the other islands in the southern part of the Atoll. The depth distributions of activity measured at three locations within the interior of the island exhibit very gradual decreases in activity with depth. Relaxation lengths of 10 cm or greater are typical.

EXTERNAL DOSE ESTIMATES

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Introduction

Our objective was to quantitatively assess the total external dose that the returning native population might receive as a result of the radiological contaminants distributed in the environs of the Enewetak Atoll. Since the external dose is almost entirely due to the gamma-emitting radionuclides, with only minor contributions from alpha and beta emitters, it was essential to obtain the best possible description of the geographical variability of the gamma exposure rates in air on each island of the Atoll. These data, in conjunction with pertinent population statistics and expected life style, will enable us to make realistic estimates of the external dose to the future inhabitants.

Several independent techniques were used to measure these exposure rates, since each technique has its own set of limitations (i.e. nonlinear energy response, portability of equipment, and extent of geographical coverage). We used results from the following techniques to satisfy the objective: ground measurements made with the use of a portable, hand-held Baird-Atomic NaI scintillation detector, two types of thermoluminescent dosimeters (TLD), and a helicopter-borne NaI detector array (aerial survey). The first two techniques are discussed below, while the details and results of the aerial survey are discussed in a separate chapter of this report. A comparison of the results obtained by these techniques and the use of the results in the population dose computation is included in the following discussions.

Measurement Techniques

Ground Measurements Made With Baird-Atomic NaI Detector

This instrument is a transistorized, hand-held portable ratemeter sensitive to gamma radiation. It consists of a photomultiplier tube optically coupled with a NaI crystal, electronic circuits, meter, associated range selector, and two "D" batteries in a sealed container. The detector assembly is a thallium-activated NaI crystal (2.54-cm diam × 3.8-cm long). It is contained in a hermetically sealed can fitted with a glass window which is optically coupled to the photocathode window of the photomultiplier tube. The radiation level indicating meter is calibrated in microroentgens per hour in three ranges corresponding to 0 to 30, 0 to 300, and 0 to 3000 μR/hr. Since the instrument is completely sealed and desiccated, it readily survived the conditions of constant exposure to sunlight, rain, salt water, and general rough handling encountered on the Atoll.

The instruments were carefully calibrated at the primary calibration range of the National Environmental Research Center, Las Vegas. The range, consisting of a horizontal track approximately 10 m long is situated in an air-conditioned concrete block room. Prior to calibration, each instrument was turned on for several hours and thoroughly inspected. The calibration was performed by attaching the detector to a traveling dolly mounted on a horizontal track. This allowed positioning of the instrument at various distances from a 1-mCi ^{137}Cs source inserted in the source holder at one end of the track. The instrument's response was then recorded at various distances from the source so that all three ranges of the instrument were checked. The response was then compared with the calculated dose rate at the corresponding distances from the source, and, if necessary, appropriate corrections were applied to the instrument.

While the energy response of this instrument is inherently nonlinear, it was not a serious limitation in this case because of the dominance of ^{137}Cs in the radiation background on the Atoll. The instrument was expected to overrespond if the gamma flux was due to scattering from a buried area source rather than from a point source as used in the calibration. This will be shown to be of minor consequence when we compare the resulting data with those obtained by other techniques. In addition, the instrument does not respond quantitatively to cosmic radiation, which is essentially the only natural source of radiation on the Atoll.

Practically all of the measurements obtained with this instrument were made by the soil-survey teams. The exposure rate at 1 m above the ground was measured at each of the soil sample locations on every island in the Atoll for possible correlation with the soil activities. The resulting data, which include a rather extensive coverage of islands, are presented in the "d" series of figures in Appendix II. Additional measurements were made at each TLD location for direct correlation with the TLD measurements.

Thermoluminescent Dosimeter (TLD) Measurements

We used LiF and CaF_2:Dy TLD chips for measuring the radiation fields at numerous locations on the Atoll. The LiF chip was used as the principal detector due to its energy linearity and its excellent thermal stability. Its response is within approximately 1% of being air equivalent for a typical environmental radiation field that contains appreciable scattered radiation in addition to the primary gamma rays that are present.

Therefore, the results derived from the LiF TLDs were chosen as a reference to which measurements obtained by the other techniques could be compared. The CaF_2 TLDs have an enhanced energy response at low energies and were used to detect possible low-energy radiation fields. A comparison of their signals with those from the LiF TLDs may provide an indication of the presence of an unsuspected concentration of low-energy radiation. For a typical radiation field, the CaF_2 TLDs were expected to overestimate the dose rate to air by approximately 30 to 40%.

The LiF and CaF_2 chips (1/8-in. square × 0.035-in. and 0.040-in. thick, respectively) were carefully selected by a process of annealing, followed by irradiation to a common total exposure. Subsequent readout then allowed the extraction of defective chips. The TLDs were transported to Enewetak and annealed on the Atoll immediately prior to being placed on the seven outlying islands that were selected for the TLD program. Two LLL plastic personnel badges containing three LiF and three CaF_2 chips were placed at each field location. The TLD packets were attached by two nails and a nylon strap to small tree limbs at a height of 1 m above the ground (Fig. 38). Each location was marked with copious quantities of fluorescent tape and paint to facilitate retrieval of the TLDs after the 3-1/2-mo exposure period. The locations were carefully chosen to obtain a representative sampling of the terrain (i. e., densely and sparsely vegetated areas and areas adjacent to sandy beaches).

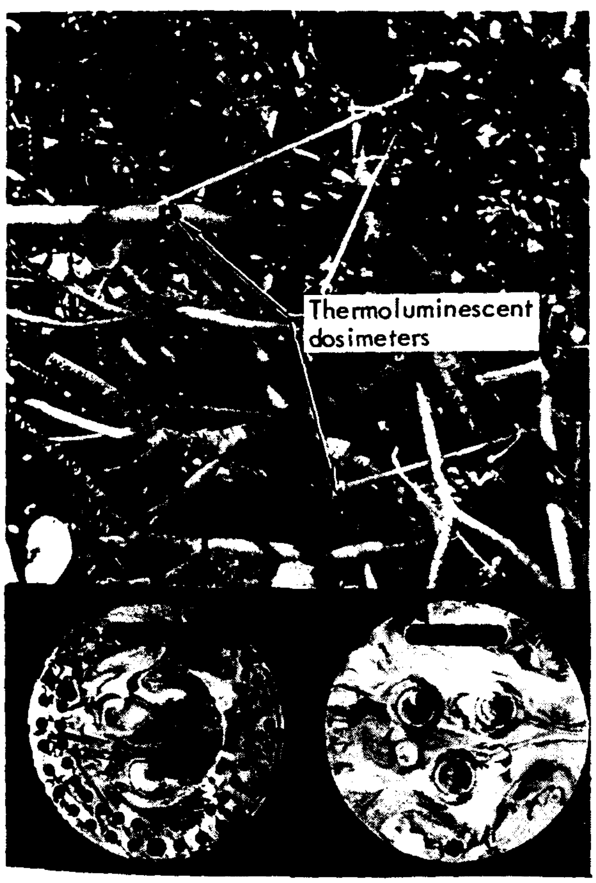

Fig. 38. Field placement of TLD's with enlarged view of TLD packet.

Upon retrieval each TLD packet was immediately placed in a lead container and handcarried to LLL where it was stored in a lead container in an underground, radiation-counting facility. Each chip was individually read on the LLL, hot-nitrogen, automatic TLD chip reader* which was interfaced to a PDP-11 computer. In this way a catastrophic reader failure would only reduce the precision of the answer and would not result in the total loss of data from any badge. This technique also eliminated undetected errors due to drift in reader sensitivity.

*K. F. Petrock and D. E. Jones, "Hot Nitrogen Gas for Heating Thermoluminescent Dosimeters," in Proceedings of the Second International Conference on Luminescent Dosimetry (Gatlinburg, Tenn., 1968).

A number of ancillary experiments were performed for calibration purposes and to insure that no errors were incorporated into the measurements. A separate set of chips was exposed to a ^{137}Cs point source at convenient times during the field exposure period for calibration and signal-fading studies. The strength of the calibration source was checked before and after field use with NBS-calibrated Radocon chambers and is known to within 3% at one standard deviation. Control TLDs were carried to the outer islands and back to measure the dose received during transit. All of the chips were then stored in the lead containers for the balance of the field measurement period. In addition, another set of control TLDs was stored within and on the periphery of the lead storage containers for environmental background studies.

The background exposure on the control TLDs was essentially all contributed by cosmic radiation during the 3-1/2-mo exposure period on the Atoll and during the aircraft flight to LLL. The average background exposure for the two types of TLDs was subtracted from all field measurements so that the results represent only the terrestrial radiation exposure rates. For verification purposes, the magnitude of the total background exposure was also estimated by using successive differences for each type of TLD on the three sets of calibration exposures and by using the sensitivity in light output per milliroentgen (mR) to estimate exposure for the average control light output. All estimates fell in the range of 10 to 12 mR, which agrees well with our previous experience of measuring cosmic ray exposures.

The TLD-signal-fading data have been carefully analyzed to determine the necessity, if any, of applying a fading correction. Figure 39 shows the net light sums for identical exposures at specified times following the start of the field measurement. The TLDs were exposed at different times during the field measurement, and thus long post-annealing times represent later exposures. Note that early exposures (day 4), have lower light sums than those at the end of the field measurement (day 111), due to thermal fading. In the analysis a constant exposure rate was assumed and the empirical fit of Fig. 39 was assumed to

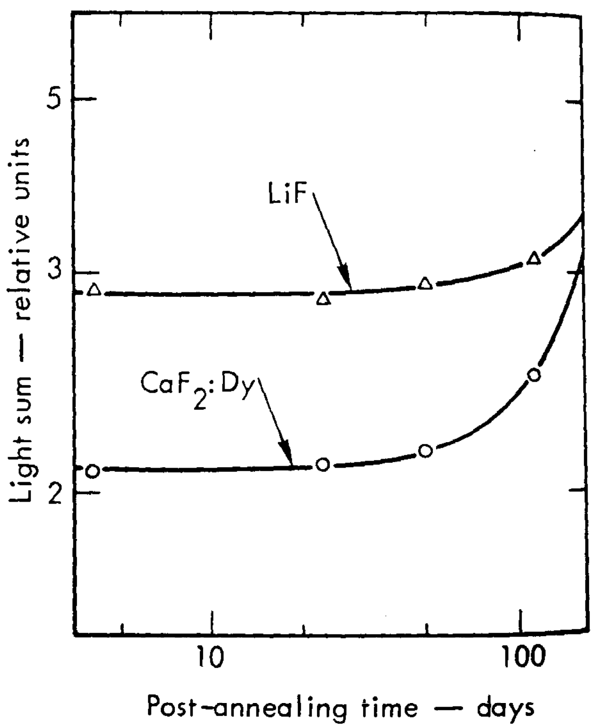

Fig. 39. A plot showing TLD fading characteristics. The TLDs were subjected to equal exposures (^{137}Cs source) at various times during the field measurement period. Annealing time was at t=0, exposures were from t=1 to t=111 days, and the light readings were taken from t=130 to t=134 days.

describe the fading. These assumptions should be quite good for the nearly constant ambient field conditions and the age of the artificial radionuclides present. Corrections of less than 1% for LiF and 3% for CaF_2 were obtained by integration and applied to the calibration data. These fading exposures were performed on the atoll and the TLDs were stored under ambient conditions.

The net light outputs from the calibration exposures are plotted against the calculated exposures in Fig. 40. Second-degree polynomial expressions are fitted to the data. From these curves, one may assign exposures to the light outputs from all the TLDs. These exposures were then separated by island and divided by the number of hours of field exposure to determine the appropriate exposure rates.

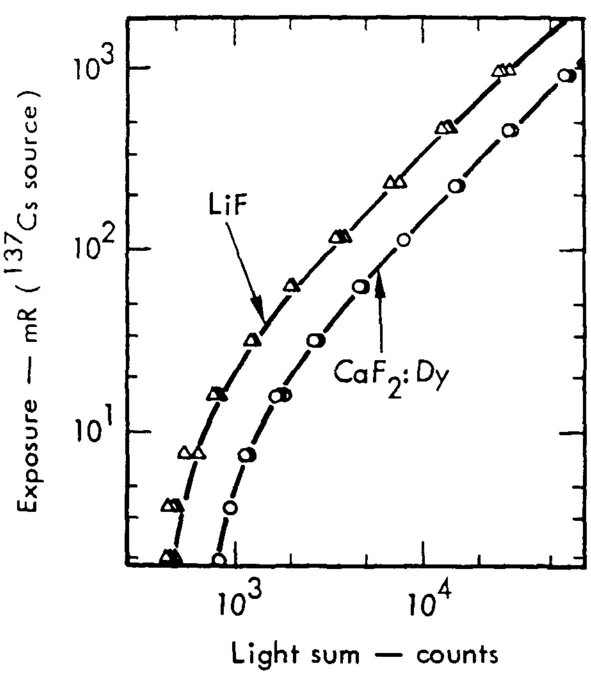

Fig. 40. Calibration curves for LiF and CaF_2: Dy TLD's. The values for CaF_2 counts have been multiplied by 0.05 to enable presentation of both sets of data in the same figure.

The LiF measurements for the islands of ALICE, BELLE, CLARA, DAISY, IRENE, JANET, AND PEARL are shown in figure overlays at the respective geographical locations where the measurements were made (see Appendix II, series h). Table 17 contains a complete listing of the CaF_2, LiF, and portable NaI measurements for each TLD location.

Table 17. Listing of exposure rate levels.

TLD location	Exposure rates, μR/hr TLD (LiF)	TLD (CaF_2)	Portable NaI detector
Island: ALICE			
17	48	59	55
18	120	132	120
19	108	120	110
55	0	4	3
56	45	52	45
57	42	50	45
58	109	128	100
59	127	142	130
60	6	10	7
61	26	28	20
Island: BELLE			
14	84	97	80
15	131	151	120
16	121	132	120
21	8	16	12
22	129	133	110
23	118	136	130
24	154	173	140
25	139	173	140
26	138	155	145, 1-m height
27	149	168	145, 0.33-m height
28	140	167	145, 0.67-m height
29	124	153	145, 1.33-m height
38	200	219	200
39	81	92	100
Island: CLARA			
20	67	65	75
41	12	15	8.5
42	58	59	50
43	49	58	50, 1-m height
44	58	66	50, 0.33-m height

Table 17 (continued)

TLD location	Exposure rates, μR/hr TLD (LiF)	TLD (CaF_2)	Portable NaI detector
45	55	61	50, 0.67-m height
46	52	52	50, 1.33-m height
47	54	58	60
51	104	112	105
52	118	144	130
Island: DAISY			
48	11	13	10
49	33	35	20
63	20	28	13
64	17	21	13
65	18	21	11
66	8	12	8
67	8	11	7, 1-m height
68	9	12	7, 0.5-m height
69	7	11	7, 1.5-m height
70	7	12	7.5
75	8	13	10
76	106	113	90
77	65	72	65
Island: IRENE			
71	92	107	90
73	194	215	200
74	25	34	45
78	72	86	75
80	26	34	25
Island: JANET			
301	62	71	70
302	65	73	80
303	56	73	80
304	70	85	90
305	30	42	45
306	36	48	55
307	45	58	65
308	36	42	45
309	37	44	45
81	1	5	5
82	19	26	18
83	8	16	12
84	32	43	27
85	50	65	65
86	46	58	60
87	54	67	65

TLD location	Exposure rates, μR/hr TLD (LiF)	TLD (CaF_2)	Portable NaI detector
88	43	58	60
89	30	42	50
310	3	8	7.5
311	33	41	45
312	110	137	135
313	79	104	110
314	47	64	75, 1-m height*
315	46	61	75, 1.5-m height*
316	55	70	75, 0.5-m height*
317	66	75	75
318	43	61	65
319	54	61	65
320	36	46	50
321	28	35	22
322	1	2	3, 1-m height in bunker*
323	1	2	3.5
324	19	19	16
327	43	60	75, 1-m height, 0.02-in.-Al cover*
328	0	1	3, 1-m height, 0.02-in.-Al cover*
Island: PEARL			
1	23	33	21
2	159	181	170
3	151	178	170
4	48	70	70
5	52	73	60
6	44	56	50
7	31	44	40
8	19	26	25
9	19	26	14
11	14	19	10
12	19	24	12
13	14	17	8
31	68	74	65
32	128	138	65
33	80	90	80
34	39	49	50
35	43	56	50
36	67	82	65
37	38	44	40

*Contiguous locations.

A statistical analysis was performed to determine the accuracy of the TLD results. Within the range of 30 to 50 $\mu R/hr$, the accuracy of the exposure rates is conservatively estimated to be 4% for CaF_2 and 6% for LiF at one standard deviation. For the CaF_2 results, this estimate does not include the nonrandom error due to the nonlinear energy response. For very low exposure rates the error becomes much larger, especially in regard to the LiF data. This is due to the subtraction of the relatively large background, the increased variability of the data at low exposure rates, and the empirical fitting technique that forces the best fit at the higher exposure rates. For instance, at an exposure rate of 4 $\mu R/hr$ the LiF results are considered to be accurate to approximately 40%; the relative precision is considerably better.

Aerial Radiological Survey

The details of this survey, including results, are provided in a separate chapter of this report. In essence, gamma rays were detected by a helicopter-borne array of 40 NaI detectors flown over each island on a 150-ft grid spacing. An inertial navigation system provided position coordinates. The output from the detectors was analyzed according to pulse height and recorded along with the position data on magnetic tape. The tape was processed on a ground-based computer to produce a very detailed mapping of the iso-exposure rate contours at 1 m above the ground for each island in the Atoll.

Comparison of Results

Because the LiF TLD has excellent thermal stability and its response is essentially air equivalent, the LiF measurements are considered to be the most accurate measure of the gamma exposure rates at the limited number of sites where TLDs were placed, and, therefore are used as the reference to which all the other measurements are compared. However, when making comparisons between results obtained with various techniques, one must be careful to avoid comparing measurements that are entirely different in nature. For instance, the radiation field measured by the TLDs and portable NaI detector is very local in nature (the order of a few square meters), while that measured by the aerial system is of the order of hundreds of square meters. Thus, local radiation gradients are averaged over large areas by the aerial system,and the results obtained from specific areas may be quite different from those obtained by the TLDs and portable survey meters.

The comparison, shown in Table 18, specifically excludes areas exhibiting steep radiation gradients so that the TLD and portable-survey-meter measurements may be considered representative of an area of several hundred square meters. With this in mind the TLD locations in Table 18 were selected from areas of uniform exposure rates in the interiors of ALICE, BELLE, DAISY, and JANET. Inspection of the data in Table 18 reveals that the LiF measurements are approximately 17% less than those of CaF_2. This is reasonable in view of the enhanced energy response of CaF_2 at low energies. This expected relative difference between the results of the two types of TLDs also gives added credence to the LiF measurements. The table also reveals that the aerial survey measurements and the

Table 18. Comparison of the gamma-ray exposure rates (μR/hr) obtained at selected locations by the various techniques.

	Exposure rate, μR/hr				Exposure rate, μR/hr			
Island	TLD location	TLD (LiF)	TLD (CaF_2)	TLD (LiF) / TLD (CaF_2)	Portable NaI detector	TLD (LiF) / Portable NaI detector	Aerial survey	TLD (LiF) / Aerial survey
ALICE	17	48	59	0.81	55	0.87	56	0.85
	18	120	132	0.91	120	1.0	81	1.48
	56	45	52	0.87	45	1.0	38	1.21
	58	109	128	0.85	100	1.09	121	0.89
	59	127	142	0.89	130	0.98	121	1.04
BELLE	22	129	133	0.97	110	1.17	101	1.28
	23	118	136	0.87	130	0.91	121	0.97
	24	154	173	0.89	140	1.10	149	1.04
	25	139	173	0.80	140	0.99	149	0.93
	38	200	219	0.91	200	1.00	122	1.64
	39	81	92	0.88	100	0.81	81	1.00
DAISY	49	33	35	0.94	20	1.65	25	1.30
	63	20	28	0.71	13	1.54	25	0.79
	64	17	21	0.81	13	1.31	17	0.99
	65	18	21	0.86	11	1.64	17	1.04
	77	65	72	0.90	65	1.00	56	1.16
JANET	85	50	65	0.77	65	0.77	43	1.17
	86	46	58	0.79	60	0.77	43	1.07
	87	54	67	0.81	65	0.83	43	1.26
	88	43	58	0.74	60	0.72	36	1.21
	89	30	42	0.71	50	0.60	38	0.79
	301	62	71	0.87	70	0.89	43	1.45
	302	65	72	0.89	80	0.81	46	1.41
	303	56	73	0.77	80	0.70	54	1.04
	304	70	85	0.82	90	0.78	52	1.34
	305	30	42	0.71	45	0.67	40	0.75
	306	36	48	0.75	55	0.65	55	0.66
	307	45	58	0.78	65	0.69	52	0.87
	308	36	42	0.86	45	0.80	35	1.04
	309	37	44	0.84	45	0.82	28	1.34
	312	110	137	0.80	135	0.81	87	1.27
	313	79	104	0.76	110	0.76	70	1.13
	317	66	75	0.88	75	0.88	43	1.54
	318	43	61	0.70	65	0.66	43	1.00
	319	54	61	0.89	65	0.88	43	1.26
	320	36	46	0.78	50	0.72	40	0.90
	321	28	35	0.80	22	1.27	32	0.88
Average ratios				0.83 ± 0.07		0.93 ± 0.26		1.10 ± 0.28

portable NaI detector results agree, on the average, within about 10% with the LiF measurements. This is within the accuracy of the measurements and the agreement is considered excellent. On the basis of this comparison and because of the extensive geographical coverage, we feel that the aerial measurements provide the most complete and accurate description of the gamma exposure rates throughout the entire Atoll. Therefore, we feel justified in using these data as a basis for determining the external dose to the returning population.

External Dose Determination

In addition to the gamma-ray exposure rates, one needs to consider the expected living patterns of the future inhabitants in order to evaluate the external dose problem. Due to the uncertainties inherent in predicting future living patterns, several cases were chosen for analysis. These are presented in Table 19. The selection of these cases was based upon the most recent information available regarding present population figures, age distributions, and expected life styles (see The Enewetak Atoll People, p. 25). Furthermore, the cases were chosen in such a manner as to bracket the most likely range of doses which could be received by any sizable segment of the population. This will allow any other reasonable pattern to be inferred by proper interpolation of the results obtained for the cases shown in Table 19.

The first four cases are based upon the assumption that some fraction of the population may choose to reside primarily on JANET (the largest island within the northern part of the Atoll), with the remainder residing on FRED, ELMER, or DAVID in the southern group of islands. Each case under consideration allows for visits to other islands. Case I_b differs from case I_a in that more time is allotted to temporary occupation of islands other than JANET at the expense of less time being spent in the JANET village area. These cases, or combinations thereof, are considered to represent the most likely living patterns.

Case V, on the other hand, represents a "worst credible" type of living pattern. The village is situated on BELLE, the island with the highest mean gamma-ray exposure rates (excluding YVONNE), and visits are only allowed to the other northern islands. Thus, Case V would most probably lead to upper-limit doses if some reasonable fraction of the population should decide to reside permanently on BELLE. However, such a plan is not being considered at this time. No attempt was made to subdivide the time spent on other islands into specific areas, since it was felt that such a breakdown would unnecessarily complicate the calculations.

Even though wide variations in gamma-ray exposure rates were measured throughout the northern islands, it was necessary, for the purpose of the dose calculation, to derive the most reasonable values of the current mean exposure rates for each specific geographical area under consideration. These values are shown in Table 20. The mean exposure rates for specific areas of JANET were obtained by examination of the ^{137}Cs and ^{60}Co iso-exposure-rate contour maps provided by the aerial survey. The village area was assumed to lie along the lagoon

Table 19. Assumed geographical living patterns.

Description	Group	Village	Beach	Interior	Lagoon	Other islands
I_a Village on JANET, visits to other northern islands only.	Infants	85[c]	5	0	0	10
	Children	55	10	15	5	15
	Men	50	5	15	10	20
	Women	60	10	10	0	20
I_b Village on JANET, visits to other northern[a] islands only.	Infants	70	5	5	0	20
	Children	50	5	15	10	20
	Men	40	5	20	10	25
	Women	50	5	15	5	25
II Village on FRED, ELMER, or DAVID, visits to northern[a] islands only (excl. JANET).	Infants Children Men Women	Same as Case I_b				
III Village on JANET, visits to southern[b] islands only.	Infants Children Men Women	Same as Case I_a				
IV Village on FRED, ELMER, or DAVID, visits to southern[b] islands only.	Infants Children Men Women	Same as Case I_b				
V Village on BELLE, visits to other northern islands only.	Infants Children Men Women	Same as Case I_b				

[a]Northern islands include ALICE, BELLE, CLARA, DAISY, IRENE, JANET, KATE, LUCY, MARY, NANCY, OLIVE, PEARL, SALLY, TILDA, URSULA, VERA, and WILMA.

[b]Southern islands include all islands from TOM through LEROY, proceeding clockwise around the Atoll.

[c]These values represent the percentage of time spent in the various areas.

side of the island. The mean values given for all of the northern islands were obtained by weighting the mean exposure rates for each individual island with the area of each island. Since the minor contamination of the southern islands is relatively uniform, the mean ^{137}Cs and ^{60}Co exposure rates were chosen by inspection of the individual aerial-survey contour maps. The cosmic-ray contribution was estimated to be 3.3 $\mu R/hr$ at this latitude and the naturally occurring radionuclides in the soil and sea water were expected to contribute an additional 0.2 $\mu R/hr$.

The relative gamma-ray exposure rate contributions from ^{60}Co and ^{137}Cs obtained from the aerial survey agrees well with values independently inferred from the soil activity-depth profile measurements. Although the soil measurements indicate trace amounts of other gamma emitters, such as ^{125}Sb, ^{155}Eu, and ^{241}Am, calculations of exposure

Table 20. Estimated mean exposure rates ($\mu R/hr$) used for dose calculations.[a]

Major geographical area	Source	Exposure rate, $\mu R/hr$ Village	Interior	Beach
JANET	^{137}Cs	9.0	33	1.0
	^{60}Co	5.0	14	0.5
	Cosmic and natural	3.5	3.5	3.5
BELLE	^{137}Cs	61	61	1.0
	^{60}Co	50	50	0.5
	Cosmic and natural	3.5	3.5	3.5
FRED, ELMER, or DAVID	^{137}Cs	0.2	0.2	0.2
	^{60}Co	0.1	0.1	0.1
	Cosmic and natural	3.5	3.5	3.5
Lagoon	Cosmic and natural	3.5	3.5	3.5
		Area-weighted mean exposure rates, $\mu R/hr$		
Northern islands (ALICE-WILMA, but excluding JANET)	^{137}Cs	14		
	^{60}Co	21		
Northern islands (ALICE-WILMA, but excluding BELLE)	^{137}Cs	15		
	^{60}Co	16		
Southern islands (TOM-LEROY)	^{137}Cs	0.2		
	^{60}Co	0.1		

[a]Based upon the mean values reported in the aerial survey section.

rates based upon the observed soil activities indicate that these radionuclides contribute at most an additional 3 to 5% of the total exposure rate. The contribution due to these radionuclides was therefore neglected. Thus, the mean exposure rates shown in Table 20 are felt to be the most reasonable values available for computing integrated dose values. In fact, these mean values may be somewhat high (conservative), even though the aerial survey data agree well with the TLD data, because the latter may have slightly overestimated the exposure rates due to the minimal beta-ray shielding afforded by the TLD badges.

Integral 5-, 10-, 30-, and 70-yr gamma-ray doses for each age group were calculated for each case or living pattern described in Table 19. The results were then combined by "folding" in the present population distribution shown in Table 21. Corrections were made for radioactive decay but not for possible weathering and subsequent deeper penetration of the radionuclides in the soil. The results of these calculations are given in Table 22 and are labeled "unmodified." Additional calculations were made to ascertain the effect of reasonable attempts to reduce the exposure rates on the Atoll.

The first modification, labeled "village graveled" in Table 22, reflects the effect of covering the village areas with about 2 in. of coral gravel – a common practice throughout Micronesia.* This action can

*J. A. Tobin, private communication, 1973.

Table 21. Population distribution of Enewetak.

Age groups	Percentage of total population
Infants (0-5 yr)	
Male	12
Female	10
Children (6-18 yr)	
Male	21
Female	21
Adults (19-50 yr)	
Male	18
Female	14
Adults (over 50)	
Male	2
Female	2

Total population 432

On Ujilang now 340

be expected to reduce the gamma exposure rates in the village area by approximately a factor of two. The second and third modifications are based upon the assumption that clearing the islands for agricultural use and housing will result in some mixing of the top soil. It appears that it would be practical during this period to also plow many of the more contaminated islands to a depth of 1 ft. Assuming that plowing results in mixing rather than burying the topsoil, an average reduction in exposure rates of about a factor of three may be obtained. This reduction factor is based upon the present 3- to 5-cm relaxation lengths (the depth at which the activity is e^{-1}, or 37%, of the surface activity) for activity depth distribution in the uppermost soil layers of the more contaminated areas. This value, however, is highly variable from site to site. In Table 22 modification (2) indicates the effect of plowing only JANET or BELLE, while modification (3) reflects the additional effect of plowing all the northern islands. Deeper plowing or turning over the soil rather than mixing would, of course, result in even greater exposure-rate reductions. For example, mixing to a depth of 2 ft would reduce the exposure rates by an additional factor of two, while covering the sources with approximately 1 ft of uncontaminated soil would essentially reduce the exposure rates to negligible values similar to those observed on the southern islands. Removing the top 6 in. of soil, which often contains about two-thirds of the activity, would result in a threefold reduction in the exposure rates. The advantages of plowing or removing the topsoil should, however, be considered on a case-by-case basis because of the highly variable distributions of activity with depth. In fact, plowing IRENE could possibly increase the exposure rates in specific areas due to the elevated activity levels beneath the surface.

A review of Table 22 reveals that extensive modifications may not be required in order to reduce the dose levels to values comparable to typical U.S. values. Keeping in mind that Cases I-IV represent approximations to the most likely living patterns, one observes that even for Cases I_a and I_b, the unmodified 70-yr integral doses are comparable to the U.S. Values,* while Cases II and IV lead to considerably lower doses. The mean integrated doses to the entire population, shown in Table 22, were derived

*H. L. Beck, W. J. Lowder, B. G. Bennett, and W. J. Condon, Further Studies of External Environmental Radiation, USAEC, Rept. HASL-170 (1966).

Table 22. Estimated integral external free air gamma doses (rads).

	Time interval, yr			
	5	10	30	70
I_a				
Unmodified	0.76	1.37	3.12	5.33
(1) Village graveled	(0.62)	(1.12)	(2.58)	(4.51)
(2) + JANET plowed	(0.41)	(0.75)	(1.77)	(3.27)
(3) + Northern islands plowed	(0.30)	(0.56)	(1.40)	(2.76)
I_b				
Unmodified	8.83	1.49	3.35	5.65
(1) Village graveled	(0.71)	(1.28)	(2.89)	(4.96)
(2) + JANET plowed	(0.49)	(0.87)	(2.01)	(3.62)
(3) + Northern islands plowed	(0.33)	(0.61)	(1.50)	(2.90)
II				
Unmodified	0.38	0.68	1.59	2.97
(3) Northern islands plowed	(0.22)	(0.41)	(1.08)	(2.26)
III				
Unmodified	0.60	1.10	2.60	4.60
(1) Village graveled	(0.48)	(0.88)	(2.14)	(3.90)
(2) + JANET plowed	(0.25)	(0.48)	(1.26)	(2.56)
IV				
Unmodified	0.14	0.28	0.83	1.92
V				
Unmodified	2.72	4.78	10.06	15.50
(1) Village graveled	(1.78)	(3.14)	(6.69)	(10.53)
(2) + BELLE plowed	(0.83)	(1.47)	(3.26)	(5.47)
(3) + Northern islands plowed	(0.68)	(1.23)	(2.77)	(4.76)
Mean population dose (average of cases I_b-IV)				
Unmodified	0.49	0.89	2.09	3.79
(1) Village graveled	(0.43)	(0.78)	(1.86)	(3.44)
(2) + JANET plowed	(0.32)	(0.58)	(1.42)	(2.77)
(3) + All northern islands plowed	(0.24)	(0.45)	(1.17)	(2.41)
Sea level U.S.A. (80 mrad/yr) Typical	0.40	0.80	2.40	5.60

by averaging those for Cases I_b, II, III, and IV. This implies that half of the returning population live on JANET and the other half live on FRED, ELMER, or DAVID and that trips to the northern or southern islands are equally likely for both groups. The unmodified mean population doses are all quite comparable to U.S. values. At most, implementation of modifications 1 and 2 should be sufficient

Table 23. Illustration of dose breakdown among population groups (Case I_a - unmodified).

Group	Total integrated dose, rad 5 yr	10 yr	30 yr	70 yr
Infants	0.64	1.15	2.66	4.53
Children	0.79	1.43	3.24	5.52
Men	0.82	1.47	3.32	5.61
Women	0.79	1.42	3.20	5.42

to assure mean population exposures well below the U.S. levels. Case V represents a "worst credible" type of living pattern which, of course, leads to appreciably higher doses. However, even in this situation, the modifications can bring the levels down to the range of U.S. values.

Because of the low amount of natural radioactivity normally present in the coral atolls, the external dose levels calculated for Cases I-III and V are still appreciably higher than corresponding levels found elsewhere in the Marshall Islands (essentially Case IV). The results for Cases II and IV indicate that restricting the permanent villages to "clean" southern islands at least temporarily would result in lower exposures. Note that for Case I_b almost as much exposure is accumulated in the first 10 years as in the succeeding 20 years. As illustrated in Table 23 for Case I_a, the differences in radiation exposure of the various population groups are minor, particularly for the longer time periods. Similar results were obtained for the other cases, indicating that the exact breakdown among age groups is not highly important. The fact that the doses for Cases I_a and I_b do not differ substantially indicates that the exact time breakdown among geographical areas is also not critical. Table 24 illustrates the distribution of dose with respect to geographical area for Cases I-IV. The large fraction received while working in the interior or on other islands reflects, of course, the higher exposure rates present in these areas.

All of the doses discussed so far are due to free-air gamma plus cosmic-ray exposures The effect of shielding by structures or the body itself on gonadal

Table 24. Percentage of unmodified exposure received from various locales.[a]

Case	Village	Beach	Interior	Lagoon	Other islands
I_a	47	2	27	1	23
I_b	36	1	33	2	28
II	22	2	8	4	64
III	58	2	33	1	5
IV	50	5	17	8	20

[a]For 30-yr intervals averaged over population distribution. Percentages for other time periods are similar.

or bone doses has been ignored. To convert from free-air dose (rads) to gonadal dose (rem), a body-shielding factor of 0.8 may be used.[*]

The free-air dose will be additionally enhanced by the presence of beta rays, originating primarily from ^{90}Sr-^{90}Y in the soil. In radiation fields produced by global fallout, where the $^{90}Sr/^{137}Cs$ activity ratio in the soil is normally about 0.67, the free-air beta dose at 1 m above the ground is expected to be about four times that due to the ^{137}Cs gamma rays. At Enewetak, however, the $^{90}Sr/^{137}Cs$ activity ratios in the soil samples showed a wide range of values with an average ratio of about three. Thus, the free-air beta dose rates may average about 600 μrad/hr in the interior of JANET and about 200 μrad/hr in the village area. The resulting beta-ray doses to the skin, eye lenses, and gonads will be about 50, 25 and 1%, respectively, of the free-air values.[†] Thus, appreciable increases in skin and eye-lens doses due to the beta contribution could be expected. The gonadal dose, on the other hand, would be insignificant.

Very little information is available to verify these calculated beta-ray air doses, but indications are that they may be unrealistically high. This is based upon data obtained from two LiF TLD badges that were equipped with aluminum shields, one of which was situated within the interior of JANET. These shielded badges only showed an approximate 10% reduction in exposure rates from those measured by the unshielded badges at the same location, thus leading one to suspect that the beta air doses are considerably less than the calculated values.

[*] Report of the United Nations Scientific Committee on The Effects of Atomic Radiation, 27th Session, Vol. 1, Supplement No. 25 (1975).

[†] K. O'Brien, Health and Safety Laboratory, USAEC, New York, private communication (1973).

MARINE PROGRAM

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Purpose

The mission of the aquatic survey was to collect enough sufficiently representative samples to define and quantify the contributing radioactivities in the lagoon and reef areas of the Atoll. The radiological data are needed to assess both the exposure pathways to persons utilizing the aquatic environment and to determine the distribution of selected radionuclides in the Enewetak marine environment. Fish, invertebrates, plankton, and water and marine sediment were collected and other marine observations conducted during October, November, and December, 1972. This section of the report describes the kinds and quantities of samples obtained, the methods of collecting and processing, and the details pertinent to each kind of sample or program.

General Program Description

Ships and Capabilities

A 17-ft Boston Whaler was flown from LLL to Enewetak for the survey of the lagoon. It was powered by a 65-hp outboard engine and carried a 7.5-hp outboard for emergency use. It was equipped with a depth sounder and davit with a hand-operated winch and 500 ft of 3/32-in. steel cable, sufficient to reach any depth in the lagoon.

This boat was used chiefly for sampling near the shore; its range was limited because it was necessary to remain within sight of land to fix the station locations, which was done with a sighting compass. We sampled the lagoon between FRED and PEARL, no more than 6 km from shore; additional collections were made between LEROY and FRED, including stations in the Wide Passage.

Sampling by the Whaler crew included water collection, sediment collection, plankton-tow and mid-lagoon trolling with rod and reel. This small boat proved very satisfactory for these collections. In all, 43 of the 126 sediment grabs, 21 water samples, many open lagoon fish, and several plankton samples were collected by the whaler during the survey in spite of bad weather which seriously hampered its operation in the lagoon. On a number of days, operations were curtailed because of wind and sea conditions.

A landing craft utility (LCU) was provided for the survey and used to support all survey programs. Its use for the marine program was on an availability basis, but the time allotted was sufficient to complete the program. A portable winch powered by a gasoline engine was mounted on the stern of the vehicle deck. The winch contained 1000 ft of 3/32-in. stainless steel hydrographic cable which passed through a metering sheave secured to the port-side davit of the vessel. All sampling operations were conducted from the port side with equipment attached to the hydrowire.

The bridge-height of the LCU was sufficient to sight on land from any location in the lagoon and the Navy crew provided all fixes necessary for locating station positions. Sample depths were determined from the wire-out readings recorded on the sheave. Water samples, sediment samples, and fish and plankton samples were obtained. Bad weather limited many operations from the LCU.

A 24-ft launch belonging to the USAEC has been stored and used at Enewetak since May 1972. It is powered by two 120-hp inboard-outboard engines and is equipped with a depth sounder.

This boat was used for transportation between sampling locations during all portions of the Enewetak Survey and for the *in situ* gamma probe work. The boat was adequate for both purposes, since it was large enough to handle the normal wind and wave conditions found in the lagoon, yet maneuverable enough to work in the shallow near-shore waters.

Equipment and Other Facilities

Both the Whaler and the LCU had complete pumping systems aboard. Surface and subsurface water samples were collected with battery-operated pumps through a weighted hose-line which was lowered to the desired depth. Each sampling operation was preceded by pumping for at least 10 min to flush out the entire system. The 55 liter black (Deldrum) polyethylene collection barrels were first rinsed with the sample water and then filled at the rate of 8 liters per min.

Sediment grab samples were collected with either Shipek, Ponar, or Ekman samplers. Plankton were collected in No. 6 or No. 10 nets, 1 m in diam. Fish were collected by trolling with rod and reel in the lagoon or with nets in the shallow near-shore areas. Invertebrates were hand collected. Crater sediments in MIKE and KOA craters were sampled with a "Benthos" model 3-in.-diam gravity corer.

Every precaution was taken to ensure against contamination of the samples. All samples were placed in plastic bags, jars, or barrels, immediately after collection. After each day's cruise, all decks and equipment were washed to remove any sediment debris accidentally spilled and overlooked.

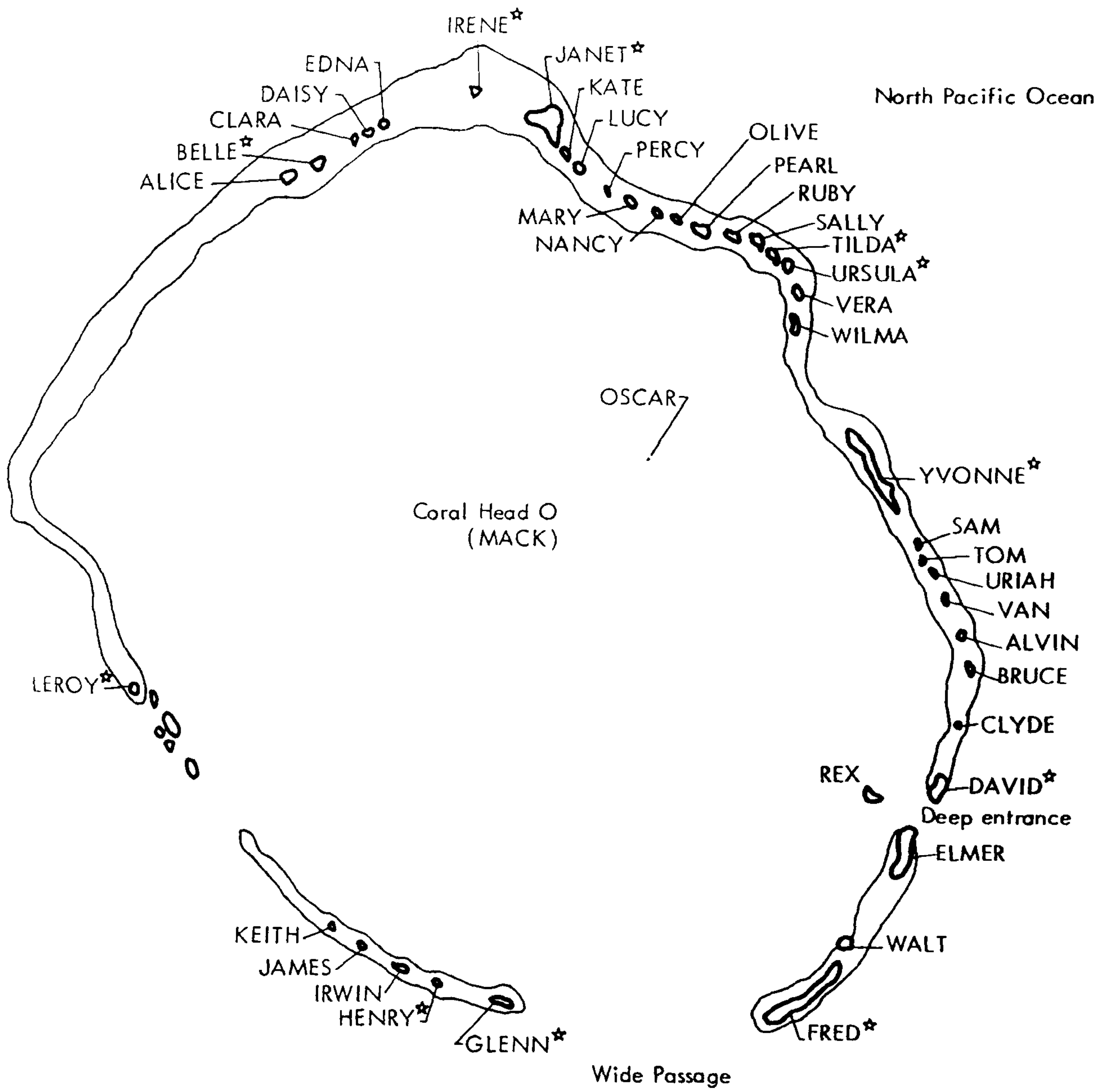

Fig. 41. Major collection locations (starred) of marine biological samples at Enewetak Atoll, October to December, 1972.

Fish

Introduction

There are more than 700 species of fish at Enewetak Atoll, but only a few species of reef, benthic, and pelagic fishes were selected for use in this study. The common anglicized names of the fishes are used in the text, but the scientific names and the Enewetakese common names, when known, are listed in Table 25. The Enewetakese names were those used by Smith Gideon, Enewetak magistrate, in his conversations with Victor Nelson at Enewetak in July 1973, and from Goo and Banner (1963).

The species selected were chosen for one or more of the following reasons: (1) they are commonly eaten by the Marshallese; (2) they are relatively aboundant at most of the collection sites; (3) they are representative of a feeding habit; or (4) there is previous relevant radiometric information about the species. The species of reef fishes selected as being representative of feeding habits include the mullet (a plankton and detritus feeder), convict surgeon (a grazing herbivore), goatfish (a bottom-feeding carnivore) and parrot-fish (a coral eater). The tunas, jacks, and dolphins – pelagic fish – and the snappers and groupers – benthic fish – are carnivores of high order in the food chain leading to man. Information about the radioactivity in Enewetak fish during the last 25 yr, including the species selected for this study, can be found in the reports of the University of Washington, Laboratory of Radiation Ecology, which include the following: Held, 1973[a]; Beasley and Held, 1972[b]; Held, 1971[c]; Welander, 1967[d]; Welander et al., 1967[e]; Seymour, 1963[f]; Held, 1963[g]; Lowman, 1960[h].

Sample Collections

Reef Fishes – The nine major collection stations are shown in Fig. 41. They are listed in clockwise order around the Atoll, and beginning with the most northern station are as follows: BELLE, IRENE, JANET, TILDA-URSULA, YVONNE,

[a] E. E. Held "Fallout Radionuclides in Pacific Ocean Tuna," in Proc. Third National Symposium on Radioecology, 10-12 May 1971 (Oak Ridge, Tennessee) CONF 710501, p. 689.

[b] T. M. Beasley and E. E. Held, "Silver-108m in Biota and Sediments at Bikini and Eniwetok Atolls," Nature 230(5294), 450 (1971).

[c] E. E. Held, Radiological Resurvey of Animals, Soils and Groundwater at Bikini Atoll 1969-1970, U.S. Atomic Energy Commission, Rept. NVO-269-8 (1971).

[d] A. D. Welander, "Distribution of Radionuclides in the Environment of Eniwetok and Bikini Atolls, August 1964," in Symposium on Radioecology, Proc. Second National Symposium, 15-17 May 1967 (Ann Arbor, Michigan) CONF-670503, p. 346 (1969).

[e] A. D. Welander et al., Bikini-Eniwetok Studies, 1964: Part II. Radiobiological Studies, U.S. Atomic Energy Commission, Rept. UWFL-93 (Pt. II) (1967).

[f] A. H. Seymour "Radioactivity of Marine Organisms from Guam, Palau, and the Gulf of Siam, 1958-1959," in Radioecology, V. Schultz and A. W. Klement Jr., Eds. (Reinhold, New York, and Amer. Inst. Biol. Sci., Washington, D.C., 1963) p. 151.

[g] E. E. Held "Qualitative Distribution of Radionuclides at Rongelap Atoll," in Radioecology, V. Schultz and A. W. Klement, Jr. Eds, (Reinhold, New York, 1963) p. 167.

[h] F. G. Lowman, "Marine Biological Investigations at the Eniwetok Test Site," in Proc. Conference on Disposal of Radioactive Wastes, Monaco, Nov. 16-21, 1959 (IAEA, Vienna, 1960) p. 105.

Table 25. Common, scientific, and Marshallese names and wet weight to dry weight ratios of tissues from aquatic organisms collected at Enewetak and Kwajalein Atolls, October to December 1972.

Common name	Scientific name	Marshallese[a] name	Tissue	Number of samples	Wet/dry ratio
		Fishes			
Barracuda	Sphyraena barracuda	Nidwa	Muscle	1	4.36
			Bone	1	
Bonefish	Albula vulpes		Muscle	1	3.38
			Viscera (solids and lipids)	1	1.57
Skipjack	Euthynnus yaito	Loj	Light muscle	9	3.51
			Dark muscle	9	3.58
			Liver	9	3.60
			Bone	9	
Butterflyfish	Chaetodon auriga	Dribob	Evisc. whole	1	3.06
			Viscera	1	4.38
Convict surgeon	Acanthurus triostegus	Kuban	Evisc. whole	30	3.54
			Viscera	28	5.26
Damselfish	Abudefduf sp.		Entire	1	3.09
Dolphin	Coryphaena hippurus		Muscle	2	4.01
			Liver	2	3.47
Flagtail	Kuhlia taeniura	Jerot	Evis. whole	1	2.76
			Viscera	1	3.09
			Entire	2	3.29
Goatfish	Mulloidichthys auriflamma	Jome	Evisc. whole	1	3.26
			Viscera	1	3.65
Goatfish	Mulloidichthys samoensis	Jo	Evisc. whole	13	3.38
			Viscera	13	3.50
Goatfish	Parapeneus barberinus	Jerrobe	Evisc. whole	4	3.78
			Viscera	3	4.31
Goatfish	Parapeneus cyclostomus	Jerrobe	Evisc. whole	2	3.29
			Viscera	2	4.03
Goatfish	M. samoensis & M. auriflamma		Evisc. whole	1	3.24
			Viscera	1	3.82
Grouper	Epinephelus merra	Momo	Evisc. whole	1	3.28
			Viscera	2	3.63
			Muscle	1	4.98
			Entire	1	3.37
			Bone	1	
Grouper	Epinephelus spilotoceps	Momo	Muscle	1	4.03
			Liver	1	2.16
Grouper	Epinephelus sp.	Momo	Evisc. whole	1	3.50
			Viscera	1	3.52
Grouper	Variola louti	Kaikbet	Muscle	1	4.76
			Liver	1	3.04
			Bone	1	
Halfbeak	Hemirhamphus laticeps	Kibu	Entire	1	4.57

Table 25 (continued).

Common name	Scientific name	Marshallese[a] name	Tissue	Number of samples	Wet/dry ratio
		Fishes (continued)			
Jack	*Caranx melampygus*	Deltokrok	Muscle	4	4.36
			Viscera	4	3.73
			Bone	2	
Jack	*Caranx sexfasciatus*		Evisc. whole	1	3.88
			Viscera	1	4.26
Mackerel	*Grammatorcynus bilineatus*		Muscle	3	4.10
			Viscera	2	3.72
			Bone	1	
Mullet	*Crenimugil crenilabis*	Iōl	Evisc. whole	3	2.88
			Viscera	4	2.68
			Muscle	1	3.94
			Remainder	1	2.40
Mullet	*Plicomugil labiosus*	Ikari	Evisc. whole	1	3.25
			Viscera	1	3.06
Mullett	*Mugil* sp.	Jomou	Evisc. whole	3	3.76
			Viscera	3	2.32
Mullet	*Neomyxus chaptalii*	Ikari	Evisc. whole	13	2.97
			Viscera	13	2.83
			Muscle	6	3.86
Needlefish	*Strongylura incisa*	Tak	Muscle	1	4.41
			Viscera	1	3.67
Parrotfish	*Scarus sordidus*	Mao	Evisc. whole	2	3.85
			Viscera	10	2.95
			Muscle	9	4.92
			Bone	9	
Rabbitfish	*Siganus rostratus*	Elik	Evisc. whole	1	3.91
Rudderfish	*Kyphosus cinerascens*	Bagrok	Muscle	1	4.95
			Viscera	1	5.69
			Remainder	1	3.15
Skipjack tuna	*Euthynnus pelamis*	Chilu	Light muscle	2	3.51
			Dark muscle	2	3,55
			Liver	2	3.52
			Bone	1	
Snapper	*Aphaerus furcatus*		Muscle	1	4.62
			Viscera	1	3.69
Snapper	*Aprion virescens*	Eowae	Muscle	1	4.34
			Viscera	1	4.18
Snapper	*Lethrinus kallopterus*	Jalia	Muscle	2	4.78
			Liver	1	3.38
			Viscera	1	3.71
			Bone	1	
Snapper	*Lutjanus monostigmus*	Ban	Muscle	2	4.34
			Viscera	2	3.20
			Liver	1	3.09
			Skin	1	1.91
			Remainder	1	2.90
			Bone	1	

Table 25 (continued).

Common name	Scientific name	Marshallese[a] name	Tissue	Number of samples	Wet/dry ratio
		Fishes (continued)			
Snapper	Lutjanus vaigiensis	Ban	Evisc. whole	1	3.41
Snapper	L. monostogmus & L. vaigiensis		Muscle	1	4.71
			Remainder	1	3.05
Surgeonfish	Ctenochaetus striatus		Evisc. whole	1	3.97
			Viscera	1	3.16
Surgeonfish	Naso lituratus	Balak	Muscle	1	4.70
			Viscera	1	5.97
			Remainder	1	2.42
Wahoo	Acanthocybium solanderi		Muscle	3	3.88
			Liver	3	2.97
Wrasse	Goris sp.		Muscle	1	4.83
			Viscera	1	3.22
			Bone	1	
Yellowfin tuna	Thunnus albacares	Pwepwe	Light muscle	5	3.78
			Dark muscle	4	3.75
			Liver	5	3.80
			Bone	3	
		Invertebrates			
Pencil urchin			Soft parts	1	2.92
			Hard parts	1	
Sea cucumber	Actinopygia mauritiana		Evisc. whole	2	6.49
			Viscera	2	5.51
Sea cucumber	Holothuria atra		Evisc. whole	2	8.21
			Viscera	2	2.92
Sea cucumber	Holothuria leucospilota		Evisc. whole	3	9.02
			Viscera	3	3.32
Sea cucumber	Holothuria sp.		Evisc. whole	5	7.56
			Viscera	5	5.31
Sea cucumber	Unidentified		Entire	1	2.26
Spincy lobster	Panulirus penicillatus		Muscle	1	4.32
			Hepatopancreas	1	2.94
			Exoskeleton	1	7.61
Top snail	Trochus sp.		Soft parts	1	4.57
Tridacna	Tridacna gigas	Kabwur	Muscle	2	4.29
			Mantle	2	7.43
			Muscle & mantle	4	6.44
			Kidney	5	3.36
			Viscera	5	6.79
			Kidney & viscera	1	4.78
			Gills	1	7.82

Table 25 (continued).

Common name	Scientific name	Marshallese[a] name	Tissue	Number of samples	Wet/dry ratio
		Invertebrates (continued)			
Tridacna	*Tridacna* sp.		Muscle & mantle	11	6.17
			Viscera & kidney	4	5.02
			Viscera	7	6.85
			Kidney	6	4.37
			Entire	3	5.03
		Algae			
Calcareous algae	*Halimeda*		Entire	2	2.59
		Turtle			
Sea turtle	*Chelonia* sp.		Muscle	1	7.43
			Liver	1	4.33
			Kidney	1	6.64
			Lungs	1	8.85
			Heart	1	6.49
			Mesenteries	1	24.37

[a]Marshallese names from the 1963 unpublished manuscript, "A preliminary compilation of Marshallese animal and plant names," by F. C. Goo and A. H. Banner, Hawaii Marine Laboratory, University of Hawaii, Honolulu, and from personal communications with Smith Gideon, Ujilang Magistrate in 1973.

DAVID, FRED, GLENN-HENRY and LEROY. These areas were selected because they are potential resettlement sites and/or were previous collection sites. In addition, "control" fish from a noncontaminated area were obtained from Enewetak, Kwajalein, and Meck Islands in Kwajalein Atoll.

Most of the reef fish were caught in variable mesh monofilament gillnets 25 to 125 ft in length and 6 ft deep. Gillnets were watched closely and unwanted fish were usually released alive. Thrownets were also used in some instances. In most cases, these methods of capture allowed us to collect only fish which were needed for analysis.

The total catch was about 200 mullet (4 species), 100 goatfish (4 species), 400 convict surgeon (1 species), 40 parrotfish (1 species), and 40 other reef fish (12 species). The miscellaneous species included flagtail, rabbitfish, wrasse, surgeon, butterflyfish, damselfish, and bonefish. The catch of reef fish by species and location is given in Table 26.

Pelagic and Benethic Fishes – Large pelagic fishes (tuna, jacks, dolphins) and benthic fishes (snapper, grouper) were collected, since they will presumably be captured and eaten by the Enewetak people and they represent carnivores of high order in the food chain leading to man. They were collected primarily on sport-fishing gear, using feathered jigs and spoons as lures while trolling in the lagoon and in the passes leading to the ocean. Most of the large yellowfin tuna and dolphins were caught in the passes between the

Table 26. Number of organisms collected at Enewetak Atoll and Kwajalein Atoll near-shore sites, October to December 1972.

Collection site[a]	Mullet	Goatfish	Convict surgeon	Parrot fish	Other reef fish	Tridacna	Sea cucumber	Other inverte-brates	Approx total
Enewetak Atoll									
GLENN-HENRY	~25	[illegible]	~50	2	10	6	4	6[b]	114
LEROY	~50	[illegible]	34	[illegible]	1	[illegible]	0	~10[c]	108
FRED	0	~20	~50	[illegible]	7	3	2		91
DAVID	0	[illegible]	~50	[illegible]	2	4	[illegible]		94
BELLE	~50		[illegible]	[illegible]	[illegible]	10	0		97
IRENE	2		12	[illegible]	[illegible]	0	0		25
JANET	~50		~40	[illegible]	0	4	0		98
TILDA-URSULA	~35	[illegible]	~50	[illegible]	[illegible]	[illegible]	[illegible]		107
YVONNE	30	~[illegible]	~55	[illegible]	[illegible]	0	3	[illegible][d]	105
Kwajalein Atoll	–	–	~[illegible]	[illegible]	5	5			41
Approximate Total	~220	~[illegible]	~400	[illegible]	42	36	13	25	870

[a]The number given is the number of collections from a given site.
[b]Pencil urchins.
[c]Top snails.
[d]Spiny lobster.

lagoon and the ocean, while the smaller skipjack, mackerel, and ulua were caught in the lagoon proper. The snappers and groupers were caught in both the shallow water of the reef and the deep lagoon waters. The number of large carnivorous fish caught is given in Table 27.

Sample Analyses

Field Processing – After capture, fish were segregated by type (e. g., goat-fish, mullet, etc.), placed in plastic bags, and transferred to ice chests containing dry ice as soon as practical (1 to 4 hr after collection). At the main camp, most fish were frozen, either in dry ice or in freezer units. Occasionally, fish were dissected fresh, the tissue dried, and then frozen.

Originally, it was planned that most of the marine biological samples would be processed at Enewetak by people from the Laboratory of Radiation Ecology. However, the disruption to the program caused by Typhoon Olga made sample processing at Enewetak impractical; therefore, the majority of the samples were processed at the home laboratory in Seattle, Washington.

Laboratory Preparation – The samples were frozen at Enewetak and remained frozen until processed at the Seattle laboratory. To begin preparation of the samples for analyses, the fish were partially thawed and dissected into the tissue types shown in Table 25. Tissue types chosen were those most useful for estimation of the radiation dose and were of sufficient size to yield a dried sample of adequate size for gamma spectros-copy or radiochemical analyses. After

Table 27. Number of carnivorous fish collected from the Enewetak and Kwajalein offshore lagoon sites, October to December 1972.

Collection site	Yellowfin tuna	Organism						Total
		Skipjack	Mackerel	Dolphin	Snapper	Grouper	Ulua	
Enewetak	2	9	3	2	8	8	8	40
Kwajalein	3	1				2		6
Total	5	10	3	2	8	10	8	46

dissection, the tissues were dried at about 80°C until a constant dry weight was reached. Two to three days were usually required for this process; oily samples (viscera, liver) took longer.

The dried samples were then ground in a food blender and packaged in standard-size containers for gamma counting. Packages were of two basic types. Dried samples larger than 25 g were packaged in containers made from sections of polyvinyl chloride (PVC) pipe. The PVC sample holders were of two sizes – 2-in. diam by 1/2-in. high for 25-g samples and 2 in. by 1 in. for 50-g samples. Dried samples were placed in the sample holder and then compacted with a press to conform to the dimensions of the container. The amount of sample used was the amount required to yield a sample density within the container of 1.1. Dried samples less than 25 g were packaged in plastic petri dishes of two sizes (23 cm^3 and 6 cm^3). These samples were not compacted and, therefore, the sample weight was not constant; however, sample density was calculated from the weight and volume.

Counting Methods – Packaged samples were shipped to Lawrence Livermore Laboratory for gamma spectroscopic analyses. After gamma analysis, most marine biological samples were analyzed for ^{55}Fe, ^{90}Sr, and ^{239}Pu. These analyses were done at the Laboratory of Radiation Ecology (LRE), Lawrence Livermore Laboratory (LLL), McClellan Central Laboratory (MCL), and LFE Environmental Laboratory (LFE). A limited number of samples were analyzed for ^{113m}Cd, ^{129}I, ^{14}C, ^{151}Sm, ^{147}Pm, ^{63}Ni, and ^{3}H. Detailed descriptions of methods used for these analyses are given in the section on the Analysis Program.

Results and Discussion

The fish samples have been analyzed for gamma-emitting radionuclides, ^{55}Fe, ^{90}Sr, and ^{239}Pu. The gamma-emitting radionuclides detected by the Ge(Li) diode system included naturally occurring ^{40}K and ^{228}Th and fission and activation products – ^{60}Co, ^{65}Zn, ^{101}Rh, ^{102m}Rh, ^{108m}Ag, ^{125}Sb, ^{137}Cs, ^{152}Eu, ^{155}Eu, ^{207}Bi, and ^{241}Am. It should be noted that the radioactivity values for the fish are given as of the date of collection in terms of dry sample weight but can be converted to wet weight values by use of the conversion factors given in Table 25 for all samples except bone. The results of the analyses are usually in terms of picocuries per gram of dry tissue because the true wet weight of some samples is difficult to determine.

The Kwajalein data are presented in only two tables since the number of samples is relatively small, but the Enewetak data have been grouped into separate tables by species.

Kwajalein Atoll – Kwajalein is environmentally similar to Enewetak, but has not been contaminated by radionuclides from local fallout. Naturally occurring radionuclides and radionuclides from worldwide fallout are present in Kwajalein fish and similar quantities would be expected in Enewetak fish. Hence, the Kwajalein fish can be considered as "control" fish and the difference in the radioactivity of the Kwajalein and Enewetak fish of similar type is an estimate of the contribution of the nuclear testing program at Enewetak Atoll to the radioactivity in the Enewetak fish.

Not all of the species of fish collected at Enewetak were collected at Kwajalein. The catch at Kwajalein included convict surgeon, parrotfish, yellowfin tuna, bonito, and groupers, but not mullet, goatfish or snappers (Tables 26 and 27). The results of the analyses are tabulated in Tables 28 and 29.

Reef fish – Reef fish from Kwajalein Atoll had tissue concentrations of naturally occurring ^{40}K which averaged 15 pCi/g, dry, and ranged from 7.3 to 52 pCi/g, dry (Table 28). These concentrations are slightly higher than values found in fish from Enewetak Atoll. In addition, 2 of 16 fish from Kwajalein Atoll had ^{125}Sb (0.21 and 0.25 pCi/g in kuhlia and convict surgeon) and one rabbitfish had 0.11 pCi of ^{137}Cs per gram of dry tissue. Similar or higher concentrations of ^{125}Sb and ^{137}Cs were found in Enewetak fish samples. Levels of ^{125}Sb are not included in the tables of the radionuclide concentrations in the Enewetak fish because they appear on such a sporadic basis.

Cobalt-60, one of the most abundant gamma-emitters found in the Enewetak fish, was not detected in fish from Kwajalein. Europium-155 and ^{207}Bi, both commonly present in Enewetak fish, were also absent in fish from Kwajalein.

In the samples analyzed, the average ^{55}Fe value was less than 1 pCi/g, dry, while the highest ^{55}Fe value was about 13 pCi/g, dry, in the reef fish and 83 pCi/g, dry, in the light muscle of a wahoo. These ^{55}Fe levels are at or below ^{55}Fe concentrations found in similar species from the southern sector of Enewetak Atoll.

Strontium-90 levels were all less than 0.5 pCi/g, dry. Plutonium-239, 240 concentrations ranged up to 0.5 pCi/g, dry, in a halfbeak from Kwajalein Island, but most other samples had less than 0.1 pCi/g, dry.

Lagoon fish – The background levels of ^{40}K in tissues of lagoon fish from Kwajalein (Table 29) tissues averaged 14 pCi/g, dry (range, 3.1 to 23 pCi/g, dry). Eight of 26 samples had detectable levels of ^{137}Cs, averaging 0.17 pCi/g, dry (range of 0.12 to 0.22 pCi/g, dry), which was slightly above the mean limit of detection, 0.13 pCi/g, dry, found for the other 18 samples. Two skipjack and

Table 28. Radionuclides in reef fish and tridacna clams collected at Kwajalein Atoll, December 1972.

Sample number	Island	Organism	Tissue	Radionuclides (pCi/g, dry)[a] ^{40}K	^{55}Fe	^{60}Co	^{125}Sb	^{90}Sr	$^{239,240}Pu$
8007	Enewetak	Convict	E. whole[b]	9.0 ± 1.1	0.18 ± 0.08	<0.17	0.21 ± 0.10	0.03 ± 0.01	0.96 ± 0.08
8006	Enewetak	surgeon	Viscera	52 ± 6.8	1.9 ± 0.9	<0.05	<1.5	0.41 ± 0.13	0.43 ± 0.03
8008	Enewetak	Damselfish	Entire	15 ± 1.8	0.68 ± 0.14	<0.14	<0.39	0.37 ± 0.04	0.23 ± 0.12
8011	Enewetak	Parrotfish	E. whole	15 ± 1.3	0.16 ± 0.08	<0.18	<0.23	<0.02	—
8010	Enewetak	Parrotfish	Viscera	NC[c]	0.86 ± 0.30	<0.40	<0.79	<0.01	0.41 ± 0.02
0485	Kwajalein	Convict	E. whole	7.7 ± 1.3	0.12 ± 0.03	<0.14	<0.26	<0.05	0.010 ± 0.001
0487	Kwajalein	surgeon	E. whole	13 ± 1.0	1.4 ± 0.2	<0.13	<0.15	0.04 ± 0.03	0.011 ± 0.005
0486	Kwajalein		Viscera	16 ± 1.4	0.58 ± 0.09	<0.20	<0.30	0.25 ± 0.08	0.009 ± 0.001
8013	Kwajalein	Convict	E. whole	16 ± 2.6	—	<0.19	<0.48	—	—
8012	Kwajalein	surgeon	Viscera	NC	13 ± 0.5	<0.37	<0.79	0.06 ± 0.03	0.11 ± 0.01
0763	Kwajalein	Grouper (E. merra)	Entire	7.3 ± 1.0	0.36 ± 0.09	<0.04	<0.11	<0.01	0.009 ± 0.001
0766	Kwajalein	Snapper (L. vaigiensis)	E. whole	14 ± 1.1	1.9 ± 0.3	<0.07	<0.18	<0.02	0.08 ± 0.005
0764	Kwajalein	Halfbeak	Entire	9.2 ± 1.1	—	<0.05	<0.12	<0.01	0.54 ± 0.01
8003	Kwajalein	Kuhlia	Entire	9.8 ± 1.1	—	<0.16	0.25 ± 0.10	0.02 ± 0.01	0.13 ± 0.01
8004	Kwajalein	Kuhlia	Entire	NC	0.50 ± 0.31	<0.03	<0.09	<0.01	0.72 ± 0.02
0765	Kwajalein	Rabbitfish	E. whole[d]	13 ± 1.6	—	<0.07	<0.13	<0.01	0.004 ± 0.001
0767	Kwajalein	Tridacna	Muscle and mantle	12 ± 2.3	—	0.22 ± 0.09	<0.17	0.02 ± 0.001	0.23 ± 0.01
0768	Kwajalein	Tridacna	Viscera and kidney	13 ± 1.6	1.3 ± 0.1	2.3 ± 0.20	<0.32	0.04 ± 0.03	0.14 ± 0.01

[a]Error values are one-sigma, counting errors.
[b]Eviscerated whole is the entire fish, less the viscera.
[c]NC = not computed.
[d]This sample also contained ^{137}Cs (0.11 ± 0.05 pCi/g, dry).

Table 29. Radionuclides in lagoon fish collected at Kwajalein Atoll, December 1972.

Sample number	Island	Common name	Tissue	Radionuclides (pCi/g, dry)[a] ^{40}K	^{55}Fe	^{65}Zn	^{137}Cs	^{90}Sr	$^{239,240}Pu$
0741	Kwajalein	Skipjack	Light muscle	11 ± 1.3	2.8 ± 0.1	NC[b]	0.11 ± 0.04	0.026 ± 0.013	<0.014
0742	Kwajalein	Skipjack	Dark muscle	14 ± 2.0	12 ± 0.1	NC	0.21 ± 0.08	0.07 ± 0.05	0.03 ± 0.005
0740	Kwajalein	Skipjack	Liver	NC	—	NC	<0.19	0.40 ± 0.03	
0773	Kwajalein	Skipjack	Bone	NC	2.6 ± 0.2	NC	<0.15	<0.11	<0.77
0779	Kwajalein	Skipjack	Light muscle	9.1 ± 1.5	2.0 ± 0.1	NC	<0.12	<0.011	0.005 ± 0.001
0780	Kwajalein	Skipjack	Dark muscle	12 ± 1.0	12 ± 0.6	NC	<0.11	<0.015	0.15 ± 0.12
0778	Kwajalein	Skipjack	Liver	7.7 ± 1.4	0.7 ± 0.1	1.8 ± 0.3	<0.08	<0.022	0.005 ± 0.001
0777	Kwajalein	Skipjack	Bone	NC	4.7 ± 0.4	NC	<0.21	<0.015	0.15 ± 0.01
0595	Meck	Skipjack	Light muscle	12 ± 1.7	7.2 ± 0.5	NC	<0.09	0.029 ± 0.002	0.009 ± 0.003
0594	Meck	Skipjack	Dark muscle	11 ± 1.3	30 ± 0.9	NC	<0.10	0.02	0.018 ± 0.001
0595	Meck	Skipjack	Liver	12 ± 1.7	13 ± 1.3	0.5 ± 0.2	<0.08	<0.011	0.006 ± 0.002
0583	Meck	Wahoo	Light muscle	17 ± 1.2	83 ± 0.8	NC	0.12 ± 0.04	0.008 ± 0.002	0.012 ± 0.003
0584	Meck	Wahoo	Liver	14 ± 1.4	11 ± 1.0	NC	0.19 ± 0.07	<0.026	0.006 ± 0.003
0585	Meck	Wahoo	Light muscle	18 ± 1.5	—	NC	0.18 ± 0.05	<0.006	<0.004
0586	Meck	Wahoo	Liver	23 ± 6.2	—	NC	<0.28	0.039 ± 0.020	0.16 ± 0.003
0771	Meck	Wahoo	Muscle	13 ± 1.4	0.24 ± 0.04	NC	<0.09	0.011 ± 0.055	0.05 ± 0.004
0772	Meck	Wahoo	Liver	3.1 ± 1.0	26 ± 0.8	0.4 ± 0.1	<0.05	0.004 ± 0.002	0.034 ± 0.002
0542	Kwajalein	Yellowfin	Light muscle	18 ± 1.2	<0.01	NC	0.22 ± 0.06	<0.01	0.007 ± 0.002
0462	Kwajalein	Yellowfin	Liver	20 ± 3.8	7.2 ± 0.4	NC	<0.19	0.11 ± 0.03	0.10 ± 0.02
0463	Kwajalein	Yellowfin	Bone	NC	1.7 ± 0.3	NC	<0.16	0.07 ± 0.04	0.024 ± 0.005
0587	Meck	Yellowfin	Light muscle	14 ± 1.0	1.2 ± 0.1	NC	0.16 ± 0.04	<0.009	<0.003
0588	Meck	Yellowfin	Dark muscle	11 ± 1.2	—	NC	0.19 ± 0.05	<0.009	0.006 ± 0.001
0589	Meck	Yellowfin	Liver	18 ± 2.2	18 ± 0.9	NC	<0.12	<0.011	0.013 ± 0.003
0591	Meck	Yellowfin	Light muscle	12 ± 1.8	1.0 ± 0.1	NC	<0.09	<0.004	0.014 ± 0.002
0590	Meck	Yellowfin	Dark muscle	20 ± 1.5	1.8 ± 0.9	NC	<0.10	0.014 ± 0.008	0.11 ± 0.01
0592	Meck	Yellowfin	Liver	19 ± 5.1	—	NC	<0.24	<0.12	0.10 ± 0.01

[a]Error values are one-sigma, counting errors.
[b]NC = not computed.

one wahoo had ^{65}Zn concentrations in their liver tissue of 1.8, 0.5, and 0.4 pCi/g, dry, respectively. Zinc-65 levels were not computed in the other 23 samples because the levels were below the limits of detection. As for the Kwajalein reef fish, no ^{60}Co, ^{155}Eu, or ^{207}Bi was detected in any of the 26 lagoon fish samples analyzed. The highest $^{239,240}Pu$ and ^{90}Sr levels in Kwajalein fish appear to be similar to average levels found in fish from the southern portion of Enewetak Atoll.

Enewetak Atoll – The results of the gamma-spectrum analyses grouped by species – goatfish, convict surgeon, mullet, parrotfish, snapper, grouper, ulua, and tuna – are given in Tables 30 to 36. When some samples in a group of samples which were averaged did not have detectable levels of a radionuclide, the limit of detection value was used. For example, in a group of four samples of eviscerated goatfish from DAVID, three samples had net ^{60}Co values greater than the one standard deviation propagated counting error (0.98, 0.65, and 0.48 pCi/g, dry) and the other sample had a limit of detection of 0.16 pCi/g, dry. For this group of four samples, the mean value was 0.57 pCi/g.

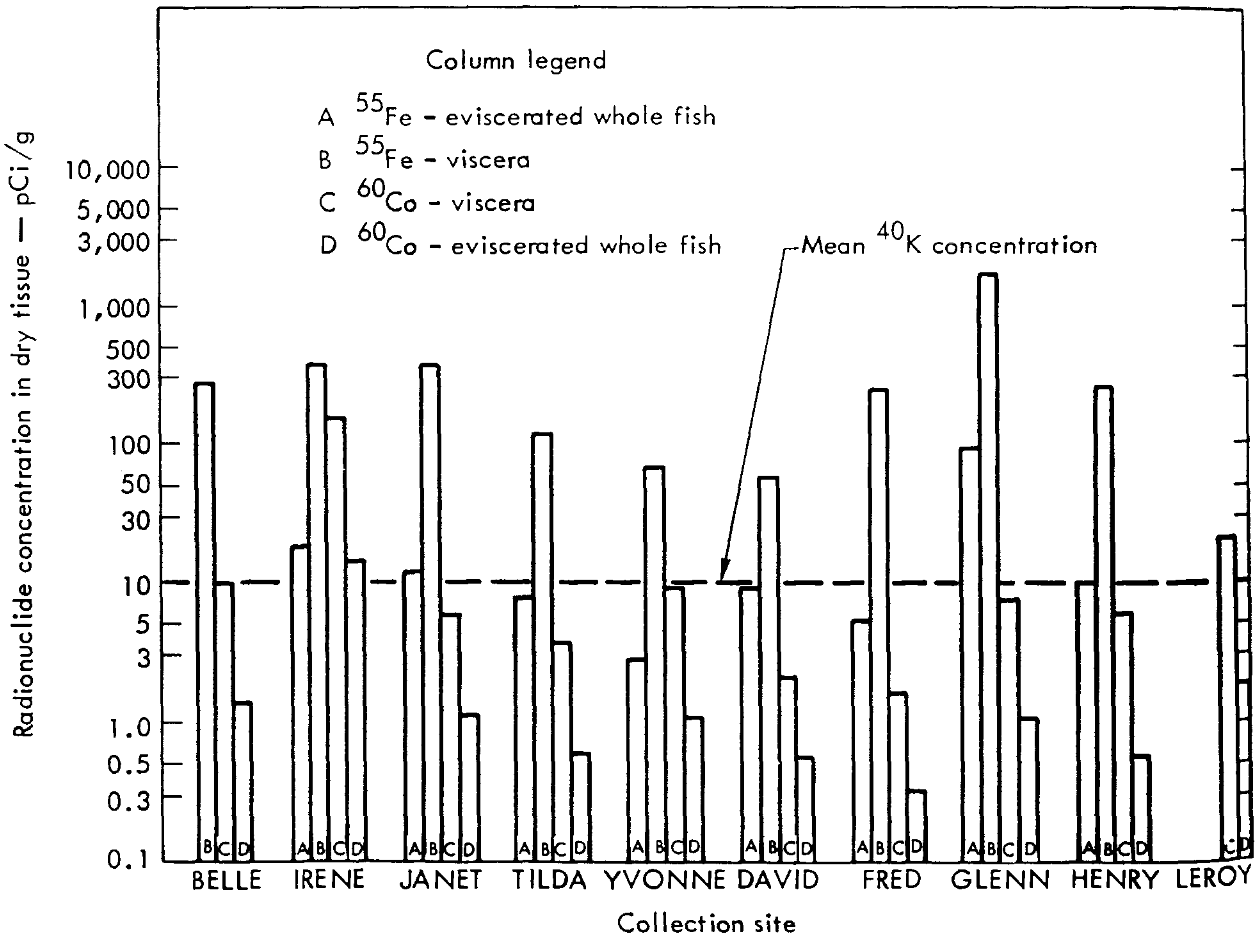

Fig. 42. Average ^{55}Fe and ^{60}Co concentration in goatfish from Enewetak Atoll, October to December, 1972. The ^{40}K value is the mean from all goatfish samples.

Table 30. **Predominant radionuclides in viscera and eviscerated whole goatfish collected at Enewetak Atoll, October to December 1972.**

Island	Tissue[b]	samples	^{40}K	^{55}Fe	^{60}Co	^{137}Cs	^{155}Eu	^{207}Bi	^{90}Sr	$^{239,240}Pu$
			Radionuclide average ± standard deviation[a] in pCi/g, dry							
BELLE	E. whole	1	13 ± 0.8		1.4 ± 0.1	0.12 ± 0.04	<0.06	0.39 ± 0.03	0.31 ± 0.03	0.008 ± 0.001
	Viscera[c]	1	NC[d]	270 ± 7	10 ± 1	<0.34	2.6 ± 0.4	24 ± 5	7 ± 0.3	5 ± 0.4
IRENE	E. whole	1	8.0 ± 0.8	18 ± 0.2	14 ± 0.2	0.98 ± 0.09	0.05	1.4 ± 0.1	0.70 ± 0.03	0.010 ± 0.003
	Viscera	1	16 ± 3.8	390 ± 1.3	160 ± 2	<0.41	<0.46	2.4 ± 0.3	1.5 ± 0.1	1.2 ± 0.04
JANET	E. whole	1	9.4 ± 1.1	12 ± 0.1	1.1 ± 0.1	<0.11	<0.10	0.18 ± 0.05	0.46 ± 0.04	0.02 ± 0.01
	Viscera	1	NC	390 ± 4	6.0 ± 0.6	<0.23	<0.35	0.76 ± 0.19	0.12 ± 0.06	0.03 ± 0.01
TILDA	E. whole	2	10 ± 0.9	8.0 ± 1.3	0.59 ± 0.17	<0.12 ± 0.01	<0.11 ± 0.01	0.57 ± 0.28	0.15 ± 0.14	0.033 ± 0.024
	Viscera	2	12 ± 2.8	130 ± 14	3.8 ± 2.7	<0.11 ± 0.01	<0.17 ± 0.01	0.42 ± 0.18	0.40 ± 0.01	0.45 ± 0.03
YVONNE	E. whole	2	7.8 ± 2.1	3.0 ± 0.2	1.1 ± 0.4	0.21 ± 0.08	<0.05 ± 0.01	0.34 ± 0.01	0.14 ± 0.17	0.047 ± 0.010
	Viscera	2	7.8 ± 0.4	73 ± 13	9.5 ± 3.6	0.32 ± 0.23	0.80 ± 0.99	0.56 ± 0.16	0.57	2.0 ± 1.2
DAVID	E. whole	4	11 ± 1.1	9.8 ± 12	0.57 ± 0.34	<0.11 ± 0.02	<0.10 ± 0.02	0.80 ± 0.70	0.06 ± 0.07	0.004 ± 0.001
	Viscera	4	13 ± 4.1	62 ± 53	2.3 ± 2.3	<0.20 ± 0.03	<0.23 ± 0.17	1.4 ± 1.5	0.61 ± 0.79	0.018 ± 0.062
FRED	E. whole	4	11 ± 3.6	9.6 ± 6.7	0.34 ± 0.03	0.12 ± 0.07	0.13 ± 0.08	0.62 ± 0.53	0.13 ± 0.09	0.022 ± 0.017
	Viscera	4	9.5 ± 7.6	260 ± 280	1.7 ± 0.5	<0.11 ± 0.06	<0.21 ± 0.12	0.79 ± 0.56	0.07 ± 0.05	0.026 ± 0.004
GLENN	E. whole	3	12 ± 0.8	110 ± 170	1.2 ± 0.4	<0.12 ± 0.07	0.22 ± 0.11	0.60 ± 0.33	0.56 ± 0.81	0.005 ± 0.001
	Viscera	2	8.3 ± 1.4	1700 ± 2200	8.1 ± 2.5	<0.29 ± 0.29	0.69 ± 0.28	2.6 ± 0.5	0.64	0.37 ± 0.37
HENRY	E. whole	2	8.6 ± 0.4	11 ± 7.8	0.59 ± 0.27	0.20 ± 0.13	<0.12 ± 0.04	1.4 ± 0.4	0.08 ± 0.07	0.004 ± 0.001
	Viscera	1	9.7 ± 1.5	270 ± 3.7	5.4 ± 0.3	0.22 ± 0.08	<0.15	2.5 ± 0.1	0.20	0.012 ± 0.003
LEROY	E. whole	1	9.0 ± 1.1	20 ± 1.4	1.9 ± 0.2	<0.07	0.21 ± 0.04	1.6 ± 0.1	0.09 ± 0.001	0.002 ± 0.001
	Viscera	1	9.8 ± 1.3	700 ± 7	23 ± 2	<0.14	0.62 ± 0.30	5.1 ± 0.2	0.04 ± 0.01	0.032 ± 0.008

[a]Single sample error values are one-sigma counting errors, while error values for two or more samples are one sample standard deviation without consideration of counting error.

[b]Eviscerated whole is the entire fish, less the viscera.

[c]This sample also contained ^{241}Am (3.8 pCi/g, dry). Two other samples of viscera from goatfish collected at Yvonne had 0.54 pCi of ^{241}Am/g, dry.

[d]NC = not computed.

Table 31. Predominant radionuclides in convict surgeon collected at Enewetak Atoll, October to December 1972.

Island	Tissue	No. of samples	Radionuclide average ± deviation[a] in pCi/g, dry							
			^{40}K	^{55}Fe	^{60}Co	^{137}Cs	^{155}Eu	^{207}Bi	^{90}Sr	$^{239,240}Pu$
BELLE	E. whole	3	11 ± 3.1	12 ± 0.6	2.3 ± 0.4	1.1 ± 0.2	< 0.09	0.11 ± 0.05	0.51 ± 0.03	0.07 ± 0.08
	Viscera	3[b]	14 ± 11	150 ± 50	16 ± 2.4	1.0 ± 0.8	0.49 ± 0.09	2.0 ± 1.6	1.9 ± 0.7	1.9 ± 0.4
IRENE	E. whole	1	13 ± 1.1	10 ± 0.1	28 ± 0.4	6.7 ± 0.2	< 0.14	< 0.15	1.2 ± 0.06	0.11 ± 0.01
	Viscera	1	14 ± 2.0	160 ± 12	210 ± 3	6.0 ± 0.4	5.8 ± 0.3	1.1 ± 0.2	17 ± 1	15 ± 1.5
JANET	E. whole	2	9.6 ± 0.7	5.4 ± 2.0	0.22 ± 0.02	0.23 ± 0.03	< 0.04 ± 0.01	0.03 ± 0.01	0.31 ± 0.01	0.03 ± 0.03
	Viscera	2	10 ± 0.8	28 ± 4.2	0.96 ± 0.20	0.16 ± 0.12	0.17 ± 0.10	0.20 ± 0.01	0.17 ± 0.04	0.36 ± 0.25
URSULA	E. whole	3	8.9 ± 1.2	3.0 ± 0.9	0.22 ± 0.08	0.17 ± 0.07	< 0.04 ± 0.01	< 0.02 ± 0.01	0.25 ± 0.28	0.071 ± 0.064
	Viscera	3	14 ± 4.8	19 ± 7.8	0.98 ± 0.37	0.19 ± 0.10	0.18 ± 0.15	0.17 ± 0.09	0.23 ± 0.06	0.81 ± 0.02[a]
YVONNE	E. whole	3	8.2 ± 0.7	1.9 ± 0.8	1.2 ± 0.6	0.58 ± 0.24	< 0.04 ± 0.01	< 0.02 ± 0.01	0.18 ± 0.22	0.022 ± 0.016
	Viscera	3	10 ± 3.3	2.8 ± 6.4	5.2 ± 1.6	0.72 ± 0.25	0.20 ± 0.09	0.33 ± 0.24	0.17 ± 0.04	0.60 ± 0.43
DAVID	E. whole	4	10 ± 3.4	1.6 ± 0.7	0.21 ± 0.09	0.13 ± 0.05	< 0.13 ± 0.08	< 0.08 ± 0.05	0.08 ± 0.10	0.026 ± 0.018
	Viscera	4	17 ± 3.4	17 ± 4.3	2.1 ± 2.1	0.14 ± 0.08	< 0.16 ± 0.13	0.21 ± 0.04	0.42 ± 0.23	0.031 ± 0.010
FRED	E. whole	3	11 ± 2.9	0.33 ± 0.2	< 0.10 ± 0.05	0.11 ± 0.04	< 0.09 ± 0.05	< 0.05 ± 0.03	0.02 ± 0.01	0.08 ± 0.09
	Viscera	3	12 ± 3.8	3.1 ± 0.8	0.57 ± 0.19	0.09 ± 0.04	< 0.10 ± 0.05	< 0.10 ± 0.05	0.05 ± 0.02	0.031 ± 0.034
GLENN	E. whole	1	11 ± 1.2	—	0.4 ± 0.40	0.18 ± 0.03	< 0.17	0.06 ± 0.02	< 0.01	0.90 ± 0.02
	Viscera	1	16 ± 0.7	12 ± 0.7	3.3 ± 0.08	0.15 ± 0.04	< 0.06	0.74 ± 0.04	< 0.20	0.05 ± 0.01
HENRY	E. whole	3	8.9 ± 0.7	8.2 ± 0.5	0.47 ± 0.32	0.10 ± 0.05	< 0.09 ± 0.07	< 0.15 ± 0.09	0.02 ± 0.01	0.074 ± 0.12
	Viscera	2	11 ± 1.3	78 ± 3.5	2.0 ± 2.6	0.15 ± 0.09	< 0.13 ± 0.02	0.96 ± 0.02	0.02 ± 0.01	0.045 ± 0.004
LEROY	E. whole	3	10 ± 3.5	16 ± 6.0	1.0 ± 0.3	0.16 ± 0.05	< 0.08 ± 0.06	0.25 ± 0.07	0.14 ± 0.07	0.008 ± 0.002
	Viscera	2	13 > 1	160 + 40	3.4 ± 4.2	0.26 ± 0.20	< 0.13	3.1 ± 1.7	0.24 ± 0.03	0.27 ± 0.15

[a]Single sample error values are one-sigma counting errors, while error values for two or more samples are one sample standard deviation without consideration of counting error.

[b]Two samples of viscera from convict surgeon collected at BELLE had an average ^{241}Am level of 0.74 pCi/g, dry. Americium-241 was also found in two samples of viscera from URSULA (average, 0.34 pCi/g, dry) and one sample of viscera from YVONNE (3.7 pCi/g, dry).

Table 32. Predominant radionuclides in mullet collected at Enewetak Atoll, October to December 1972.

Radionuclide, average ± standard deviation[a] in pCi/g, dry

Table 32. **Predominant radionuclides in mullet collected at Enewetak Atoll, October to December 1972.**

Island	Tissue	No. of samples	Radionuclide, average ± standard deviation[a] in pCi/g, dry: ^{40}K	^{55}Fe	^{60}Co	^{137}Cs	^{155}Eu	^{207}Bi	^{90}Sr	$^{239,240}Pu$
BELLE	Muscle	1	15 ± 1.2	6.8 ± 0.2	3.7 ± 0.2	0.63 ± 0.09	< 0.10	0.13 ± 0.05	—	0.006 ± 0.001
	E. whole	3	6.9 ± 2.3	7.1 ± 0.6	2.8 ± 0.3	0.34 ± 0.10	< 0.05 ± 0.01	< 0.05 ± 0.03	0.16 ± 0.04	0.04 ± 0.03
	Viscera[b]	3	4.5 ± 0.4	100 ± 60	9.4 ± 2.3	1.5 ± 0.4	3.0 ± 0.2	0.61 ± 0.16	6.1 ± 1.8	8.0 ± 2.6
IRENE	Muscle	1	15 ± 1.3	14 ± 0.56	20 ± 0.5	4.3 ± 0.2	< 0.14	0.20 ± 0.09	0.01	0.020 ± 0.003
	E. whole	1	5.2 ± 1.0	13 ± 0.4	18 ± 0.5	1.8 ± 0.2	< 0.14	< 0.14	0.06 ± 0.01	0.19 ± 0.01
	Viscera	1	3.5 ± 1.6	220 ± 0.1	90 ± 1.1	9.8 ± 0.5	22 ± 0.3	2.2 ± 0.2	< 0.02	24 ± 0.5
JANET	Muscle	2	10 ± 1.5	1.3 ± 0.4	0.44 ± 0.40	0.13 ± 0.03	< 0.11 ± 0.06	0.05 ± 0.03	0.05 ± 0.01	0.001 ± 0.001
	E. whole	2	3.9 ± 1.3	1.4 ± 0.4	0.23 ± 0.11	0.15 ± 0.08	< 0.10 ± 0.07	< 0.05 ± 0.03	0.03 ± 0.03	0.017 ± 0.018
	Viscera	2	3.9 ± 0.1	19 ± 0.7	1.1 ± 0.6	0.06 ± 0.04	< 0.09 ± 0.06	< 0.04 ± 0.01	0.46 ± 0.47	0.29 ± 0.30
TILDA	Muscle	1	17 ± 2	1.9 ± 0.3	< 0.19	< 0.12	< 0.15	< 0.08	< 0.03	< 0.027
	E. whole	2	7.4 ± 3.4	1.3 ± 0.5	< 0.17 ± 0.02	< 0.10 ± 0.01	< 0.15 ± 0.01	< 0.07 ± 0.02	0.05 ± 0.05	5.8 ± 11
	Viscera	2	4.7 ± 0.9	13 ± 16	0.79 ± 0.13	0.08 ± 0.02	0.18 ± 0.03	0.06 ± 0.01	0.56 ± 0.16	0.63 ± 0.29
YVONNE	E. whole	3	6.6 ± 1.8	0.95 ± 0.82	0.95 ± 0.61	0.26 ± 0.28	< 0.13 ± 0.04	< 0.07 ± 0.01	0.03 ± 0.02	0.016 ± 0.016
	Viscera	3	5.2 ± 1.9	11 ± 8.6	4.9 ± 2.0	0.54 ± 0.70	2.2 ± 1.8	0.12 ± 0.04	0.70 ± 0.27	3.8 ± 4.7
GLENN	E. whole	1	7.2 ± 1.6	—	0.85 ± 0.09	< 0.10	< 0.16	< 0.08	< 0.01	0.63 ± 0.01
	Viscera	1	5.5 ± 1.2	28 ± 1.1	3.3 ± 0.2	0.16 ± 0.05	0.17 ± 0.03	1.8 ± 0.1	0.26 ± 0.02	0.30 ± 0.02
HENRY	E. whole	4	6.3 ± 1.1	2.7 ± 0.8	0.73 ± 0.11	0.04 ± 0.02	0.10 ± 0.06	< 0.04 ± 0.01	0.07 ± 0.07	0.011 ± 0.010
	Viscera	4	4.2 ± 0.5	21	2.9 ± 0.6	< 0.07 ± 0.05	< 0.11 ± 0.07	0.13 ± 0.05	0.01 ± 0.01	0.58 ± 0.88
LEROY	Muscle	2	11 ± 1.6	4.1 ± 0.8	1.1 ± 0.2	0.12 ± 0.02	< 0.11 ± 0.08	< 0.06 ± 0.04	0.07 ± 0.04	0.34 ± 0.48
	E. whole	3	6.6 ± 2.9	32 ± 48	1.2 ± 0.9	0.09 ± 0.04	< 0.10 ± 0.04	< 0.05 ± 0.03	0.04 ± 0.02	0.004 ± 0.001
	Viscera	3	3.6 ± 0.0	92 ± 63	3.4 ± 1.0	< 0.11 ± 0.01	0.20 ± 0.05	0.73 ± 0.18	0.38 ± 0.22	0.33 ± 0.14

[a] Single sample error values are one-sigma counting errors, while error values for two or more samples are one sample standard deviation without consideration of counting error.

[b] The viscera samples from BELLE also had an average ^{241}Am level of 4.0 pCi/g, dry. One viscera sample from TILDA and three from YVONNE also had ^{241}Am levels of 0.22 and 1.6 pCi/g, dry, respectively.

Table 33. Predominant radionuclides in parrotfish collected at Enewetak Atoll, October to December 1972.

Island	Tissue	No. of samples	Radionuclide, average ± standard deviation[a] in pCi/g, dry: ^{40}K	^{55}Fe	^{60}Co	^{137}Cs	^{155}Eu	^{207}Bi	^{90}Sr	$^{239,240}Pu$
BELLE	E. whole	1	12 ± 1.1	13 ± 0.4	4.4 ± 0.1	3.0 ± 0.1	<0.06	<0.04	0.75 ± 0.05	0.02 ± 0.002
	Viscera[b]	1	21 ± 5.3	150 ± 5.0	13 ± 1.0	2.5 ± 0.5	1.2 ± 0.6	<0.25	5.3 ± 0.30	2.9 ± 0.30
JANET	Muscle	1	22 ± 1.6	0.36 ± 0.04	<0.23	0.98 ± 0.09	<0.12	<0.07	<0.08	0.14 ± 0.12
	Viscera	1	5.8 ± 1.0	14 ± 0.5	0.39 ± 0.12	0.25 ± 0.07	0.17 ± 0.08	<0.07	1.3 ± 0.1	0.24 ± 0.01
	Bone	1	NC[c]	1.3 ± 0.8	<0.34	<0.28	<0.44	<0.18	0.27 ± 0.12	<0.22
TILDA	Muscle	1	22 ± 1.6	0.12 ± 0.07	<0.20	0.42 ± 0.07	<0.10	<0.02	<0.03	0.05 ± 0.01
	Viscera	1	6.7 ± 0.8	4.9 ± 0.1	0.38 ± 0.10	0.12 ± 0.01	0.20 ± 0.06	<0.05	<0.18	0.45 ± 0.01
	Bone	1	NC	0.76 ± 0.20	<0.18	<0.13	<0.02	<0.11	<0.12	0.018 ± 0.003
YVONNE	Muscle	2	19 ± 6.4	0.15 ± 0.04	<0.16 ± 0.03	0.49 ± 0.30	<0.10 ± 0.05	<0.06 ± 0.01	0.02 ± 0.01	0.026 ± 0.021
	Viscera	2	6.7 ± 0.8	7.5 ± 3.2	2.5 ± 2.9	0.20 ± 0.16	0.88 ± 0.88	0.69 ± 0.87	0.42 ± 0.39	1.8 ± 2.0
	Bone	2	8.1 ± 0.7	2.0 ± 2.2	0.30 ± 0.16	<0.12 ± 0.01	<0.07 ± 0.01	<0.08 ± 0.01	0.07 ± 0.03	2.5
DAVID	Muscle	2	14 ± 5.7	<1.7	<0.05 ± 0.02	0.07 ± 0.06	<0.04 ± 0.01	<0.03 ± 0.01	<0.18	<0.01
	Viscera	2	9.4 ± 3.7	4.6 ± 3.6	0.33 ± 0.22	<0.09 ± 0.04	<0.10 ± 0.03	0.10 ± 0.02	0.17 ± 0.21	0.19 ± 0.21
	Bone	2	11 ± 1.4	<5.5	<0.22 ± 0.13	<0.16 ± 0.10	<0.28 ± 0.18	<0.11 ± 0.06	2.2 ± 2.4	0.033 ± 0.008
FRED	Muscle	1	22 ± 1.5	2.7 ± 0.7	<0.23	1.8 ± 0.1	<0.11	<0.07	<0.01	<0.019
	Viscera	1	3.8 ± 0.9	170 ± 12	0.47 ± 0.12	<0.11	<0.11	1.4 ± 0.1	0.07 ± 0.05	0.18 ± 0.02
	Bone	1	14 ± 22	2.4 ± 0.1	<0.23	<0.23	<0.21	<0.14	0.15 ± 0.05	0.004 ± 0.002
HENRY	Muscle	1	27 ± 2.2	5.0 ± 0.3	<0.20	0.40 ± 0.10	<0.24	0.11	<0.01	—
	Bone	1	NC	—	0.20 ± 0.03	0.07 ± 0.02	<0.05	0.02	0.07 ± 0.01	<0.004
LEROY	Muscle	1	23 ± 1.4	10 ± 0.9	<0.09	0.28 ± 0.05	<0.08	<0.04	<0.019	<0.005
	Viscera	1	3.9 ± 1.0	300 ± 3.2	1.9 ± 0.2	<0.07	0.35 ± 0.11	1.3 ± 0.1	1.5 ± 0.1	0.45 ± 0.30

[a]Single sample error values are one-sigma counting errors, while error values for two or more samples are one sample standard deviation without consideration of counting error.

[b]This sample also had an ^{241}Am level of 1.4 pCi/g, dry. Americium-241 was also detected in a viscera sample from TILDA (0.21 pCi/g, dry) and one viscera sample from YVONNE (0.58 pCi/g, dry).

[c]NC = not computed.

Table 34. Predominant radionuclides in single, pooled samples of snappers collected at Enewetak Atoll, October to December 1972.

Sample number	Island	Tissue	No. of fish	Species (size in mm)	Radionuclide, average ± standard deviation[a] in pCi/g, dry: ^{40}K	^{55}Fe	^{60}Co	^{137}Cs	^{207}Bi	^{90}Sr	$^{239,240}Pu$
0447	IRENE	Muscle	4	L. monostigmus	21 ± 2.5	7.2 ± 1.0	11 ± 0.4	2.1 ± 0.17	<0.14	<0.84	0.063
0448		Remainder	4	(140-240)	8.1 ± 1.0	36 ± 0.3	35 ± 0.5	0.72 ± 0.17	0.22 ± 0.10	0.79 ± 0.03	0.068 ± 0.006
0488	TILDA	Muscle	2	L. monstigmus	17 ± 1.7	6.5 ± 0.6	<0.28	0.32 ± 0.09	<0.09	0.23	<0.059
0489		Viscera	2	(220, 225)	13 ± 1.4	120 ± 4.9	<0.45	<0.28	0.20	—	0.59 ± 0.02
0490		Remainder	2		9.8 ± 1.1	6.5	<0.17	<0.11	0.06	1.4 ± 0.1	0.002
0575	TILDA	Muscle	4	L. monostigmus	NC[b]	4.7 ± 0.3	<0.15	<0.17	<0.15	0.11	—
0576		Liver	4	(195-333)	19 ± 5.7	640 ± 13	3.1 ± 0.4	<0.32	<0.23	2.9 ± 0.12	0.045 ± 0.006
0577		Bone	4		3.4 ± 0.9	2.6 ± 0.5	<0.07	0.10 ± 0.03	<0.03	0.25	<0.013
0578		Viscera	4		4.5 ± 0.8	37 ± 0.8	0.28 ± 0.05	<0.05	<0.04	0.004 ± 0.002	0.023 ± 0.001
0579		Skin	4		4.6 ± 1.2	4.3 ± 0.6	<0.07	<0.05	<0.03	<0.23	0.44 ± 0.03
0580	TILDA	Muscle	1	L. kallopterus	18 ± 1.3	0.50 ± 0.06	0.06 ± 0.06	0.14 ± 0.03	0.12 ± 0.03	0.01 ± 0.004	0.005 ± 0.001
0581		Viscera	1	(290)	19 ± 3.2	19 ± 2.3	0.98 ± 0.22	<0.16	<0.14	0.29 ± 0.06	0.10 ± 0.01
0582		Bone	1		NC	<0.33	<0.39	<0.28	<0.21	<0.92	<0.042
0437	ELMER	Muscle	1	A. virescens	20 ± 1.2	2.8 ± 0.3	0.36 ± 0.05	0.13 ± 0.05	0.34 ± 0.04	<0.10	0.003
0438		Viscera	1	(360)	16 ± 3.0	310 ± 7.0	4.9 ± 0.3	<0.15	0.42 ± 0.11	<1.0	—
0400	FRED	Muscle	1	L. kallopterus	16 ± 1.4	3.1 ± 0.1	<0.15	<0.10	<0.07	0.01 ± 0.001	<0.001
0401		Liver	1	(300)	NC	—	5.8 ± 0.8	<0.49	1.5 ± 0.4	0.44 ± 0.28	0.09 ± 0.04
0398	GLENN	Muscle	1	A. furcatus	25 ± 2.3	8.3 ± 0.2	0.68 ± 0.11	0.31 ± 0.13	1.9 ± 0.1	0.011 ± 0.004	0.006 ± 0.001
0397		Viscera	1	(302)	NC	360 ± 8.0	22 ± 0.51	<0.25	2.0 ± 0.2	<1.3	<0.07

[a]Single sample error values are one-sigma counting errors, while error values for two or more samples are one sample standard deviation without consideration of counting error.

[b]NC = not computed.

Table 35. Predominant radionuclides in single, pooled samples of groupers[a] collected at Enewetak Atoll, October to December 1972.

Sample number	Island	Tissue	No. of fish	Radionuclide, average ± standard deviation[b] in pCi/g, dry						
				^{40}K	^{55}Fe	^{60}Co	^{137}Cs	^{207}Bi	^{90}Sr	$^{239,240}Pu$
0543	TILDA	E. whole	2	NC[c]	1.3 ± 0.3	< 0.17	< 0.11	< 0.09	< 0.08	< 0.003
0544		Viscera	2	14 ± 3.8	94 ± 3.5	1.1 ± 0.3	< 0.19	< 0.17	< 0.70	< 0.043
8022	YVONNE	Muscle	1	18 ± 1.4	5.6 ± 0.1	< 0.74 ± 0.12	0.33 ± 0.09	2.5 ± 0.1	< 0.03	< 0.001
8023		Viscera	1	19 ± 2.7	430 ± 1.3	36 ± 0.6	< 0.24	4.6 ± 0.2	0.10 ± 0.07	0.036 ± 0.019
8024		Bone	1	NC	3.1 ± 0.2	< 0.23	< 0.15	< 0.13	< 0.04	0.50 ± 0.04
0403	FRED	Muscle	1	15 ± 1.1	0.47 ± 0.05	< 0.14	0.53 ± 0.07	2.1 ± 0.1	< 0.03	< 0.014
0404		Liver	1	3.1 ± 0.8	160 ± 0.5	2.1 ± 0.1	< 0.05	1.1 ± 0.1	0.14 ± 0.01	0.11 ± 0.04
0405	FRED	Muscle	1	15 ± 1.5	13 ± 0.3	< 0.43 ± 0.11	0.51 ± 0.09	0.63 ± 0.07	< 0.01	0.007 ± 0.001
0406		Liver	1	NC	4900 ± 50	94 ± 2	< 0.53	< 0.40	< 0.22	0.038 ± 0.007
0407		Bone	1	9.7 ± 3.1	13	2.0 ± 0.3	< 0.18	< 0.13	0.09 ± 0.04	0.034 ± 0.003
0369	FRED	E. whole	3	8.4 ± 1.2	1.1 ± 0.1	< 0.10	< 0.06	< 0.06	< 0.02	0.003 ± 0.001
0370		Viscera	3	NC	—	1.3 ± 0.2	< 0.12	< 0.10	0.05 ± 0.01	0.13 ± 0.01

[a]All groupers were Epinephelus sp. except one grouper from FRED (0405-0407) which was variola louti.

[b]Error values are one-sigma, counting errors.

[c]NC = not computed.

Table 36. Predominant radionuclides in single, pooled samples of ulua[a] collected at Enewetak Atoll, October to December 1972.

Table 36. Predominant radionuclides in single, pooled samples of ulua[a] collected at Enewetak Atoll, October to December 1972.

Sample number	Island	Tissue	No. of fish	Radionuclide, average ± standard deviation[b] in pCi/g, dry: ^{40}K	^{55}Fe	^{60}Co	^{137}Cs	^{207}Bi	^{90}Sr	$^{239,240}Pu$
0545	TILDA	Muscle	1	15 ± 1.0	5.8 ± 0.2	0.06	0.24 ± 0.05	0.25 ± 0.04	<0.11	<0.001
0546		Viscera	1	9.6 ± 1.1	—	0.68 ± 0.08	<0.08	11 ± 0.2	0.11 ± 0.01	0.011 ± 0.001
0547		Bone	1	3.2 ± 1.1	4.0 ± 0.2	<0.05	0.13 ± 0.05	3.0 ± 0.11	0.37 ± 0.05	0.59 ± 0.01
8032	YVONNE	Muscle	2	18 ± 1.6	10 ± 0.1	1.3 ± 0.12	0.46 ± 0.1	0.33 ± 0.11	0.04	—
8033		Viscera	2	15 ± 1.8	350 ± 1	13 ± 2.1	<0.15	2.5 ± 0.15	<0.07	0.032 ± 0.006
8034		Bone	2	NC[c]	3.3 ± 0.2	<0.20	0.20	0.62 ± 0.19	0.10 ± 0.04	<0.016
0457	ELMER	Muscle	1	19 ± 1.2	25 ± 0.3	1.5 ± 0.15	0.54 ± 0.08	0.92 ± 0.06	<0.11	<0.002
0456		Viscera	1	NC	33 ± 1.8	7.5 ± 0.75	<0.27	2.8 ± 0.27	<1.5	<0.002 ± 0.001
0434	FRED	Muscle	1	21 ± 1.4	150 ± 0.6	2.2 ± 0.19	0.36 ± 0.10	5.7 ± 0.13	0.05 ± 0.01	0.003 ± 0.001
0435		Viscera	1	NC	510 ± 3	8.9 ± 0.52	<0.64	206 ± 6.0	0.24 ± 0.05	15 ± 0.3
0266	HENRY	E. whole	2	16 ± 2.6	20 ± 0.6	3.0 ± 0.39	1.0 ± 0.29	248 ± 1.5	0.48 ± 0.02	0.004 ± 0.001

[a] All ulua were Caranx melampygus except fish from HENRY, which were C. sexfasciatus.

[b] Error values are one-sigma counting errors.

[c] NC = not computed.

Goatfish – The results of the radiological analyses of the goatfish tissues are given in Table 30. Each sample was made up of the tissues from an average pool of five fish. Although four species of goatfish of various size classes were present in the samples, no apparent species or size differences in radionuclide content were noted and samples from all species and sizes were pooled to form the data in Table 30. Seventy-five percent of the goatfish collected for samples were Mulloidichthys samoensis.

The two most prevalent radionuclides found in the goatfish were ^{55}Fe and ^{60}Co, followed by ^{40}K, ^{207}Bi, ^{137}Cs, and ^{155}Eu. Americium-241 was found in 3 of 19 viscera samples, 1 from BELLE and 2 from YVONNE, while ^{90}Sr, ^{55}Fe, and ^{239,240}Pu were found in most samples.

Potassium-40 levels showed little variability between sampling locations or between eviscerated whole fish and viscera samples. The ^{40}K values for all areas and the two tissue types averaged 9.8 pCi/g, dry. These levels are similar to ^{40}K levels found in goatfish collected from other areas and times in the Central Pacific and indicate the natural levels of ^{40}K in goatfish from that area.

Iron-55 and ^{60}Co were the predominant man-produced radionuclides in the

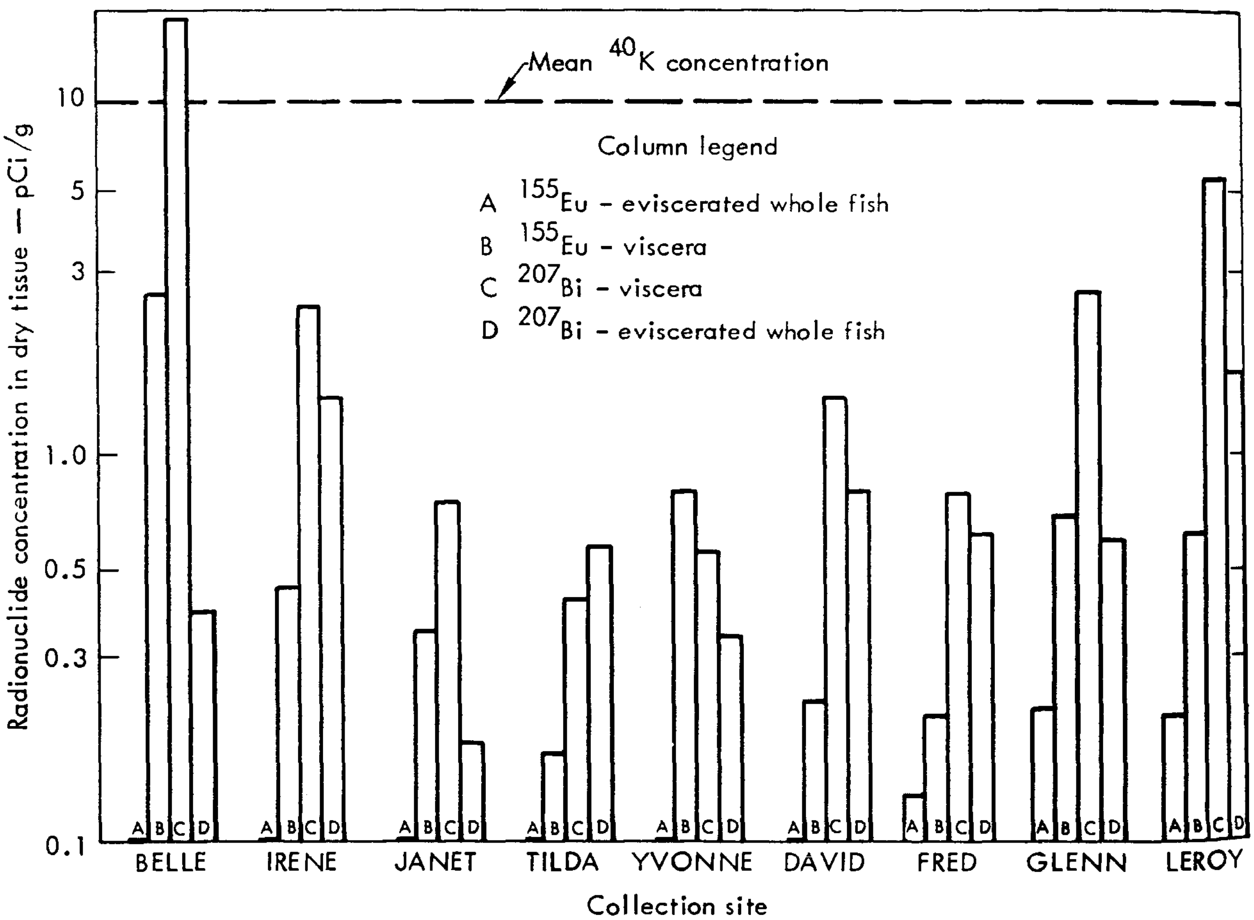

Fig. 43. Average ^{40}K, ^{155}Eu, and ^{207}Bi concentration in goatfish from Enewetak Atoll, October to December, 1972. The ^{40}K value is the mean of all goatfish samples.

goatfish. A comparison of the amounts of ^{40}K, ^{55}Fe, and ^{60}Co in goatfish is shown in Fig. 42. Iron-55 and ^{60}Co were higher in the viscera than in the eviscerated whole fish by a factor of about 20 for ^{55}Fe and 7 for ^{60}Co. The viscera sample from goatfish collected at IRENE had the highest levels of ^{60}Co (160 pCi/g, dry), while the goatfish viscera from GLENN had the highest ^{55}Fe level (1700 pCi/g, dry). Goatfish from LEROY, JANET, and YVONNE also had comparatively high levels of ^{55}Fe, while goatfish from LEROY, BELLE, YVONNE, and GLENN had higher than average levels of ^{60}Co for goatfish collected at Enewetak.

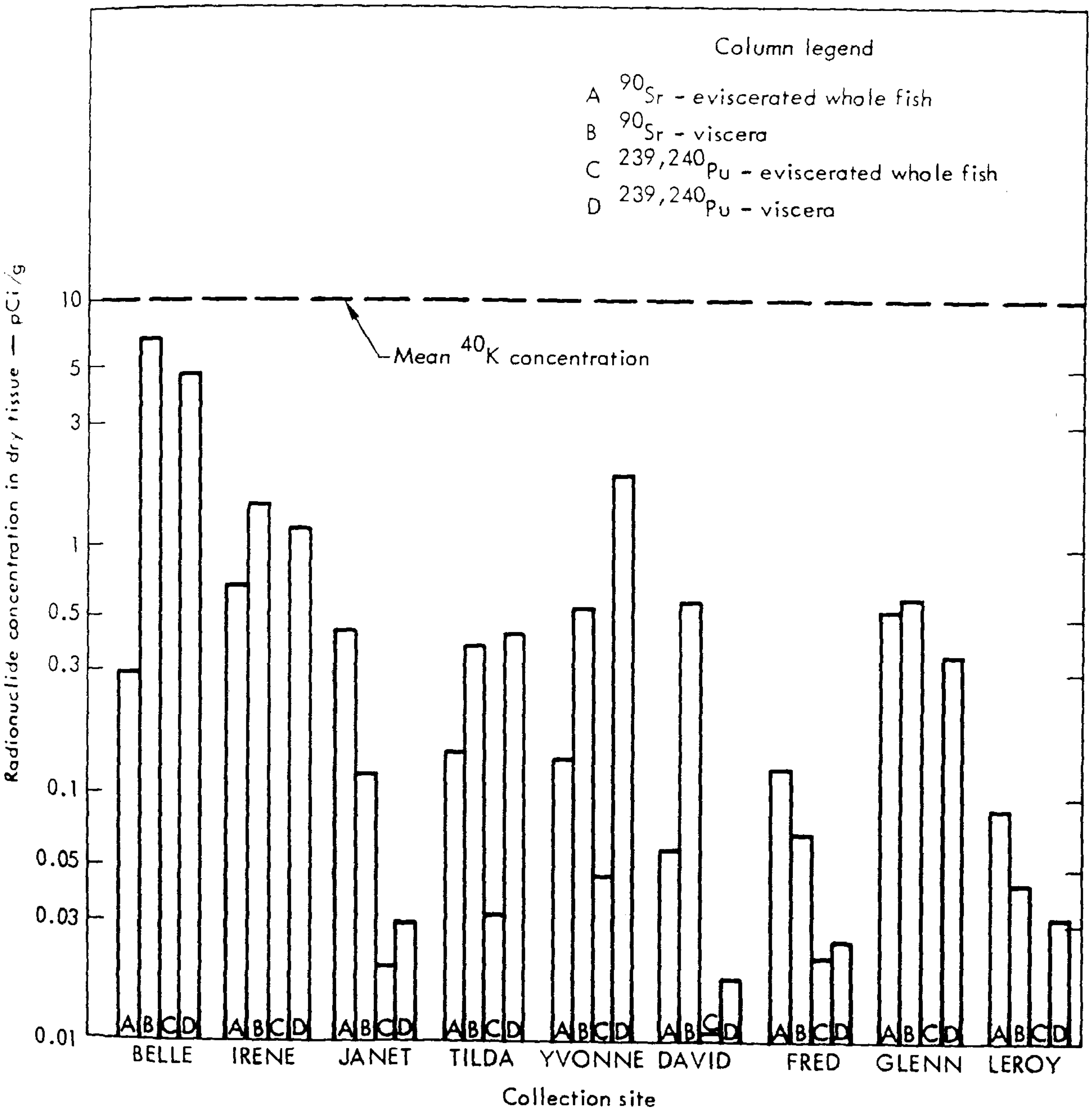

Fig. 43a. Average ^{90}Sr and $^{239,240}Pu$ concentration in goatfish from Enewetak Atoll, October to December, 1972. The ^{40}K value is the mean for all goatfish samples.

Bismuth-207 was detected in most samples, but ^{137}Cs and ^{155}Eu were detected in less than 50% of the samples. A comparison between ^{155}Eu and ^{207}Bi levels in the goatfish is shown in Fig. 43. Levels of ^{207}Bi, ^{155}Eu, and ^{137}Cs were generally less than 3, 0.8, and 0.4 pCi/g, dry, respectively. The viscera samples from goatfish collected at BELLE had the highest levels of ^{207}Bi (24 pCi/g, dry) and ^{155}Eu (2.6 pCi/g, dry). Cesium-137 was highest in eviscerated whole goatfish from IRENE (0.98 pCi/g, dry). Europium-155 and ^{207}Bi concentrations were higher in the viscera of the goatfish than in the eviscerated whole fish by factors of up to 43 for ^{155}Eu and 62 for ^{207}Bi, but the average ratio was less than 5 for ^{155}Eu and 5 for ^{207}Bi. Cesium-137 levels were similar in the two tissue types analyzed.

Strontium-90 and Pu data indicate that higher levels are found in the viscera than in the eviscerated whole fish. The highest level of these radionuclides is found in the viscera of goatfish from BELLE (^{90}Sr = 7.0 pCi/g), (^{239,240}Pu = 5.0 pCi/g). Goatfish from the northeast sector (BELLE to YVONNE) of the Atoll generally had higher levels of these two radionuclides than fish from the southwest sector (DAVID to LEROY). Strontium-90 and ^{239,240}Pu (viscera samples) concentrations averaged less than 0.5 and 0.05 pCi/g, dry, in the northern and southern sectors of the atoll, respectively.

Convict Surgeon — The results of the radiological analyses of the convict surgeon samples are given in Table 31. Each sample was made up of the tissues from an average pool of 15 fish, and all stations except IRENE and GLENN had 2 or more samples of both eviscerated whole fish and viscera. All fish were one species, Acanthurus triostegus. No differences due to size of fish pooled for a sample were noted and samples from all size classes were pooled to form the data in Table 31.

Naturally occurring ^{40}K and man-made ^{55}Fe and ^{60}Co were the predominant radionuclides in the convict surgeon. Cesium-137, ^{155}Eu, and ^{207}Bi were also present in the samples from 50% or more of the collection sites. Americium-241 was found in 5 of 24 viscera samples, 2 each from BELLE and YVONNE and 1 from IRENE, while ^{239,240}Pu and ^{90}Sr were found in most samples. Potassium-40 levels showed little variability between sampling sites. The viscera samples, however, had a greater ^{40}K concentration (13 pCi/g, dry) than did the eviscerated whole fish sample (9.9 pCi/g, dry). Iron-55 concentrations were about 10 times higher in the viscera than in the eviscerated whole fish and were highest in the viscera of convict surgeon from LEROY and IRENE (160 pCi/g, dry). Viscera samples from convict surgeon collected from YVONNE to GLENN averaged < 10 pCi/g, dry. The viscera and eviscerated whole fish samples from convict surgeon collected from the Seminole Crater area of IRENE had the highest ^{60}Co content (210 and 28 pCi/g, dry, respectively) of any of the convict surgeon samples. The viscera of convict surgeon from BELLE had 16 pCi of ^{60}Co/g, dry, and all other samples had < 5.2 pCi/g, dry. The levels of ^{60}Co, ^{55}Fe, and ^{40}K in the convict surgeon are compared in Fig. 44.

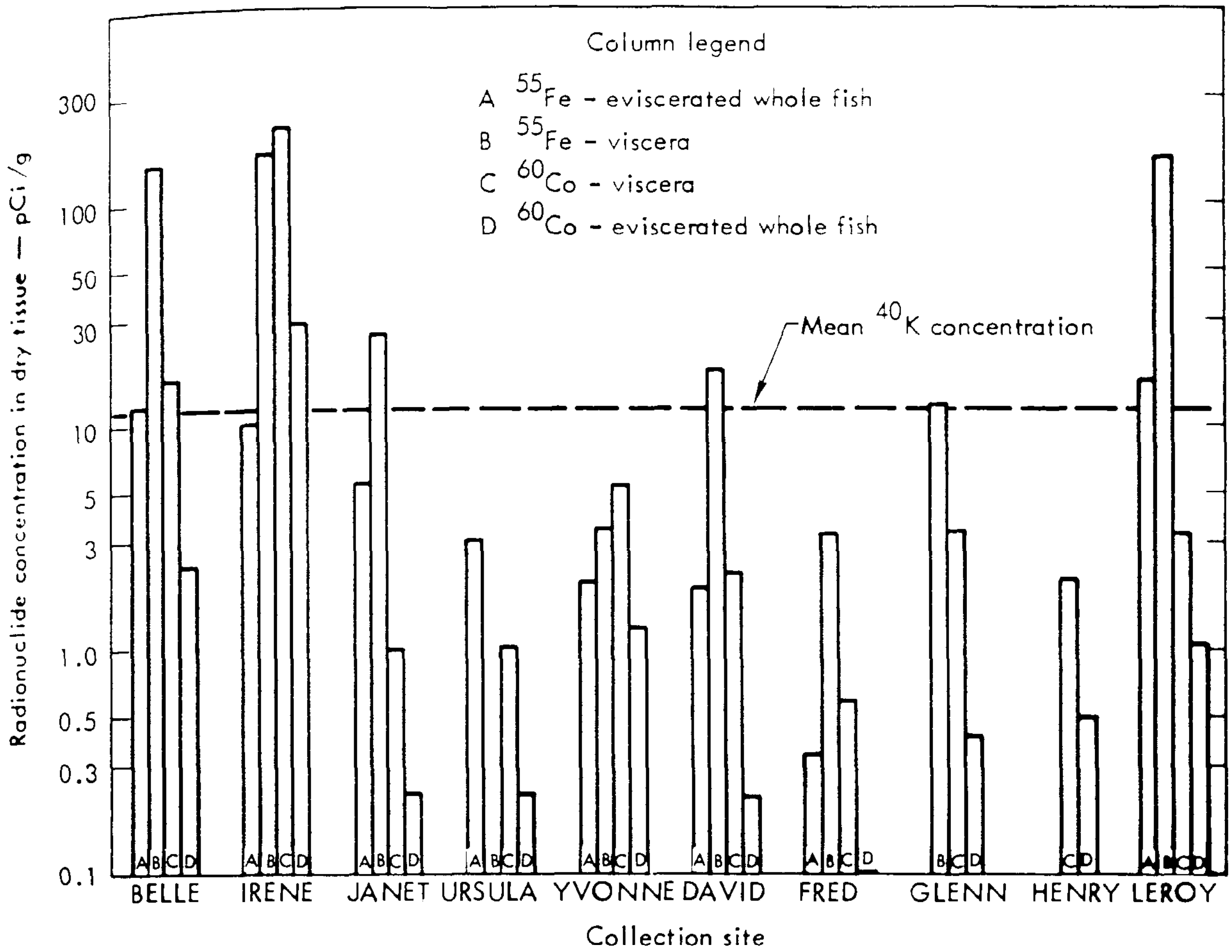

Fig. 44. Average ^{40}K, ^{55}Fe, ^{60}Co concentration in convict surgeon from Enewetak Atoll, October to December, 1972. The ^{40}K value is the mean for all convict surgeon samples.

Cesium-137, ^{155}Eu, and ^{207}Bi concentrations were less than 7 pCi/g, dry, in all samples and averaged less than 1 pCi/g, dry. The highest levels of ^{137}Cs and ^{155}Eu were found in convict surgeon collected from IRENE, while ^{207}Bi was highest in convict surgeon from LEROY. A comparison of ^{137}Cs, ^{155}Eu, and ^{207}Bi levels in the convict surgeon is shown in Fig. 45.

Iron-55, ^{60}Co, ^{155}Eu, and ^{207}Bi levels were generally higher in the viscera of the convict surgeon than in the eviscerated whole fish. Differences between tissues were similar to those found in the goatfish. Cesium-137 was equally distributed in the viscera and eviscerated whole fish.

Data on ^{90}Sr and $^{239,240}Pu$ concentrations in the convict surgeon indicate that the viscera of convict surgeon from IRENE has the highest concentration of both ^{90}Sr (17 pCi/g, dry) and $^{239,240}Pu$ (15 pCi/g, dry) of any of the convict surgeon samples analyzed so far. Convict surgeon from BELLE also have higher than average concentrations of these radionuclides. Convict surgeon collected from DAVID to HENRY had ^{90}Sr and $^{239,240}Pu$ tissue concentrations of <0.1 pCi/g, dry.

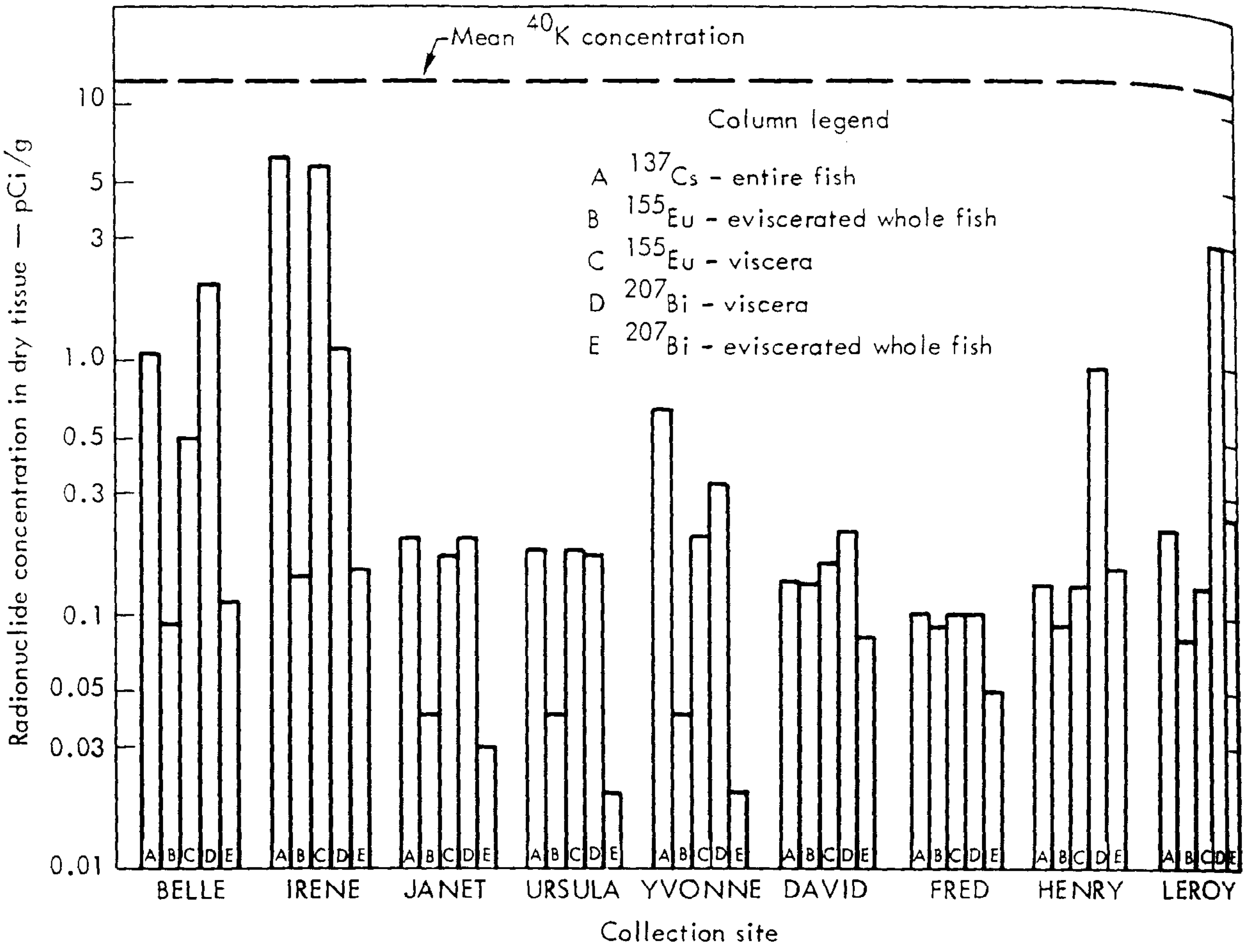

Fig. 45. Average ^{137}Cs, ^{155}Eu, and ^{207}Bi concentration in convict surgeon from Enewetak Atoll, October to December, 1972. The ^{40}K value is the mean for all convict surgeon samples.

Mullet – The results of the radiological analyses of the mullet tissues are given in Table 32. Each sample was made up of the tissues from an average pool of 10 fish. Although four species of mullet of various size classes were present in the samples, no correlation of radionuclide concentration with species or size was noted and samples from all species and sizes were pooled to form the data in Table 32. Sixty percent of the mullet collected for samples were Neomyxus chaptalii.

Of the three commonest radionuclides found in the mullet, ^{40}K and ^{55}Fe were found in all samples, while ^{60}Co was found in over 90% of the samples. Cesium-137, ^{155}Eu, and ^{207}Bi were found in 44%, 26%, and 26% of the samples, respectively. Americium-241 was found in all the viscera samples from BELLE and YVONNE and in one of two viscera samples from TILDA. Plutonium-239,240 and ^{90}Sr were found in most samples.

Variability of ^{40}K levels between sampling locations was within the normal range of expected values. Muscle tissue had the highest average ^{40}K concentration, 13 pCi/g, dry, of the three tissue types analyzed. Eviscerated whole fish and

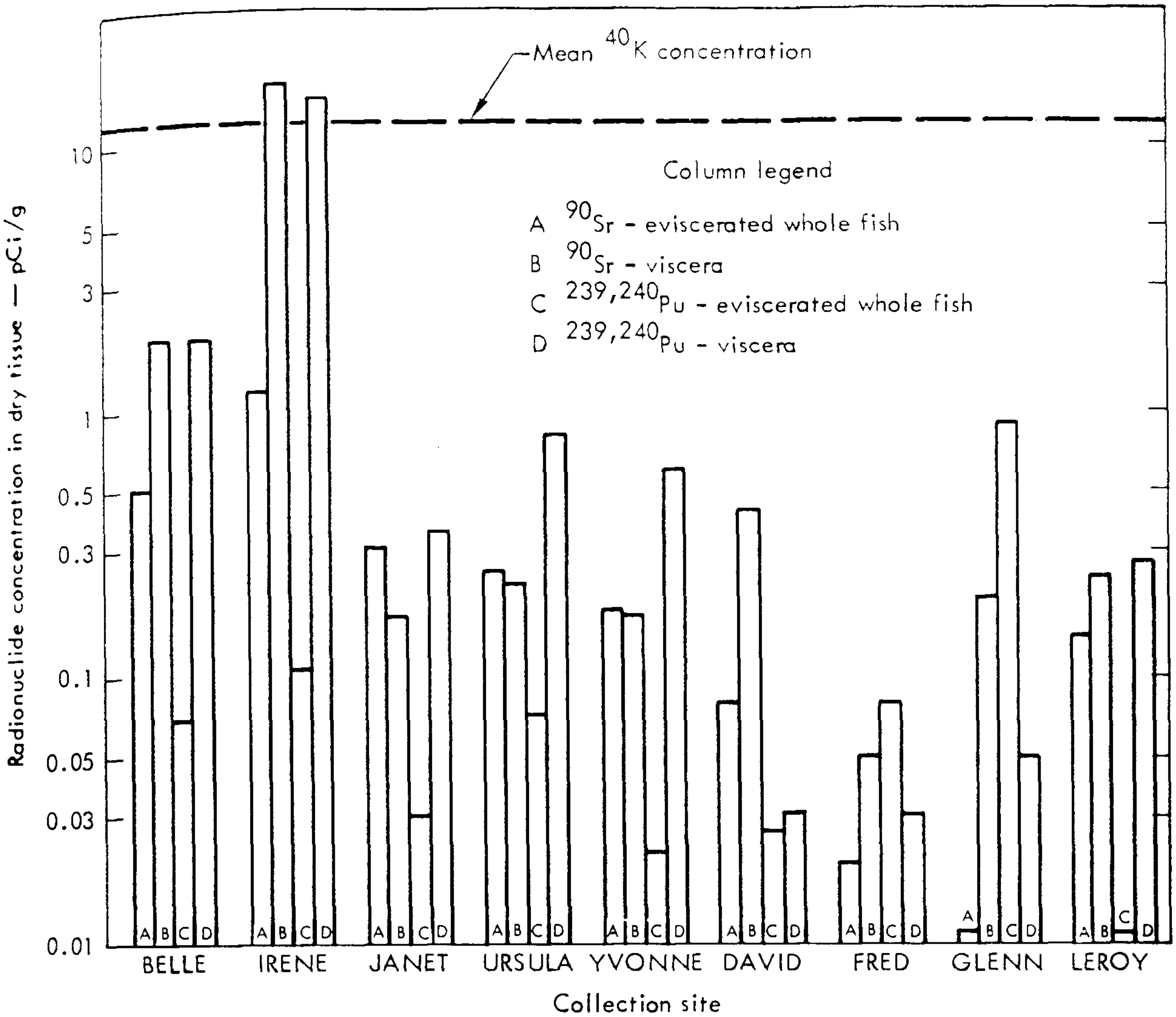

Fig. 45a. Average ^{90}Sr and $^{239,240}Pu$ concentration in convict surgeon from Enewetak Atoll, October to December, 1972. The ^{40}K value is the mean for all convict surgeon samples.

viscera averaged 6.3 and 4.3 pCi/g, dry, respectively. A comparison of ^{40}K, ^{55}Fe, and ^{60}Co in the mullet is shown in Fig. 46. Concentrations of ^{55}Fe and ^{60}Co, the most abundant man-produced radionuclides in the mullet, were higher in the viscera than in the muscle or eviscerated whole fish, two tissues which had similar concentrations. Cesium-137, ^{155}Eu, and ^{207}Bi were also present in the viscera in higher concentrations than in the other two tissues. Where ^{155}Eu was detected, it was present in higher concentrations than either ^{137}Cs or ^{207}Bi.

The highest concentration of each of the predominant man-made radionuclides was found in the viscera samples taken from mullet collected at IRENE. These concentrations in pCi/g, dry, are as follows: ^{55}Fe (220), ^{60}Co (90), ^{137}Cs (9.8), ^{155}Eu (22), and ^{207}Bi (2.2). Viscera samples from mullet collected at BELLE and YVONNE also had higher than average man-made radionuclide levels, but the

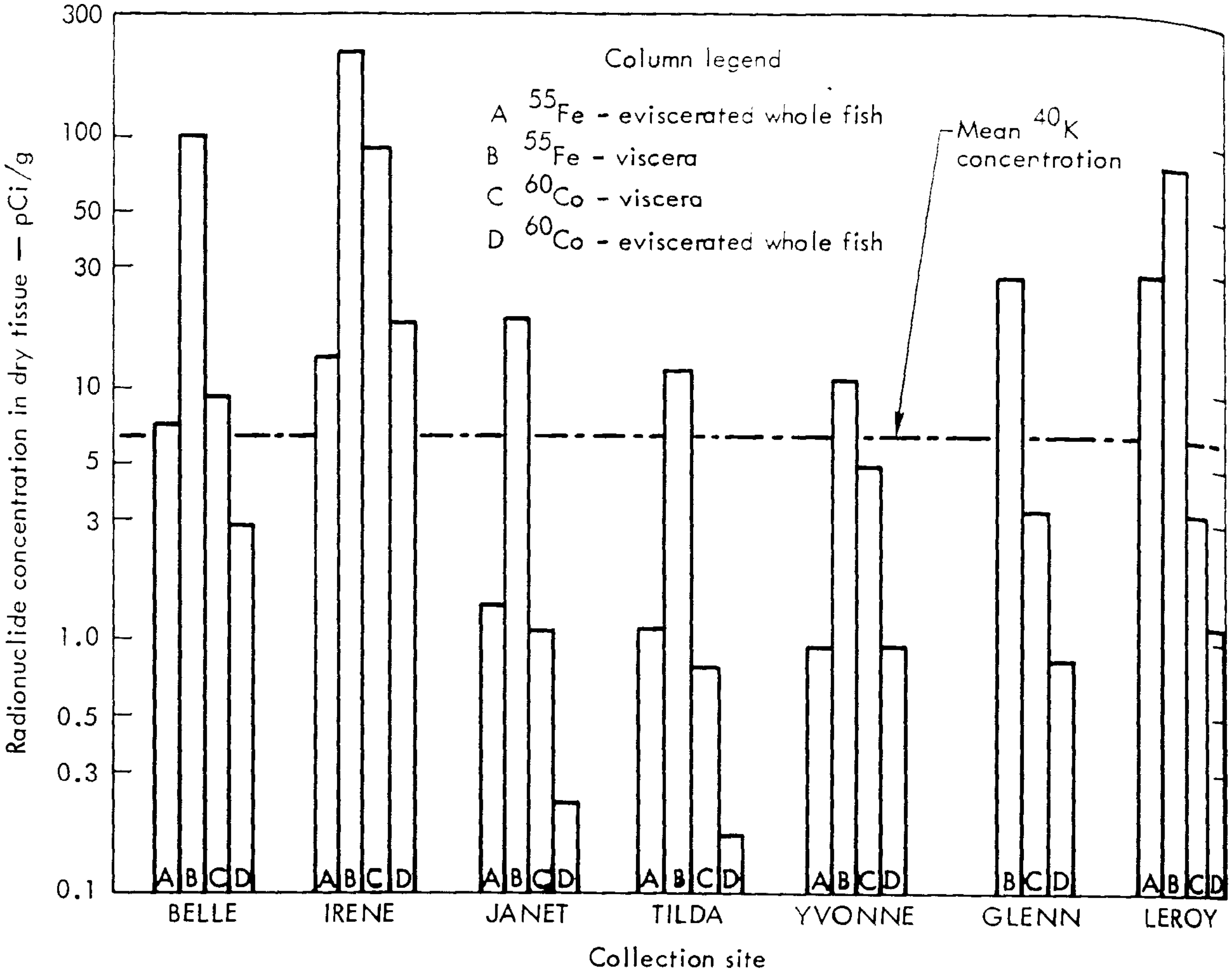

Fig. 46. Average ^{40}K, ^{55}Fe, and ^{60}Co concentration in mullet collected at Enewetak Atoll, October to December, 1972. The ^{40}K value is the mean from all mullet samples.

levels were lower than those in IRENE fish by factors of roughly 8 (BELLE) and 20 (YVONNE). Generally, levels of the man-made radionuclides in fish from GLENN, HENRY, and LEROY were slightly lower than levels of the same radionuclide in YVONNE mullet; however, one viscera sample from mullet collected from GLENN had 1.8 pCi/g, dry, of ^{207}Bi, which was only slightly lower than the ^{207}Bi content in the viscera sample from IRENE mullet. Mullet from JANET had the lowest man-made gamma-emitting radionuclide content.

The highest ^{90}Sr level (6.1 pCi/g, dry) in the mullet was found in the viscera of mullet from BELLE, while the viscera of mullet from IRENE have the highest ^{239,240}Pu content (24 pCi/g, dry). Concentrations of ^{239,240}Pu in the viscera of mullet from BELLE were also higher (8.0 pCi/g, dry) than the average ^{239,240}Pu concentration of < 1 pCi/g, dry.

Parrotfish – The results of the radiological analyses of the parrotfish tissues are given in Table 33. Each sample was made up of the tissues from an average pool of four fish. All fish were a single

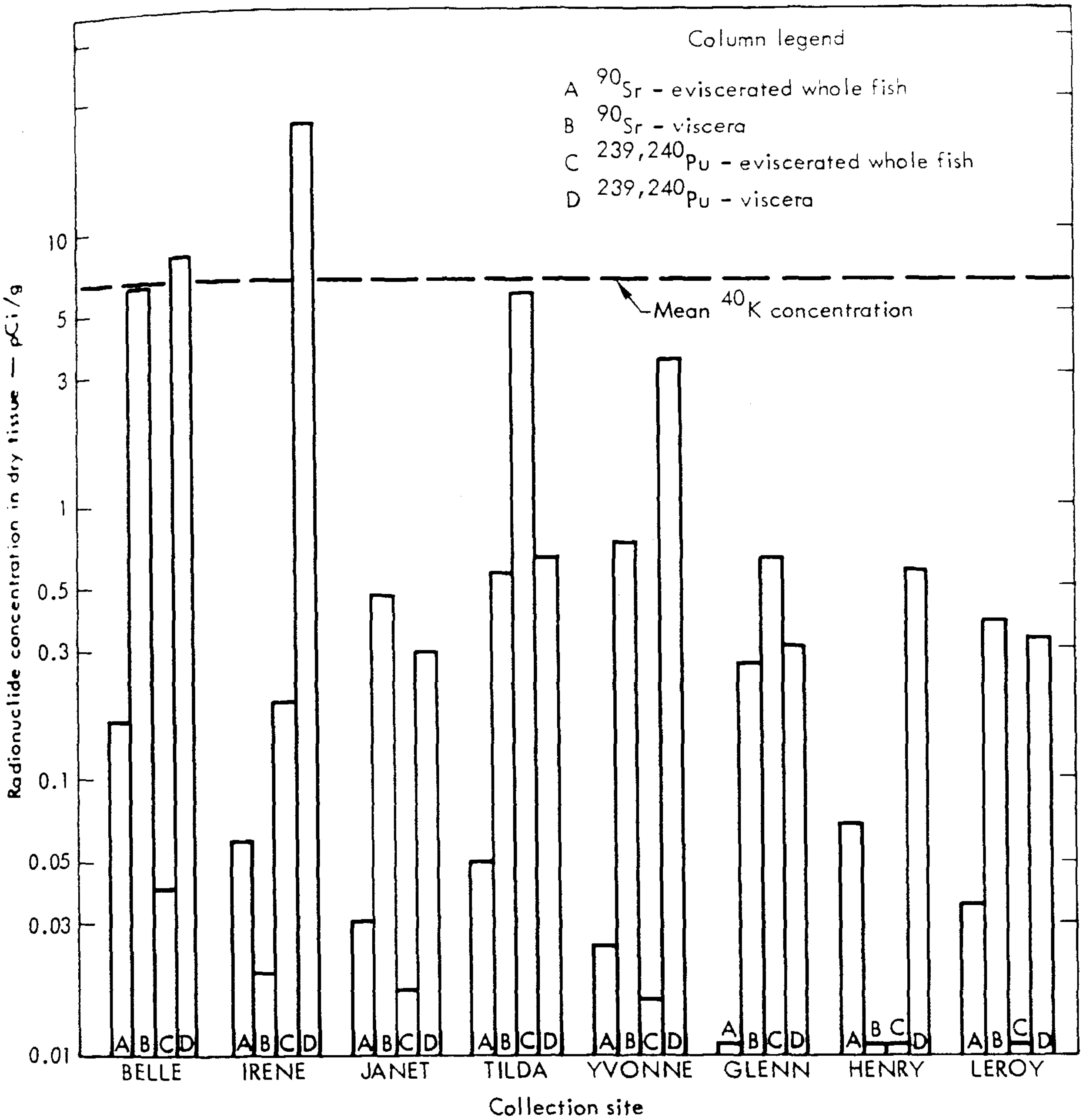

Fig. 46a. Average ^{90}Sr and $^{239,240}Pu$ concentration in mullet collected at Enewetak Atoll, October to December, 1972. The ^{40}K value is the mean for all mullet samples.

species, Scarus sordidus, and most were of the same size class (24 to 36 cm).

Potassium-40 was the most abundant naturally occurring radionuclide and was detected in all of the parrotfish samples. Of the man-produced radionuclides, only ^{55}Fe and ^{137}Cs were present in more than 50% of the samples. Cobalt-60, ^{155}Eu, and ^{207}Bi were detected in 44%, 22%, and 15% of the samples, respectively. Americium-241 was detected in three viscera samples, one each from BELLE (1.4 pCi/g, dry), TILDA (0.21 pCi/g, dry), and YVONNE

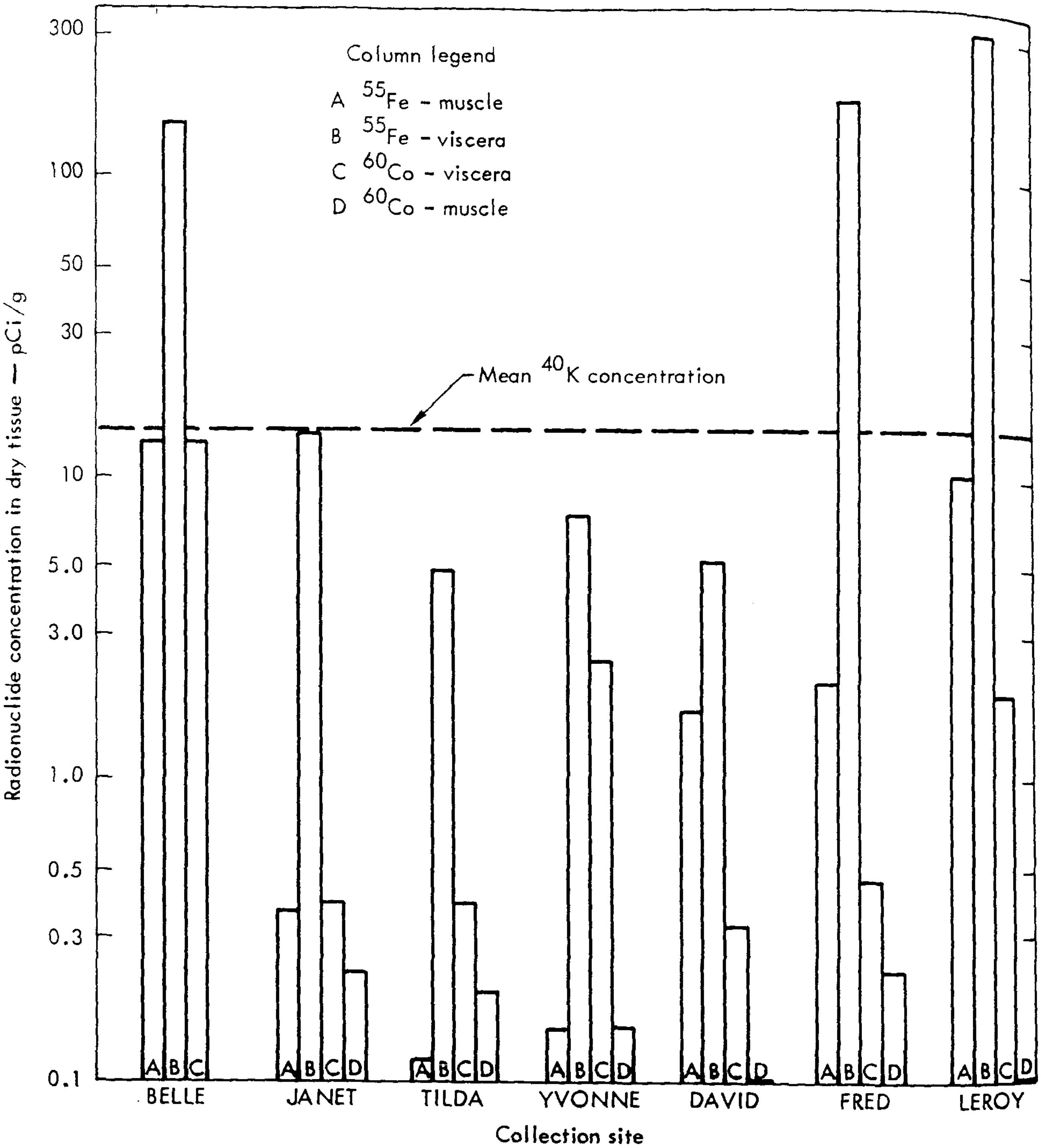

Fig. 47. Average ^{40}K, ^{55}Fe, and ^{60}Co concentration in muscle and viscera samples from parrotfish collected at Enewetak Atoll, October to December, 1972. The ^{40}K value is the mean for all parrotfish muscle and viscera samples.

(0.58 pCi/g, dry). Plutonium-239,240 and ^{90}Sr were detected in most samples.

Potassium-40 levels showed little variability between sampling locations, except for one viscera sample from fish collected at BELLE, which had a ^{40}K concentration of 21 pCi/g, dry, which was about three times greater than the average value for parrotfish viscera. All samples had ^{40}K values within the expected range of natural levels, with muscle and viscera averaging 18 and 6.5 pCi/g, dry, respectively.

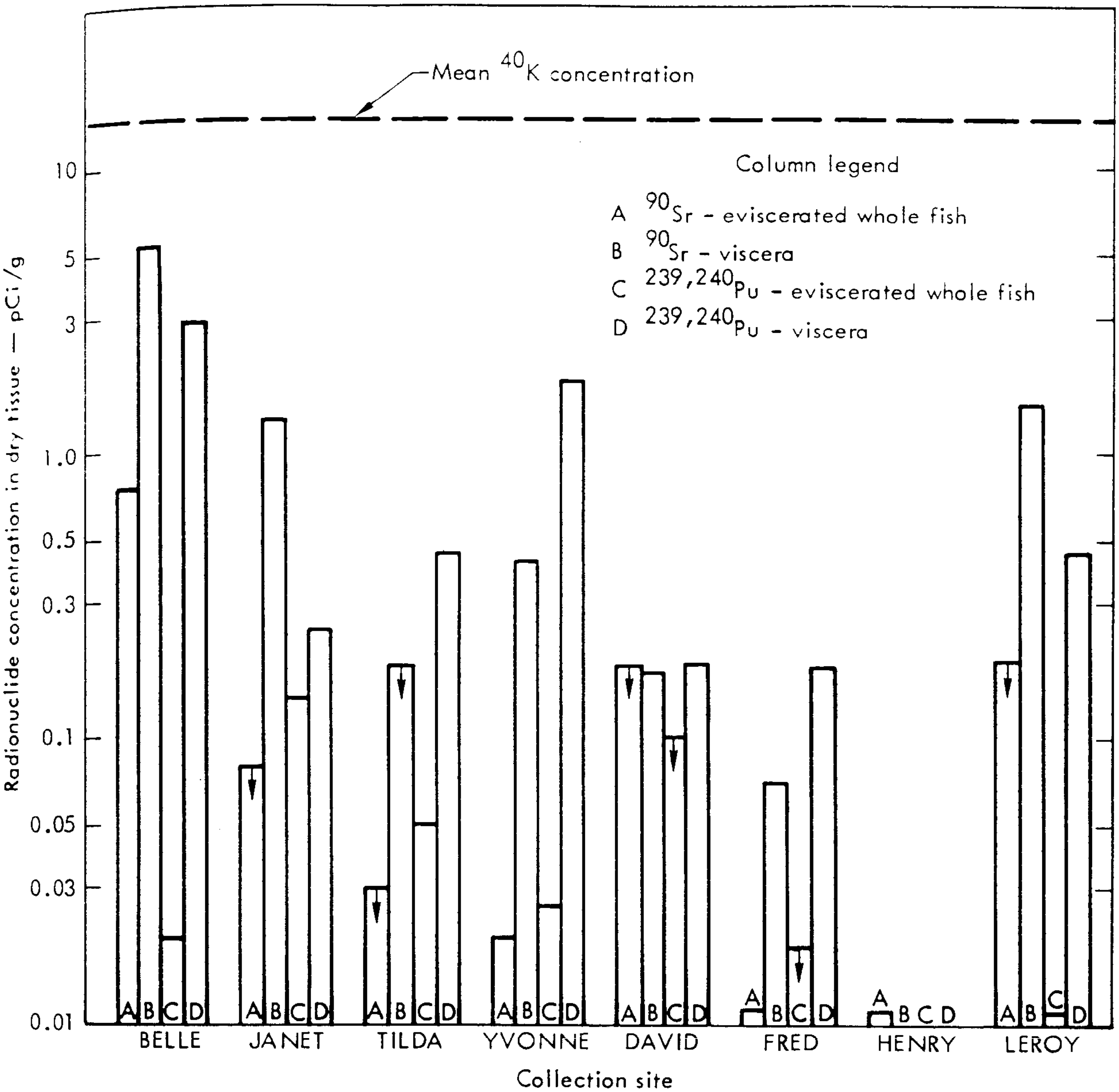

Fig. 47a. Average ^{90}Sr and $^{239,240}Pu$ concentration in muscle and viscera samples from parrotfish collected at Enewetak Atoll, October to December, 1972. The ^{40}K value is the mean for all parrotfish muscle and viscera samples.

A comparison of ^{40}K, ^{55}Fe, and ^{60}Co levels in the parrotfish is shown in Fig. 47.

Iron-55 was the most abundant man-produced radionuclide detected in the parrotfish samples. The highest ^{55}Fe levels were found in the viscera (300 pCi/g, dry) and muscle of parrotfish from LEROY, while the average level was 2.6 pCi/g, dry, in muscle and 82 pCi/g, dry, in viscera.

The other two common man-made gamma-emitting radionuclides detected in the parrotfish were ^{60}Co and ^{137}Cs. Cesium was detected in more samples (55%) than ^{60}Co (44%), but the highest ^{60}Co level (13 pCi/g, dry) in viscera from BELLE parrotfish was higher than the highest ^{137}Cs level (3.0 pCi/g, dry) in eviscerated whole fish from BELLE. In addition to the samples from BELLE, ^{60}Co was high in viscera from YVONNE (2.5 pCi/g, dry) and LEROY (1.9 pCi/g, dry), and ^{137}Cs was high in muscle from FRED (1.8 pCi/g, dry). Other ^{60}Co and ^{137}Cs concentrations averaged less than 0.40 pCi/g, dry.

Europium-155 and ^{207}Bi were present in only a few samples. Europium-155 was high in viscera from BELLE (1.2 pCi/g, dry) and YVONNE (0.88 pCi/g, dry), while ^{207}Bi was high in viscera from FRED (1.4 pCi/g, dry) and LEROY (1.3 pCi/g, dry).

Of the five man-produced radionuclides discussed above, only ^{137}Cs was present in higher amounts in the muscle than in the viscera. Iron-55, ^{60}Co, ^{155}Eu, and ^{204}Bi levels were greater in the viscera than in the muscle of parrotfish.

The highest ^{90}Sr and ^{239,240}Pu concentrations in the parrotfish were found in the viscera sample from BELLE (^{90}Sr = 5.3 pCi/g, dry; ^{239,240}Pu = 2.9 pCi/g, dry). Plutonium was also high in parrotfish from YVONNE (1.8 pCi/g in the viscera). Other samples had <1 pCi/g, dry, of these radionuclides. Strontium-90 and ^{239,240}Pu levels were higher in the viscera than in the muscle by factors of 8 and 10, respectively.

Snappers and Groupers – The results of the radiological analyses of the snappers and groupers are given in Tables 34 and 35. These fish will be considered together because of the similarity in the results of the radiological analyses, which probably is a consequence of the similarity in their feeding habits.

The three most abundant radionuclides found in the snappers and groupers were ^{40}K, ^{55}Fe, and ^{60}Co. Cesium-137 and ^{207}Bi in lesser amounts were found in about one-third of the samples. A small amount of ^{155}Eu (0.13 pCi/g, dry) was found in one liver sample from a grouper collected at FRED, while ^{241}Am (1.4 pCi/g, dry) was found in one bone sample from a grouper collected from YVONNE. Strontium-90 and ^{239}Pu were detected in about 50% of the samples. Naturally occurring ^{40}K levels were similar at all collection sites. Muscle and viscera tissue samples averaged 19 and 14 pCi/g, dry, respectively.

Iron-55 and ^{60}Co were the predominant man-produced radionuclides found in the snappers and groupers. These two radionuclides were present in the viscera or liver in concentrations over 10 times higher than those found in the muscle. The highest ^{55}Fe level, by a factor of 8, (4900 pCi/g, dry) was in a liver sample from a grouper collected at FRED. Several snapper and grouper viscera or liver samples from GLENN, ELMER, TILDA, and YVONNE also had ^{55}Fe concentrations from 310 to 640 pCi/g, dry. Cobalt-60 levels were highest in grouper liver from FRED (94 pCi/g, dry), grouper viscera from YVONNE (36 pCi/g, dry), and snapper remainder (including viscera) from GLENN (22 pCi/g, dry). Only the muscle from the snapper sample from IRENE had a ^{60}Co concentration above 1 pCi/g, dry (11 pCi/g, dry). Cobalt-60 concentrations in muscle samples averaged 1.4 pCi/g, dry, while ^{60}Co in viscera or liver samples averaged 16 pCi/g, dry.

Bismuth-207 concentrations were lower then ^{55}Fe and ^{60}Co concentrations, but like those radionuclides, ^{207}Bi levels were higher in the viscera or liver than in the muscle. The degree of difference between the ^{207}Bi concentrations in the two types of tissue was less than twofold and was not nearly as great as it was for ^{60}Co and ^{55}Fe. The highest ^{207}Bi concentration was found in the viscera (4.6 pCi/g, dry) and muscle (2.5 pCi/g, dry) of a grouper collected at YVONNE. A grouper and a snapper from FRED and a snapper from GLENN also had ^{207}Bi levels of between one and two pCi/g, dry, in their tissues. Other ^{207}Bi levels averaged less than 0.17 pCi/g, dry.

Cesium-137 levels in the groupers generally were less than 0.5 and averaged 0.25 pCi/g, dry, while one snapper muscle sample from IRENE had a ^{137}Cs level of 2.1 pCi/g, dry, and the remainder of the samples averaged less than 0.22 pCi/g, dry.

The highest ^{90}Sr concentration (2.9 pCi/g, dry) was found in the liver of a snapper collected off TILDA. Most other ^{90}Sr levels were < 1 pCi/g, dry. The highest $^{239,240}Pu$ concentration (0.6 pCi/g, dry) was detected in the viscera of a snapper collected off TILDA. Most other $^{239,240}Pu$ levels were < 0.1 pCi/g, dry, with most of the Pu concentrated in the viscera.

Ulua – The results of the radiological analyses of the ulua tissues are given in Table 36. Potassium-40 was present in all tissues at an average concentration of 15 pCi/g, dry. Iron-55 and ^{207}Bi were the most abundant man-made radionuclides and they were detected in all the ulua samples. Cobalt-60 and ^{137}Cs were found in over 50% of the samples, but at lower levels than ^{55}Fe and ^{207}Bi. Europium-155 and ^{241}Am were not detected in any of the ulua samples analyzed. Strontium-90 and $^{239,240}Pu$ were found in 50 and 75% of the samples, respectively.

Iron-55 was the most abundant man-made radionuclide found in the ulua. Iron-55 concentrations of up to 510 pCi/g, dry, were found in the viscera of a ulua from FRED. Viscera concentrations in ulua from YVONNE and ELMER were 350 and 33 pCi/g, dry, respectively, while muscle averaged 60 pCi/g, dry, in four samples, including the FRED ulua which had 150 pCi/g, dry, in its muscle tissue.

Bismuth-207 concentrations were quite variable between collection sites. One ulua from FRED had a ^{207}Bi concentration in its viscera of 206 pCi/g, dry, and a sample of two eviscerated whole ulua from HENRY had a ^{207}Bi concentration of 248 pCi/g, dry. The ^{207}Bi concentrations averaged 3.0 pCi/g, dry, in the other nine samples of muscle and viscera.

Cobalt-60 levels were 8 times higher in the viscera samples than in the muscle samples. The greatest amount (13 pCi/g, dry) was in the viscera of two ulua collected at YVONNE. Cobalt-60 averaged 1.3 pCi/g in the muscle samples and 7.5 pCi/g in the viscera samples.

Cesium-137 levels ranged from 1.0 pCi/g, dry (HENRY – eviscerated whole) to less than 0.08 pCi/g, dry, with an average concentration of less than 0.37 pCi/g, dry. Cesium-137 concentrations were higher in the muscle than in the viscera. An exact factor of the tissue difference could not be determined, since all the ^{137}Cs levels in the viscera were below the limits of detection.

The highest ^{90}Sr concentration (0.5 pCi/g, dry) was found in an eviscerated whole ulua collected off HENRY. Other ulua samples analyzed for ^{90}Sr averaged <0.2 pCi/g, dry. Plutonium-239,240 levels were below 1.0 pCi/g, dry, except for the viscera sample from ulua collected at FRED which contained 15 pCi/g, dry.

Tuna and Other Large Pelagic Lagoon Fish – The results of the radiological analyses of large pelagic lagoon fish are given in Table 37. These fish include skipjack, yellowfin tuna, mackerel, dolphin, and barracuda. Of these fish the yellowfin tuna and the dolphin are likely to be resident in the lagoon on a more temporary basis than the skipjack, mackerel, or barracuda. Each tissue sample was from an individual fish except for mackerel sample No. 0440, which was a composite sample from two fish.

The results indicate that naturally occurring ^{40}K is present in background amounts. All samples averaged 14 pCi/g, dry, with light muscle, dark muscle, and liver or viscera averaging 16, 12, and 11 pCi/g, dry, respectively. These levels are similar to those found at Kwajalein Atoll where pelagic lagoon fish had an average ^{40}K tissue concentration of 14 pCi/g, dry.

Of the man-produced radionuclides found in these fish, ^{55}Fe was by far the most abundant (Fig. 48). Iron-55 levels in the large pelagic fish were generally higher than levels found in other fish types, with the liver of the skipjack having the highest concentrations (maximum - 2500 pCi/g, dry; average - 840 pCi/g, dry) of the tissues analyzed. Iron-55 in the skipjack was less in the light muscle than in the liver or dark muscle by factors of 18 and 7, respectively.

Cobalt-60 was found in most samples of lagoon fish, but at lower levels than ^{55}Fe. The highest ^{60}Co concentration in the pelagic lagoon fish was 36 pCi/g, dry, in the liver of a skipjack captured near YVONNE. Light muscle of tuna and muscle of the other fish averaged 0.58 pCi/g, dry, while dark muscle of tuna and liver or viscera of all these pelagic lagoon fish averaged 8.4 and 11 pCi/g, dry, respectively. There was considerable variation in the amount of ^{60}Co present in tissue samples from the same species of fish. For instance, a yellowfin tuna taken from the Deep Channel had ^{60}Co concentrations of 8.4 and 2.1 pCi/g, dry, in the dark muscle and liver, while a yellowfin taken off the ocean side of GLENN, had 0.55 pCi/g, dry, in its dark muscle and less than 0.61 pCi/g, dry, in its liver. The two dolphin exhibited similar differences. This indicates that the residence time of some of these fish near or in the lagoon, which is the major source of the ^{60}Co and other man-produced radionuclides in their tissues, is quite variable. Fish (i.e., skipjack) which tend to stay within the atoll had a more consistent distribution of radionuclides among individuals, although there is still a wide variability between individuals and the average radionuclide concentration of the total group of fish. For instance, livers from three skipjack taken off YVONNE averaged 23 pCi/g, dry, and had a range from 5.2 to 36 pCi/g, dry, while liver tissue from five skipjack taken from the southern end of the atoll averaged 12 pCi/g, dry, with a range of <0.68 to

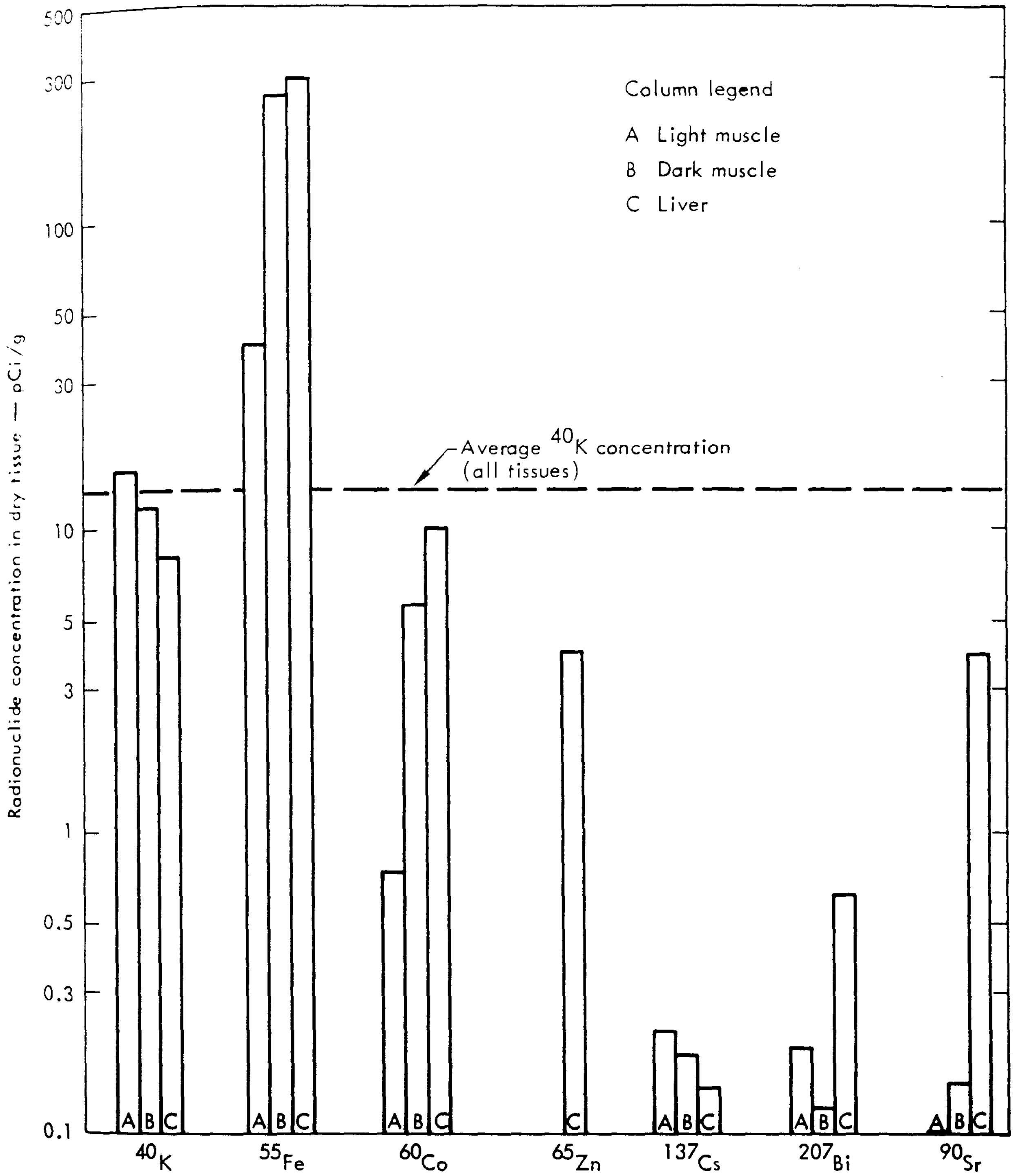

Fig. 48. Average concentration of seven radionuclides in the light muscle (A), dark muscle (B), and liver (C) of three skipjack from Enewetak Atoll, October to December, 1972.

19 pCi/g, dry. This difference between skipjack from the portions of the atoll was found to be not significant when tested with analysis of variance methods. Dark and light muscle tissue from all skipjack taken at Enewetak had average ^{60}Co concentrations of 9.4 and 9.8 pCi/g, dry, respectively. There was no significant

Table 37. Predominant radionuclides in large pelagic lagoon fish collected at Enewetak Atoll, October to December 1972.

Sample No.	Collection site	Common name (size in cm)	Tissue[b]	Radionuclide, average ± standard deviation[a] in pCi/g, dry: ^{40}K	^{55}Fe	^{60}Co	^{65}Zn	^{137}Cs	^{207}Bi	^{90}Sr	$^{239,240}Pu$
0229	Wide Pass	Skipjack (49)	Light muscle	19 ± 1.0	37 ± 0.3	0.98 ± 0.13	NC[c]	0.22 ± 0.05	0.13 ± 0.04	<0.04	<0.001
0240			Dark muscle	16 ± 2.4	280 ± 2	5.9 ± 0.3	NC	0.21 ± 0.10	0.19 ± 0.08	<0.18	<0.002
0264			Liver	9.6 ± 0.9	280 ± 2	13 ± 0.2	6.6 ± 0.4	<0.07	0.86 ± 0.06	0.06	0.010 ± 0.001
0253			Bone	10 ± 1.3	19 ± 0.4	0.17 ± 0.13	NC	0.22 ± 0.09	0.15 ± 0.05	0.14 ± 0.05	0.023
0273	Wide Pass	Skipjack (46)	Light muscle	12 ± 1.4	39 ± 0.8	0.52 ± 0.08	NC	<0.10	0.08	0.04 ± 0.02	1.2 ± 0.01
0268			Dark muscle	9.3 ± 1.0	—	8.4 ± 0.2	NC	0.18 ± 0.08	<0.08	<0.01	0.032 ± 0.001
0237			Liver	11 ± 2.1	650 ± 6.5	<0.68	1.8 ± 0.5	0.48 ± 0.18	0.56 ± 0.13	0.06 ± 0.02	0.009 ± 0.001
0252			Bone	NC	33 ± 0.4	<0.36	NC	<0.21	<0.19	<0.18	1.2
0235	Wide Pass	Skipjack (48)	Light muscle	17 ± 1.4	47 ± 1.1	0.87 ± 0.14	NC	0.28 ± 0.05	0.21 ± 0.04	<0.10	0.009
0274			Dark muscle	9.9 ± 1.4	270 ± 2.7	5.8 ± 0.20	NC	0.13	0.10	<0.10	0.011
0269			Liver	8.4 ± 0.9	410 ± 4.1	12 ± 0.4	2.9 ± 0.3	0.26 ± 0.08	0.55 ± 0.05	<0.23	0.009 ± 0.001
0254			Bone	12 ± 3.5	—	<0.29	NC	<0.17	<0.14	<0.08	<0.014 ± 0.005
0481	WALT	Skipjack (54)	Light muscle	17 ± 1.2	73 ± 1.1	1.2 ± 0.2	NC	0.67 ± 0.09	6.1 ± 0.1	<0.10	<0.004
0482			Dark muscle	14 ± 1.0	460 ± 4.6	15 ± 0.3	NC	0.76 ± 0.09	3.7 ± 0.1	<0.10	<0.005
0483			Liver	21 ± 2.0	2 500 ± 25	19 ± 0.4	NC	2.7 ± 0.2	1.7 ± 0.2	<0.02	0.022 ± 0.007
0324	DAVID	Skipjack (45)	Light muscle	14 ± 0.9	29 ± 0.6	0.62 ± 0.03	NC	0.16 ± 0.02	<0.02	<0.01	0.005 ± 0.001
0325			Dark muscle	13 ± 1.6	330 ± 4.4	11 ± 0.4	NC	0.31 ± 0.11	<0.07	<0.44	—
0326			Liver	8.7 ± 2.1	520 ± 1.0	13 ± 0.6	2.5 ± 0.8	0.60 ± 0.20	0.44 ± 0.13	0.04	<0.012
0327			Bone	NC	5.0 ± 3.3	<0.36	NC	<0.23	<0.21	<1.1	0.039
0524	YVONNE	Skipjack (58)	Light muscle	17 ± 1.1	58 ± 1.2	1.1 ± 0.1	NC	0.44 ± 0.05	1.1 ± 0.1	<0.01	0.036 ± 0.002
0523			Dark muscle	14 ± 1.0	400 ± 4.1	12 ± 0.2	NC	0.39 ± 0.07	0.82 ± 0.06	0.004 ± 0.003	0.005 ± 0.001
0525			Liver	14 ± 2.7	1300 ± 13	36 ± 0.6	1.5 ± 0.6	<0.22	2.2 ± 1.8	0.022 ± 0.009	0.023 ± 0.002
0526			Bone	3.4 ± 1.0	14 ± 0.14	0.33 ± 0.06	NC	0.15 ± 0.06	0.13 ± 0.06	0.05 ± 0.005	0.002 ± 0.001
0528	YVONNE	Skipjack (57)	Light muscle	10 ± 1.2	42 ± 1.5	0.80 ± 0.08	NC	0.28 ± 0.06	0.87 ± 0.08	<0.009	0.009 ± 0.002
0527			Dark muscle	13 ± 2.2	38 ± 0.8	11 ± 0.07	NC	<0.22	0.89 ± 0.15	0.007 ± 0.002	0.72 ± 0.014
0534			Liver	9.7 ± 1.6	—	28 ± 0.5	2.8 ± 0.9	<0.16	3.2 ± 0.2	0.010 ± 0.005	0.014 ± 0.002
0529			Bone	6.5 ± 0.9	19 ± 0.37	0.28 ± 0.06	NC	<0.07	0.24 ± 0.04	0.024 ± 0.02	0.006 ± 0.003
0531	YVONNE	Skipjack (53)	Light muscle	13 ± 1.3	54 ± 1.5	0.37 ± 0.05	NC	0.15 ± 0.05	0.24 ± 0.04	<0.05	0.007 ± 0.002
0530			Dark muscle	11 ± 1.0	240 ± 1.1	5.0 ± 0.20	NC	0.19 ± 0.08	<0.07	<0.035	0.002 ± 0.001
0532			Liver	6.3 ± 1.7	200 ± 0.6	5.2 ± 0.3	2.2 ± 0.5	<0.09	0.43 ± 0.09	<0.062	0.004 ± 0.001
0533			Bone	8.9 ± 1.3	5.8 ± 0.3	<0.13	NC	<0.09	<0.07	<0.05	0.07
0552	GLENN	Yellow-fin (~100)	Light muscle	16 ± 1.0	0.17 ± 0.03	<0.07	NC	0.10 ± 0.03	<0.03	<0.02	0.006 ± 0.001
0553			Dark muscle	12 ± 1.7	50 ± 1.5	0.55 ± 0.10	NC	0.21 ± 0.07	<0.04	0.023 ± 0.003	0.02 ± 0.003
0554			Liver	NC	66 ± 1.3	<0.61	NC	<0.33	<0.27	0.11 ± 0.05	4.6 ± 0.14
0555			Bone	NC	13 ± 0.6	0.20	NC	<0.19	<0.15	<0.09	0.20 ± 0.02