



LAWRENCE LIVERMORE LABORATORY

G25 45079

January 27, 1978

Mr. Tommy F. McCraw  
Department of Energy  
Safety, Standards & Compliance  
Washington, DC 20545

Dear Tommy,

Enclosed is an update of the initial report I sent to you on the potential dose at Enewetak due to transuranic radionuclides. The primary changes involve an update of the terrestrial foodchain assessment and also a correction in the summary tables where I had summed one pathway in terms of "rem" instead of "rad" doses. Please destroy the initial report and use this version for pathway comparisons and predicted total dose levels.

If there are any questions please give me a call.

Sincerely,

William L. Robison  
Environmental Sciences Division

WLR:lb  
Enclosures

FROM  
CIC

Assessment of Potential Doses to Populations from the  
Transuranic Radionuclides at Enewetak Atoll

W. L. Robison, V. E. Noshkin and W. A. Phillips

The following assessment was requested by the Division of Biological and Environmental Research and the Division of Operational and Environmental Safety within the Assistant Secretary for Environment & Safety in the Department of Energy.

The assessment is a more thorough evaluation of the potential dose to a population from the transuranic radionuclides in the terrestrial and aquatic ecosystems at Enewetak Atoll in the Marshall Islands.

The initial assessment was made in 1973 (1). The transuranics contributed a very small percentage (< 1%) of the total dose predicted for the various living patterns at the Atoll. As a result there was no effort made to look in detail at the potential contribution from the transuranic via the various exposure pathways.

This report supplies a more detailed look at the estimated doses that might be expected at Enewetak from  $^{239,240}\text{Pu}$ ,  $^{241}\text{Am}$  and  $^{238}\text{Pu}$ . Although neptunium has been observed in the marine environment (2) it is not considered in the dose assessment nor are other transamericium radionuclides. However, doses from these other radionuclides are expected to be a small fraction of that due to Pu and Am.

Marine Pathway

The following assessment of the potential dose to a population living at Enewetak via the marine foodchain is based upon new data obtained by Victor Noshkin (3). The stimulus for obtaining new samples and doing a careful analysis for the transuranics was the discrepancy in much of the Pu analytical data reported by three different laboratories during the 1973 survey and reported in the Enewetak Radiological Survey Report Volume 1 (1).

The major portion ( $\geq 98\%$ ) of the predicted doses at Enewetak Atoll for the various living patterns is due to  $^{90}\text{Sr}$  and  $^{137}\text{Cs}$ . There was no statistically significant difference in the concentration of these isotopes for fish muscle from different parts of the lagoon. Therefore, the doses for the marine pathway in reference 1 were based upon an average for the entire lagoon.

However, the concentration of  $^{239,240}\text{Pu}$  and  $^{241}\text{Am}$  is very dependent upon location. The distribution, retention and release of these two isotopes is entirely different from  $^{137}\text{Cs}$  and  $^{90}\text{Sr}$  and the concentration of Am and Pu in fish can vary greatly depending upon the concentrations in the sediment and water in the localized areas where the reef fish feed.

Therefore, we have averaged the Pu concentrations in fish for the islands in the northern half of the atoll for which we have new data (Janet, Belle, Sally, Yvonne) and for the southern half of the atoll (Fred, David, Leroy). Averaging over the northern and southern halves of the atoll is reasonable in that the Marshallese living on Janet would fish the islands on either side and the people living on Fred would similarly fish the islands on either side. In fact, the people should be encouraged to do so because the reef fish do not migrate over long distances and tend to remain in a very localized environment. As a result, heavy fishing around one island can drastically reduce the fish population.

The marine pathway in general, and Pu and Am in particular, contributed such a small fraction of the total predicted dose at Enewetak, that no effort was made in NVO-140 to separate data on fish muscle from data on eviscerated whole fish. However, as the focus is now on the transuranics

and the potential dose therefrom, these data should be separated because the concentration of Pu in the bone of fish is higher than in fish muscle. The people eat the fish muscle and sometimes skin but not the bones. Thus a more accurate picture of the expected doses from Pu and Am via the marine foodchain is obtained by using fish muscle and skin data only for this assessment.

The results of the new data are shown in Table 1 and compared with the values used in the dose assessment of reference 1.

Table 1. Pu Concentration in Fish at Enewetak Atoll

<u>Organ</u>	<u><sup>239,240</sup>Pu Concentration pCi/g wt weight</u>		<u>NVO-140, 1973 Includes all Fish</u>
	<u>Noshkin 1977<sup>†</sup></u>	<u>Noshkin 1977<sup>†</sup></u>	
Muscle Northern Is.	$7.3 \times 10^{-4}$		
Muscle Southern Is.	$1.2 \times 10^{-4}$		
Muscle + Skin Northern Is.		$2.9 \times 10^{-3}$	
Muscle + Skin Southern Is.		$4.8 \times 10^{-4}$	
All Fish			$7.1 \times 10^{-2*}$

\*Value used in NVO-140 Dose Assessment

<sup>†</sup>Mullet data only

The concentration in fish muscle for the northern islands is approximately a factor of 100 less than the concentration used in the NVO-140 report. For the southern islands the concentration is less by a factor of nearly 600. When skin is included the concentration in muscle plus skin is less by a factor of 25 than the value used in NVO-140 for the northern islands and less by a factor of 150 than that used for the southern islands. The resulting

30, 50 and 70 year integral doses and the maximum dose rate are listed in Table 2. The predicted doses are based upon a daily intake of fish muscle plus skin of 600 g. The gut transfer coefficient used for this dose assessment for  $^{239,240}\text{Pu}$  is  $3 \times 10^{-5}$ .

Table 2. Integral Doses and Dose Rates for  $^{239,240}\text{Pu}$  Via the Marine Pathway\*

Area	Integral Bone Doses, mrem			Dose Rate mrem/yr at 70 year
	30 year	50 year	70 year	
Northern Islands	3.1	8.0	15	0.40
Southern Islands	0.52	1.4	2.5	0.068

\*Based upon a 600 g per day intake of fish muscle plus skin

On the average the concentrations observed in fish reflect the average concentrations of the environment and for  $^{238}\text{Pu}$  are approximately 13% of the  $^{239,240}\text{Pu}$  concentrations. The transfer coefficients are assumed to be the same for  $^{238}\text{Pu}$ \* as for  $^{239,240}\text{Pu}$  and the dose will scale directly with concentration. The values in Table 2 therefore will be increased by about 13% due to  $^{238}\text{Pu}$ .

$^{241}\text{Am}$  concentrations in the sediment and water are about 40% of the  $^{239,240}\text{Pu}$  concentrations. An additional 10% might result from grow-in from  $^{241}\text{Pu}$ . Therefore the  $^{241}\text{Am}$  concentration (in the marine environment) is considered to be about 50% of the  $^{239,240}\text{Pu}$  concentration.

The analysis for  $^{241}\text{Am}$  in the fish samples collected in 1976 is presently underway. Lacking direct fish muscle concentration data for

\*EPA uses for the oxides a gut transfer coefficient of  $10^{-3}$  for  $^{238}\text{Pu}$  and  $10^{-4}$  for  $^{239,240}\text{Pu}$ . If adopted this would make the estimated dose from  $^{238}\text{Pu}$  slightly greater than the predicted dose from  $^{239,240}\text{Pu}$  and would also increase the doses predicted in this report for  $^{239,240}\text{Pu}$ .

$^{241}\text{Am}$  it is assumed that  $^{241}\text{Am}$  is transferred across the gut wall in both fish and humans 10 times more readily than  $^{239,240}\text{Pu}$ . As a result of the  $^{241}\text{Am}$  concentration in the marine environment being 0.5 that of  $^{239,240}\text{Pu}$  and as a result of the transfer to man being 100 times greater (10 x for fish gut transfer and 10 x for human gut transfer) for  $^{241}\text{Am}$  than for  $^{239,240}\text{Pu}$  the predicted doses from  $^{241}\text{Am}$  are 50 times that resulting from  $^{239,240}\text{Pu}$ . It should be emphasized that it is not at all clear that  $^{241}\text{Am}$  is transferred to fish muscle 10 times more readily than  $^{239,240}\text{Pu}$ .

Thus the doses in Table 2 if multiplied by a factor of 50 would essentially represent the predicted rem doses for all of the transuranics (i.e.,  $^{238}\text{Pu}$ ,  $^{239,240}\text{Pu}$ ,  $^{241}\text{Am}$ ) via the marine pathway at Enewetak Atoll. However, the EPA guidance is set in terms of "rad" doses. Therefore, to convert to "rad" doses the "rem" bone doses in Table 2 should be divided by a factor of 50. The net result is, therefore, that the "rem" doses listed in Table 2 for  $^{239,240}\text{Pu}$  are essentially numerically equivalent to the "rad" doses for  $^{238}\text{Pu}$ ,  $^{239,240}\text{Pu}$  and  $^{241}\text{Am}$ .

It is emphasized that the marine dose assessment is based upon the assumed consumption of fish muscle and the best available concentration data for the radionuclides in that tissue. However, the concentration of  $^{239,240}\text{Pu}$  in fish bone is higher than in muscle and very high concentrations of Pu have been observed in the viscera and gills of fish. If for any reason the bone and viscera were consumed along with the muscle the predicted doses from the transuranics would be expected to be much higher.

Inhalation Pathway

The doses for the inhalation pathway are calculated for two cases:

1. Soil concentrations of 40 pCi/g and
2. Soil concentrations of 400 pCi/g.

The calculations are made assuming a mass loading of  $100 \mu\text{g}/\text{m}^3$  of surface soil in air (all of which is assumed to be respirable), an AMAD of  $0.5 \mu\text{m}$  and a breathing rate of  $20 \text{ m}^3/\text{day}$ . The resulting intake of  $^{239,240}\text{Pu}$  in pCi/day is therefore  $100 \times 10^{-6} \frac{\text{g}}{\text{m}^3} \frac{20 \text{ m}^3}{\text{day}} 40 \text{ pCi/g} = 0.08 \text{ pCi/day}$  and for 400 pCi/g - 0.8 pCi/day.

The resulting integral doses and dose rates are given in Table 3.

Table 3. Integral Lung Doses and Dose Rates for  $^{239,240}\text{Pu}$  Via the Inhalation Pathway

Soil Concentration	Integral Doses, mrem			Maximum Annual Dose Rates mrem/yr
	30 year	50 year	70 year	
40 pCi/g	680	1200	1600	24
400 pCi/g	680	12,000	16,000	240

The "rad" doses will be less by a factor 10 than the "rem" doses in Table 3. Therefore for the 40 pCi/g concentration in soil the 70 year integral lung dose is 0.16 rad and the maximum dose rate is 2.4 mrad/yr.

The corresponding bone doses are listed in Table 4.

Table 4. Integral Bone Doses and Dose Rates for  $^{239,240}\text{Pu}$  Via the Inhalation Pathway

Soil Concentration	Integral Doses, mrem			Annual Dose Rates at 70 Years mrem/yr
	30 year	50 year	70 year	
40 pCi/g	220	660	1300	37
400 pCi/g	2200	6600	13,000	366

The corresponding "rad" bone doses would be less by a factor of 50 than the doses listed in Table 4.

The bone and lung doses resulting via the inhalation pathway from any other soil concentration of  $^{239,240}\text{Pu}$  can be scaled directly by ratioing to either of the above soil concentrations and the respective doses.

The doses resulting from  $^{241}\text{Am}$  and  $^{238}\text{Pu}$  via the inhalation pathway would be approximately 50% of the  $^{239,240}\text{Pu}$  doses listed in Tables 3 and 4.

The predicted "rad" doses from  $^{239,240}\text{Pu}$ ,  $^{241}\text{Am}$  and  $^{238}\text{Pu}$  via the inhalation

pathway are listed in Table 5.

Table 5. Predicted Integral Bone and Lung Doses and Dose Rates for  $^{239,240}\text{Pu}$  and  $^{241}\text{Am}$  Via the Inhalation Pathway\*

Soil Concentration	Integral Bone Doses, mrad			Dose Rate At 70 year m rad/yr	Integral Lung Doses, mrad			Maximum Annual Dose Rate m rad/yr
	30 year	50 year	70 year		30 year	50 year	70 year	
40 pCi/g	6.6	20	33	1.1	102	180	240	3.6
10 pCi/g (Janet)	1.7	5.0	9.8	0.29	26	45	60	0.9
0.07 pCi/g	0.0099	0.030	0.059	0.0017	0.15	0.27	0.36	0.0054

\*Includes the 50% increase in the doses in Tables 3 and 4 to account for  $^{241}\text{Am}$  and the reduction of 10 and 50 for lung and bone respectively to go from "rem" to "rad."

The major residence island in the northern half of the atoll, i.e., Engeb1 (Janet), has an average soil concentration of  $^{239,240}\text{Pu}$  of approximately 10 pCi/g. Using this value rather than the 40 pCi/g guideline and assuming that the  $^{241}\text{Am}$  concentrations also scale directly leads to a predicted maximum annual dose rate to lung of 0.9 mrad/year and to a 70 year integral dose of approximately 60 mrad.

The southern island living patterns has an average  $^{239,240}\text{Pu}$  soil concentration of approximately 0.06 pCi/g. This leads to a predicted maximum annual dose rate to lung of 0.0054 mrad/yr and a 70 year integral dose of 0.36 mrad.

### Terrestrial Foodchain

Because of the relatively small contribution of  $^{239,240}\text{Pu}$  to the total doses predicted over 70 year time periods, no effort was made in 1972-73 report (1) to thoroughly evaluate the dose from the plutonium. In addition, no attempt was made to include other transuranic radionuclides because they would still not significantly affect the total predicted doses which are dominated by  $^{137}\text{Cs}$  and  $^{90}\text{Sr}$ .

A more thorough evaluation of the predicted doses from  $^{239,240}\text{Pu}$  was made in a subsequent report (7). There was no attempt to incorporate the expected dose from other transuranics, however. In the present report we have taken the predicted doses for the terrestrial foodchain for  $^{239,240}\text{Pu}$  from reference 6 and have added an estimate of impact upon the transuranic dose from  $^{241}\text{Am}$  and  $^{238}\text{Pu}$ .

Therefore, the  $^{241}\text{Am}$  contribution is now included assuming that the present  $^{241}\text{Am}$  concentrations are about 40% of the  $^{239,240}\text{Pu}$  concentrations and assuming another 10% grow-in from  $^{241}\text{Pu}$ . Thus the total  $^{241}\text{Am}$  concentrations are about half of the  $^{239,240}\text{Pu}$  concentrations. Again, assuming that the gut transfer of  $^{241}\text{Am}$  is 10 times greater than for  $^{239,240}\text{Pu}$ , the dose from  $^{241}\text{Am}$  could be 5 times that from  $^{239,240}\text{Pu}$ . The contribution from  $^{238}\text{Pu}$  would be negligible when compared to the sum of the dose resulting from  $^{239,240}\text{Pu}$  and  $^{241}\text{Am}$ .

The results in "mrem" are listed in Table 6 and in "mrad" in Table 7.

Table 6. Integral Bone Doses from  $^{239,240}\text{Pu}$  and  $^{241}\text{Am}$  Via the Terrestrial Foodchain

Integral Bone Dose, <u>mRem</u>				
Location	Nuclide	5 year	30 year	70 year
Southern Islands	$^{239,240}\text{Pu}$	0.078	2.9	16
	$^{241}\text{Am}$	0.39	15	80
Janet	$^{239,240}\text{Pu}$	0.052	12	82
	$^{241}\text{Am}$	0.26	60	410

Table 7. Integral Bone Doses from  $^{239,240}\text{Pu}$  and  $^{241}\text{Am}$  Via the Terrestrial Foodchain

Integral Bone Dose, <u>mRad</u>				
Location	Nuclide	5 year	30 year	70 year
Southern Islands	$^{239,240}\text{Pu}$	1.6(-3)	0.058	0.32
	$^{241}\text{Am}$	7.8(-3)	0.29	1.6
Janet	$^{239,240}\text{Pu}$	1.0(-3)	0.24	1.6
	$^{241}\text{Am}$	5.2(-3)	1.2	8.2

The predicted concentrations of  $^{239,240}\text{Pu}$  in subsistence crops and meat were developed from a very limited data base using correlation methods and the concentration factor approach (7). More direct data on  $^{239,240}\text{Pu}$  and  $^{241}\text{Am}$  concentrations will be available in the future from our follow-up research program at Enewetak and Bikini Atoll's and will permit us to make a more refined assessment of the predicted dose via the terrestrial foodchain.

It is also emphasized that the 5 year integral dose is based upon the 1974 diet at time of return listed in Table 8. The 30 year and 70 year integral doses are based upon the diet in 1982 after many of the subsistence crops are again available. Any dietary program which supplies foods other than those locally grown will greatly reduce the dose estimates from this pathway. For example, at Bikini at the present time imported foods account

Table 8. Postulated Diet for the Returning Adult Enewetak Population

Food item	Diet, g/day	
	At time of return	10 yr post-return
Fish	600	600
Domestic meat	60	100
Pandanus fruit	0	200
Breadfruit	0	150
Wild birds	100	20
Bird eggs	20	10
Arrowroot	0	40
Coconut	100	100
Coconut milk	100	300
Coconut crabs	25	25
Clams	25	25
Imports	200-1000	200-1000
	1030 plus imports	1570 plus imports

for a majority of the diet. There is little dependence upon locally grown subsistence crops. In view of the significance of the terrestrial foodchain in the predicted doses if a full subsistence diet is used as in Table 6, a careful evaluation of the potential is critical to an accurate dose estimate for a returning population.

### Groundwater

The average Pu concentrations in groundwater for Engebi and other northern islands are reported in reference 4. These concentrations could be compared with concentrations and doses reported in reference 5 and 6 for Bikini and Eneu Islands in order to assess the drinking water pathway assuming the consumption of groundwater. This pathway, particularly if rain water provides a part of or the major fraction of the drinking water, should contribute a very small fraction of the total predicted dose.

### Summary

The summary of the integral bone and lung doses and the dose rates resulting from transuranics at Enewetak Atoll are listed in Table 9 for the southern island living pattern and the northern living pattern involving Engebi Island. The predicted dose rates for the southern islands and Engebi Island do not exceed the 1 mrad/yr to lung nor the 3 mrad/yr to bone guidance proposed by EPA. For example the northern island living patterns lead to the higher doses and for Engebi Island the maximum annual predicted dose rate for lung is 0.6 mrad/yr and the dose rate to bone at 70 years is 0.85 mrad/yr.

In many cases it is more useful to consider "rem" doses rather than "rad" doses. To help in assessing the dose levels predicted from the transuranics Table 10 lists the dose summary in terms of "rem".

**Table 9 Integral Bone and Lung Doses and Dose Rates from  $^{239}\text{Pu}$  and  $^{241}\text{Am}$  for the Southern Islands and Engebi at Enewetak, Atoll mrad**

Location	Pathway	Integral Bone Doses, mrad		Dose Rate At 70 yr, mrad/yr	Integral Lung Doses, mrad			Maximum Annual Lung Dose Rate mrad/yr	
		30 yr	50 yr		70 yr	30 yr	50 yr		70 yr
Southern Islands	Inhalation	0.0099	0.030	0.059	0.0017	0.15	0.27	0.36	0.0054
	Marine	0.52	1.4	2.5	0.068	-	-	-	-
	Terrestrial	0.35	-	1.9	0.051	-	-	-	-
	Total	0.88	-	4.5	0.12	0.15	0.27	0.36	0.0054
Engebi (Janet)	Inhalation	1.7	5.0	9.8	0.29	26	45	60	0.9
	Marine	3.1	8.0	15	0.40	-	-	-	-
	Terrestrial	1.4	-	9.8	0.26	-	-	-	-
	Total	6.2	-	35	0.95	26	45	60	0.9

Table 10. Integral Bone and Lung Doses and Dose Rates from  $^{239,240}\text{Pu}$  and  $^{241}\text{Am}$  for the Southern Islands and Engebi Island at Enewetak Atoll, mrem

Location	Pathway	Integral Bone Doses, mrem			Dose Rate At 70 yr, mrem/yr	Integral Lung Doses, mrem			Maximum Annual Lung Dose Rate mrem/yr
		30 yr	50 yr	70 yr		30 yr	50 yr	70 yr	
Southern Islands	Inhalation	0.50	1.5	3.0	0.085	1.5	2.7	3.6	0.054
	Marine	26	68	126	3.4	-	-	-	-
	Terrestrial	18	-	96	2.6	-	-	-	-
	Total	45	-	225	6.1	1.5	2.7	3.6	0.054
Engebi (Janet)	Inhalation	85	250	490	15	260	450	600	9
	Marine	154	400	750	20	-	-	-	-
	Terrestrial	72	-	490	13	-	-	-	-
	Total	311	-	1740	48	260	450	600	9

1. Enewetak Radiological Survey  
NVO-140 Report Volume 1  
U.S. Atomic Energy Commission  
Nevada Operations Office 1973
2. V. E. Noshkin, K. M. Wong, R. J. Eagle and C. Gatrouris  
Transuranics at Pacific Atolls
  1. Concentrations in the Waters at Enewetak and Bikini  
Lawrence Livermore Laboratory, Rept. UCRL-51612, 1974
3. Noshkin, V. E.  
Comparison of Pu Concentrations in Mullet Tissue from Bikini and  
Enewetak Atoll (in press)
4. V. E. Noshkin, K. M. Wong, K. Marsh, R. Eagle and G. Holladay  
Plutonium Radionuclides in the Groundwater at Enewetak Atoll in  
Transuranium Nuclides in the Environment  
IAEA Symposium San Francisco 17-21 November 1975  
IAEA Vienna, 1976
5. V. E. Noshkin, W. L. Robison, K. M. Wong and R. J. Eagle  
Evaluation of the Radiological Quality of the Water on Bikini and  
Eneu Islands in 1975: Dose Assessment Based on Initial Sampling  
Lawrence Livermore Laboratory Report UCRL-51879 Part 4 1977
6. W. L. Robison, W. A. Phillips and C. S. Colsher  
Dose Assessment at Bikini Atoll  
Lawrence Livermore Laboratory Report UCRL-51879 Part 5  
1977
7. D. W. Wilson, Y. C. Ng and W. L. Robison  
Evaluation of Plutonium at Enewetak Atoll  
Health Physics Vol. 29, 599-611 (1975)

## EVALUATION OF PLUTONIUM AT ENEWETAK ATOLL

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(Received 10 February 1975)

**Abstract**—An extensive survey was carried out in 1972-1973 to assess the current radiological status of Enewetak Atoll. The radionuclides detected in the Atoll environment were studied for their potential contributions to the dose commitment of the returning population according to several pathways of exposure. Plutonium was detected in air and in the terrestrial and aquatic environment at concentrations that varied from background levels due to world-wide fallout to levels several orders-of-magnitude above. The dose commitments from plutonium via the terrestrial food chain and inhalation vary according to the postulated living pattern. The dosages via marine foods can be expected to be insensitive to living pattern and to exceed those via terrestrial foods. Plutonium would contribute nearly all of the dosage via inhalation, but this pathway ranks low in overall importance compared with the food-chain and external-dose pathways. Although the potential dose from plutonium via all pathways is low relative to that from  $^{60}\text{Co}$ ,  $^{90}\text{Sr}$  and  $^{137}\text{Cs}$ , plutonium will still remain in the Atoll environment after the other major isotopes have decayed away.

### INTRODUCTION

ENEWETAK Atoll in the central Pacific Ocean 2380 naut. miles southwest of Honolulu was the site of 43 nuclear weapons tests carried out by the U.S. from 1948 to 1958. Testing resulted in the deposition of fission products, activation products, and nuclear fuel materials in the terrestrial and aquatic environment of the Atoll, in particular in the north and northeast portions.

In late 1972 the AEC carried out a radiological survey of Enewetak aimed at gathering data needed to develop clean-up and rehabilitation procedures for the resettlement of the Enewetak people to their homeland. An intensive measurements and evaluation program was carried out to define the present distribution of radionuclides and their significance to the radiation exposures of an indigenous population. This paper is drawn from the results of the survey (NVO, 1973) and highlights the findings with special emphasis upon results obtained for plutonium.†

\* This work was performed under the auspices of the U.S. Atomic Energy Commission.

† Unless otherwise stated, plutonium refers to measured  $^{239}\text{Pu}$  and  $^{240}\text{Pu}$  together.  $^{239}\text{Pu}$ ,  $^{240}\text{Pu}$  and  $^{241}\text{Pu}$  are present in the Atoll, but constitute less than 10% of the total plutonium.  $^{241}\text{Am}$  is also

Enewetak Atoll consists of 40 islands on an elliptical coralline reef, approx  $23 \times 17$  naut. miles, with the long axis running northwest to southeast (Fig. 1). The total land area is but 2.75 miles<sup>2</sup>, and the mean height above sea level is only 10 ft. The large, central, ocean lagoon is 388 miles<sup>2</sup> in area.

The Atoll climate is tropical marine with high humidity and about 60 in/yr of precipitation. The islands are vegetated heavily with native and introduced species. The Enewetak people have not inhabited the Atoll since testing, so cultivation has been absent and the system appears to be succeeding toward a forest of native trees. Succession has been arrested in some areas as a result of continuing military operations on the Atoll which involved construction and earth moving. While the terrestrial ecosystem is relatively simple, the marine ecosystem is complex and biologically active, typical of tropical reef and lagoon communities.

The Enewetak people, returning, can be expected to practice nonintensive agriculture for coconuts, pandanus, breadfruit and arrowroot and to rely heavily upon the abundant

present and is still increasing slightly due to decay of  $^{241}\text{Pu}$ ; however, dose contributions expected from  $^{241}\text{Am}$  are less than those from Pu.

## EVALUATION OF PLUTONIUM AT ENEWETAK ATOLL

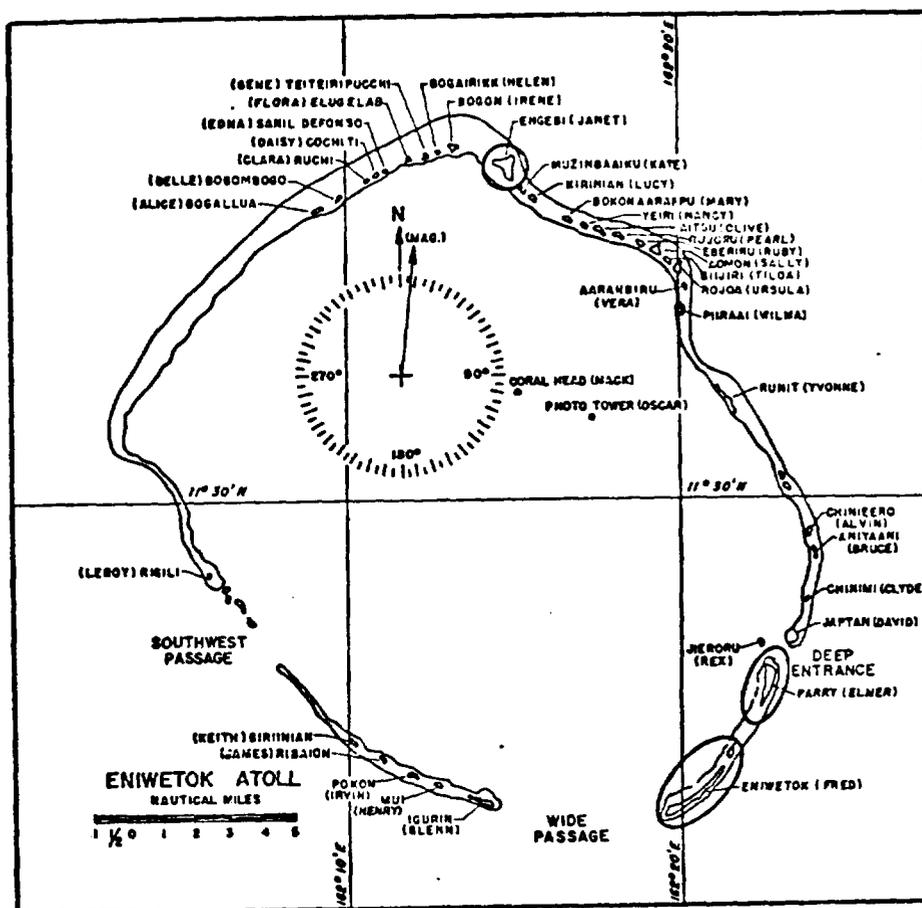


FIG. 1. Enewetak Atoll with true island names and corresponding U.S. site names. Encircled islands are the islands of choice for residence by the Enewetak people.

marine resources of the Atoll. They will continue to import rice, flour, sugar and other staple foods. Resettlement will involve a major program in replanting desired species for food and cash crops such as coconuts. While the population of over 400 people will choose to live centrally on one or more of the large islands, they will utilize most all of the Atoll for agricultural and food gathering purposes. Village areas will be chosen, and houses, community structures, and roads will be built. The choices among the various options in living patterns (agriculture practices, villages, houses, dietary habits) are important variables in the radiological assessment.

#### HIGHLIGHTS OF THE SURVEY METHODS

The survey was a detailed documentation of present radioactivity levels in soil, sediments, water, air and biota. The sampling design was developed to meet the needs for assessing all the potentially significant pathways of dose to man. In the terrestrial environment, measurements of radioactivity were made of the soil and biota of all islands, so that assessments could be made island-by-island. To the extent possible, edible crops were sampled, but the low numbers of edible plants limited the data base. As an alternative, abundant and ubiquitous species of nonedible vegetation were measured to obtain an understanding of the distribution

Table 1. Plutonium in Eniwetok Soils, pCi/g

Island	In Top 15 cm		In Top 2 cm	
	Median	Range	Median	Range
Alice	12	3.9-68	96	3.9-105
Belle	-	-	96	12-230
Dense	26	7.2-130	-	-
Sparse	11	3.8-26	-	-
Clara	22	3.8-88	40	11-80
Daisy	-	-	50	8-180
Dense	41	22-98	-	-
Sparse	15	3.8-33	-	-
Edna	18	13-24	18	-
Irene	11	2.4-280	13	2.3-43
Janet	8.5	0.08-170	21	2.8-100
Kate	-	-	28	1.8-62
Dense	17	8.6-50	-	-
Sparse	2.3	0.17-14	-	-
Lucy	7.7	2.4-22	34	8.0-49
Mary	8.0	2.0-35	18	2.0-26
Nancy	9.1	2.3-28	23	9.6-35
Percy	3.5	1.5-23	11	5.5-16
Olive	-	-	54	2.8-87
Dense	7.7	2.2-30	-	-
Sparse	2.8	1.9-4.1	-	-
Pearl	-	-	70	4.0-400
Hot Spot	51	15-530	-	-
Remainder	11	0.85-100	-	-
Ruby	7.3	3.0-24	2.7	-
Sally	4.3	0.21-130	18	1.7-62
Tilda	-	-	5.8	2.0-16
Dense	7.6	1.4-17	-	-
Sparse	2.5	1.1-34	-	-
Urvula	1.3	0.26-7.3	1.5	0.6-2.7
Vera	2.5	0.60-25	22	1.5-35
Wilma	1.1	0.1-5.3	3.3	1.2-7.0
Southern Yvonne	3.2	0.02-50	10	0.24-32
Northern Beaches	2.7	0.34-18	-	-
David, Elmer, Fred	0.04	0.004-0.31	0.12	0.01-0.90
Leroy	0.63	0.02-2.0	1.7	1.1-2.6
All Other				
Southern Islands	0.07	0.004-1.1	0.12	0.01-0.45

of radionuclides in vegetation on each island. Thorough study was made of the gamma ray fields produced by  $^{137}\text{Cs}$  and  $^{60}\text{Co}$  in soils.

Similarly, a large number of samples were obtained from the water and sediments of the marine ecosystem, resulting in a detailed inventory of radionuclides in the ecosystem. Marine biota were extensively sampled with consideration for the preferred diet of the Enewetak people.

Air sampling was carried out over the ocean and on several islands to measure the amount of radioactivity in the air due to resuspended particles from the soil. Several kinds of air samplers were employed to determine levels close to heavily contaminated areas, to examine particle size ranges in the suspended aerosol, and to look for evidence of any systematic elevation of radioactivity in air in the vicinity of the islands.

Necessarily, not much detail of the survey techniques nor the resulting data can be

reproduced here. Readers desiring more detail are directed to the survey report (NVO, 1973).

#### HIGHLIGHTS OF SURVEY RESULTS ON PLUTONIUM

The plutonium distribution in Enewetak soils is variable over the Atoll, with levels in the southern islands corresponding to values expected due to world-wide fallout, to small areas containing hundreds of pCi of plutonium/g of soil on northern islands (Table 1). The measured distribution is consistent with that expected on the basis of testing history.

The amount of plutonium in soil generally decreases with depth down the soil column, but the effects of more recent earth moving in some locations are noticeable in inverting the depth profile. The general trend can be seen by comparing the median values for plutonium in the top 2 cm of soil with values for the top 15 cm of soil. A small area on northern Yvonne contains the highest levels of plutonium measured and an unpredictable depth distribution.

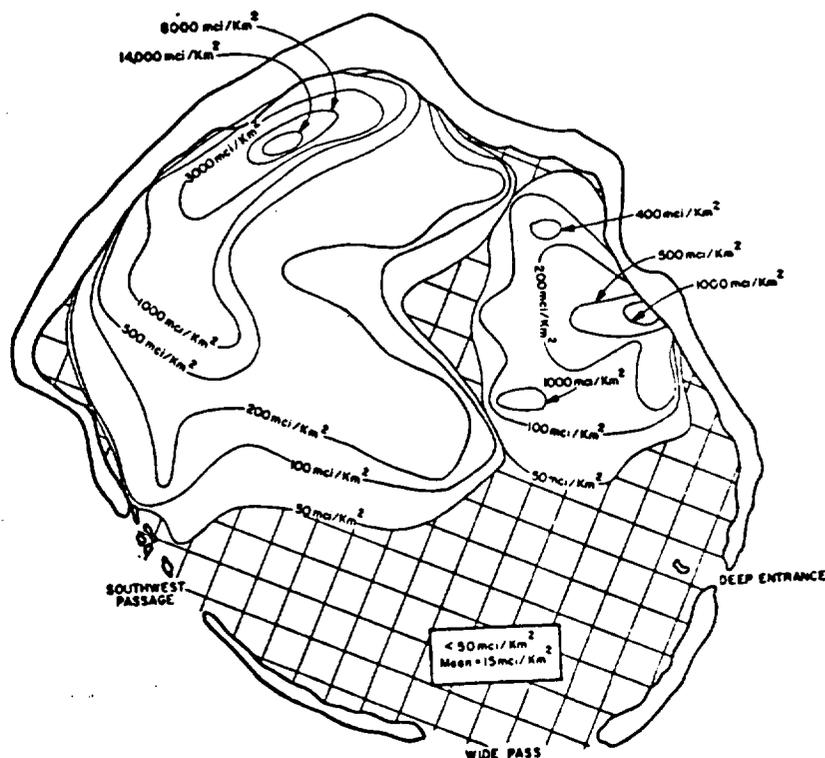


FIG. 2. Plutonium in the bottom sediments of Enewetak Lagoon.

In this area, in spite of the appearance of some samples containing as high as 3000 pCi/g, most samples taken contained less than 100 pCi/g.

The largest inventory of plutonium at Enewetak was measured in the marine bottom sediments. Plutonium is non-uniformly distributed over the lagoon floor with highest levels in the northeast (see Fig. 2). The mean plutonium concentration in bottom sediments of the lagoon was 463 mCi/km<sup>2</sup>, some 200 times world-wide fallout background. Crater areas in the lagoon near Alice and Belle were the highest plutonium areas measured on the Atoll.

The plutonium concentration in lagoon water ranged from 43 fCi/l. in the northeast quadrant to 9 fCi/l. in the southeast quadrant. The ocean east of Enewetak contained 0.3 fCi/l. Surface waters in the lagoon on the average contained 30% more plutonium than did deep water, suggesting that runoff from the reef and land is a more important source of plutonium to the lagoon water than the large burden of plutonium in the bottom sediments.

The surface atmosphere of the Atoll contained plutonium in a range of <0.003–0.008 fCi/m<sup>3</sup>, which is comparable to levels expected due to world-wide fallout. Extreme conditions of high winds led to levels of <0.04–0.13 fCi/m<sup>3</sup> downwind from a plutonium hot spot on Yvonne. While survey results showed that air levels were very low, it is conceivable

that human activities, say in village areas would be a sufficient disturbance of soil surfaces to result in higher air loading with plutonium.

The major emphasis in the marine food chain study was on sampling of the reef fish which will comprise the largest diet component from the marine ecosystem. Almost 900 marine specimens were obtained for radionuclide analysis. The specimens were pooled and analyzed in four categories to determine any differences between species or location of catch. The concentration of plutonium in fish was not strongly dependent on the species or on the location of the catch. The average concentration for pelagic fishes plus reef fishes (mullet, goatfish and convict surgeon) was 0.2±8 pCi/g, range 0.005 to 23 pCi/g (see Table 2).

Over 1000 specimens of plants, birds, eggs, rats and land crabs were taken in the terrestrial biota survey (see Table 3). Coconut was obtained on 16 islands, but only a few samples of pandanus and tacca (arrowroot), and no breadfruit were obtained. *Messerschmidia* and *Scaevola*, and other indicator plants were obtained throughout the Atoll. Birds, bird eggs and rats were plentiful for sampling, but coconut crabs were taken only from a few of the southern islands.

The greatest concentration of plutonium in coconut was 0.036 pCi/g in a sample from Irene. The concentrations in coconut from the other

Table 2. Summary of plutonium concentrations in muscle of fish at Enewetak

Species	No. of Samples	Concentration (pCi/g dry wt.)				
		Average <sup>a</sup>	Standard Deviation	Range	Normal Median	
Mullet	25	0.981	0.964	4.60	0.000482 - 23.1	0.0145
Surgeon	28	0.0768	0.0772	0.169	0.00428 - 0.887	0.0260
Goatfish	21	0.0223	0.0130	0.0151	0.00161 - 0.0531	0.00778
Other Fish	49	0.0637	0.0700	0.238	0.000788 - 1.21	0.00909
All Fish	123	0.244	0.248	2.08	0.000482 - 23.1	0.0126

<sup>a</sup>If a measurement was below the limits of detection, the concentration was set equal to zero.

<sup>b</sup>If a measurement was below the limits of detection, the concentration was set equal to the limits of detection.

Table 3. Plutonium in terrestrial biota at Enewetak Atoll

Type of Sample	Concentrations (pCi/g dry wt)	
	Niulikaofu	Naali Island
Meat		
Bird	0.0013 (Yvonne)	0.056 (Elmer)
Milk	B	
Pandanus		
Fruit	0.0034 (Belle) <sup>b</sup>	
Leaves	0.0013 (David)	0.013 (Sally)
Tacca		
Corn	0.0011 (David) <sup>b</sup>	
Birds		
Muscle	0.0010 (Keith)	0.12 (David)
Liver	0.0015 (Janet)	0.062 (Alvin)
Egg	0.00045 (Yvonne)	0.015 (Janet, Sally)
Coconut Crab		
Muscle	0.00076 (Yvonne)	0.0031 (LeRoy)
Hepatopancreas	0.0019 (Yvonne)	0.0098 (Keith)
Messerschmidia	0.0019 (Yvonne)	0.77 (Yvonne)
Scaevola	0.00050 (David)	1.29 (Yvonne)
Rat		
Viscera	0.0074 (Elmer)	1.77 (Pearl)
Muscle	0.0023 (Janet)	0.12 (Pearl)
Liver	0.008 (Sally, Yvonne)	0.041 (Orville)
Bone	0.020 (Janet)	3.25 (Janet)

<sup>a</sup>Measurements at levels below the limits of detection.

<sup>b</sup>Only a single sample was collected.

islands were less by an order-of-magnitude or more or were below the limits of detection. The only concentration reported in pandanus fruit, 0.0034 pCi/g, was for the sample from Belle. Concentrations in pandanus leaves varied from 0.0013 pCi/g in the sample from David to 0.015 pCi/g in that from Sally. The concentration in the single sample of tacca corm (David) was 0.0011 pCi/g. Concentrations in muscle and liver of birds varied irregularly from island to island and ranged from 0.0010 to 0.12 pCi/g in muscle and from 0.0015 to 0.062 pCi/g in liver. The range of plutonium concentrations in bird eggs was 0.00045–0.015 pCi/g. The range in muscle of coconut crabs was 0.00076–0.0031 pCi/g, that in hepatopancreas was 0.0019–0.0098 pCi/g. The concentrations in *Messerschmidia* and *Scaevola* from the same location were comparable and varied over an extreme range of 0.00050 pCi/g on David to 1.29 pCi/g on Yvonne. Plutonium levels in rat tissues were greatest in bone and decreased in the order bone, viscera, liver and muscle. The greatest concentration in bone, 3.25 pCi/g, was measured in a rat taken from Janet.

#### EVALUATION OF PATHWAYS

Exposures to plutonium were evaluated for the inhalation of airborne dust, and for doses

derived from ingestion of foods from terrestrial and marine food chains. Calculations were made on an island-by-island basis using the survey measurements data obtained for each island. These results were applied to a hypothetical living pattern model which had the island of residence and islands used for agriculture as variables. Two of the living patterns are covered here. These cases are solutions which include the likely islands of residence, Fred and Janet (see Fig. 1):

Living Pattern I: Live on Fred and Elmer, carry out agriculture on Alvin through Keith

Living Pattern III: Live on Janet and carry out agriculture on Janet.

In both living patterns, fishing is carried out over the entire Atoll. These two living patterns approximate a limiting low radiation background case (in the southern islands) and a limiting high radiation background case (living and farming in the north only). Other living patterns can be constructed and evaluated by using the results of the island-by-island assessment.

#### Inhalation pathway

It has been well documented that radioactivity in soils can resuspend in the atmosphere and be available for inhalation. Quantitative models of this pathway and the doses obtainable from a given level of contamination are under development, but there are large uncertainties inherent in them. These limitations are discussed in detail in NVO-140 and in a paper by ANSPAUGH *et al.* (1975) in this issue of *Health Physics*. A completely empirical approach to assessing this pathway would require a large measurement program carried out under actual conditions of occupation of the Atoll. As an alternative, a predictive model was developed which utilizes world-wide data on dust loading in the atmosphere, the soil measurements at Enewetak, and a set of conservative assumptions discussed below.

It is important to provide an evaluation that considers, as far as possible, the potential for exposure to a returned population, which takes into account both the population distribution on the Atoll and the patterns of living. Under conditions of habitation, large areas of soil surface will become stabilized by cultivated

vegetation, coral layering in the village areas, and by buildings. These activities will tend to reduce the possibility for resuspension of soil particles. However, human activities such as construction, earth moving, agricultural activities, and children playing, tend to stir up dust. Exposure levels to individuals will depend on such local sources.

The objectives of the measurements and this assessment were to obtain sufficient understanding to place this pathway for dosage in perspective to the food chain pathways. The air sampling program showed that resuspension levels were measurably above background only in the downwind vicinity of scattered hot spots of soil contamination.

Estimates of potential population exposures were made by applying the model,

$$Dt = C_s \cdot Rt \cdot L_a$$

where:

$Dt$  = dose in rem to organ of reference after  $t$  yr of continued exposure

$C_s$  = concentration of plutonium in soil, pCi/g

$Rt$  = dose conversion factor, rem/pCi/m<sup>3</sup>, for cumulative dose to organ of reference from  $t$  yr of continued exposure

$L_a$  = soil loading in air, g/m<sup>3</sup>.

This model assumes that plutonium concentrations in soil are conserved in the resuspension process. A value of 100  $\mu\text{g}/\text{m}^3$  was used for  $L_a$ , based upon evaluation of a set of measurements of dust in non-urban U.S. air (NAPCA, 1968). In this study, mean dust loads ranged from 9 to 79  $\mu\text{g}/\text{m}^3$  with an overall average of about 40  $\mu\text{g}/\text{m}^3$ . Enewetak soils are moist and dust loading is minimal; however, a value of 100  $\mu\text{g}/\text{m}^3$  was adopted for  $L_a$  to insure a reasonably conservative accounting for the close proximity of individuals to sources of soil disturbance.

Calculations were carried out for each island using soil measurements of plutonium (see Table 1), and dose conversion factors derived by BENNETT (1974a) using the ICRP Lung Dynamics Model for 0.4- $\mu\text{m}$  plutonium fallout particles of low solubility. Calculations were made for the 0-2 cm of soil samples and for the 0-15 cm samples.

Table 4. Cumulative rems in 70 yr to organs from plutonium via inhalation pathway (based upon plutonium concentration in 0-2 cm of soil)

Living Pattern	Lung	Liver	Bone
I (Southern Islands)	0.002	0.002	0.004
III (Live on Janet)	0.306	0.289	0.612

Results of these calculations (see Table 4) show that the population exposures to be expected fall in the mrem range for a lifetime of occupation. Occupation of the southern islands, Living Pattern I, results in organ doses in 70 yr the order of a few mrem, while occupation of northern islands will lead to organ doses approaching a rem in 70 yr. The highest dosages from this pathway were calculated for occupation of Belle, 2.77 rem in 70 yr. These results indicate that the inhalation pathway will not be a significant feature of population dosages. Removal of hot spot radioactivity and land use planning can insure that plutonium resuspension is a negligible pathway to man in the rehabilitated Atoll.

#### Terrestrial and marine food chains

Two dietary cases were developed (see Table 5); the first, which is associated with the time of return is distinguished by the absence of pandanus fruit, breadfruit and arrowroot. These items appear only in the 10-yr post-return diet since it requires several years for these crops to reestablish and come to full production. This

Table 5. Postulated diet for the returning adult Enewetak population

Food item	Diet, g/day	
	At time of return	10 yr post-return
Fish	600	600
Domestic meat	60	100
Pandanus fruit	0	200
Breadfruit	0	150
Wild birds	100	20
Bird eggs	20	10
Arrowroot	0	40
Coconut	100	100
Coconut milk	100	300
Coconut crabs	25	25
Clams	25	25
Imports	200-1000	200-1000
	1030 plus imports	1570 plus imports

diet is based on the carefully considered judgement of persons who have lived in the Marshall Islands in intimate association with the native residents and therefore have first-hand knowledge of their living habits. Accurate assessment of the role of imported foods is not possible, but it is generally recognized that imported foods, such as rice, flour, tea, canned fish and canned meats, will be major components of the diet. Accordingly, the dosage via food chains may be overestimated to the extent that imported food items will replace food items listed in the table.

Many of the items expected in the terrestrial diet were not available in sufficient quantity for adequate sampling at the time of the survey, and other constituents of the ecosystem, i.e. soil and native plants and animals were sampled. In the case of plutonium, prediction of the concentrations in terrestrial foods was carried out following two basic approaches. In one approach it was based largely on the concentrations measured in edible or indicator species. Pandanus leaves served as the direct indicator for pandanus fruit, breadfruit and coconut, and rats served as the direct indicator for domestic meat (pork and chicken) wherever edible species were not sampled or the measurements were inadequate. The concentration of plutonium in a given edible or indicator item for a particular island group was determined as the mean of the samples collected in that island group. The concentration in meat was determined as the overall mean in muscle and liver of rats. In the other approach, prediction was based largely on concentrations estimated from data on average soil concentration and concentration factors between indicator species and soil. Pandanus leaves and rats served in similar fashion as indicator species. The two approaches are not entirely independent, since in each case the concentrations of plutonium in birds, bird eggs and coconut crabs were based on measurements.

Concentration factors were determined by pairing plant or animal and soil data for the same location and then calculating pCi/g dry plant or animal tissue per pCi/g soil (see Tables 6 and 7). The concentration in meat was calculated assuming a concentration factor of 0.005, the overall median for muscle and liver

Table 6. Relationship between plutonium concentrations in animal tissues and soil

Species, Tissue	No.	Concentration Factor (pCi/g dry tissue ÷ pCi/g dry soil)		
		Min.	Median	Max.
Rat				
Muscle	11	0.00009	0.013 <sup>a</sup>	0.79
Liver	13	0.00014	0.0033 <sup>a</sup>	2.0
Bone	15	0.0017	0.014	9.1
Pooled	39	0.00009	0.094	9.1
Coconut Crab				
Muscle	5	0.0032	0.013	0.118
Hepatopancreas	4	0.0039	0.026	1.12
Exoskeleton	5	0.0084	0.026	0.017
Pooled	14	0.0032	0.016	0.12
Hermit Crab				
Muscle	6	0.0030	0.093	0.53
Hepatopancreas	4	0.0087	0.031	0.11
Exoskeleton	5	0.00074	0.010	0.18
Pooled	15	0.00074	0.048	0.53
Pooled Coconut Crab & Hermit Crab	29	0.00074	0.026	0.53

<sup>a</sup>Overall median of muscle and liver combined is 0.005.

of rat (see Table 6). The concentration in pandanus leaves was estimated using a concentration factor of 0.003, the median concentration factor for *Messerschmidia* and *Scaevola* (see Table 7). The average concentration of plutonium in the 0-15-cm soil profile was computed from Table 1 to be 0.065 pCi/g for island group Alvin-Keith and 8.5 pCi/g for Janet.

It is not surprising that the ranges of concentration factor vary greatly by as much as factors of 10<sup>3</sup> or more since this procedure is inherently lacking in precision. However, the major fraction of the calculated concentration factors is within an order-of-magnitude of the median value. Although the concentrations of

Table 7. Soil-to-plant uptake of plutonium

Plant Type	No. of Samples	Concentration Factor (pCi/g dry plant ÷ pCi/g dry soil)		
		Min.	Median	Max.
<i>Messerschmidia</i>	24	0.00017	0.0030	0.20
<i>Scaevola</i>	24	0.00013	0.0031	0.14
Pooled <i>Messerschmidia</i> & <i>Scaevola</i>	48	0.00013	0.0030	0.20
Coconut Meat	2	0.0013		0.0077
Pandanus Leaves	4	0.00046	0.0056	0.01

plutonium in rat tissues were not significantly correlated with those in soil, there were statistically significant correlations between the logarithms of the plutonium concentrations in *Messerschmidia*, *Scaevola*, and pooled *Messerschmidia* and *Scaevola* and those in soil (*Messerschmidia*  $P = 0.05$ , *Scaevola*  $P = 0.01$ , pooled *Messerschmidia* and *Scaevola*  $P = 0.001$ ). Furthermore the linear regression lines for *Messerschmidia* and *Scaevola* were found to be statistically indistinguishable with common slopes and common intercepts.

The concentrations of plutonium predicted for terrestrial foods from island groups Alvin-Keith and Janet were selected by the approach yielding the greater values of concentration (see Table 8). Those listed for Alvin-Keith were based on measurements, those for Janet were based primarily on concentration factors and levels in soil. The concentrations are listed according to two different start dates. Meat, birds, bird eggs, coconut crabs and coconut from the southern islands are assumed to be available relatively soon following return to the Atoll and their concentrations are listed under 1 January 1974, the postulated date of return. The edible plants are generally assumed to become available for the first time 8 yr after

return and their concentrations are listed under 1 January 1982. Most of the plutonium concentrations are considerably in excess of the concentrations reported in terrestrial foods from the 1972 New York diet, which range from  $9 \times 10^{-7}$  pCi/g fresh weight in canned vegetables to  $8.5 \times 10^{-8}$  pCi/g fresh weight in bakery products (BENNETT, 1974b).

Plutonium in the marine food chain was evaluated in four main fish groups—surgeonfish, goatfish, mullet and "other" fish—where "other" includes not only other species of fish but also tridacna clams and *lingusta*. The mean concentrations in the four fish groups did not differ significantly, and furthermore, dependence of concentrations on island location was not discernible. Accordingly the mean concentration of plutonium in muscle of all fish from the entire Atoll was used to predict exposure to plutonium from the ingestion of marine foods. The overall mean concentration of 0.248 pCi/g was used in the assessment of dose rather than the lognormal median value, which is about a factor of 20 less (see Table 2).

By way of comparison the mean plutonium concentration in fish collected in contaminated waters at Thule, Greenland in 1968 was 0.14 pCi/g fresh weight; the median and mean in soft tissues of bivalves from Zone I were 8.0 pCi/g and 150 pCi/g fresh weight (AARROG, 1971). The concentration reported for shellfish in the 1972 New York diet was  $1.1 \times 10^{-5}$  pCi/g fresh weight (BENNETT, 1974b). Thus the mean plutonium concentration in fish from Enewetak is comparable to that in fish from Thule and exceeds the concentration reported for shellfish in the 1972 New York diet by more than three orders-of-magnitude.

Rates of ingestion of plutonium were determined by combining the results of Tables 5 and 8. Except for coconut and arrowroot the diets listed in Table 5 refer to ingestion of fresh food. The following values of water content were used to calculate rates of ingestion of plutonium via foodstuffs: coconut meat 50%, coconut milk 95%, pandanus 80%, breadfruit 70%, bird muscle and liver 70%, bird eggs 75%, coconut crab liver 81%, coconut crab hepatopancreas 62%, rat muscle and liver 73% and fish 71% (NVO, 1973). Rates of ingestion (see Table 9) have been computed for the diet at the time of

Table 8. Concentrations of plutonium in terrestrial foods

	Concentration, pCi/g dry wt	
	Jan. 1, 1974	Jan. 1, 1982
Island Group		
Alvin-Keith <sup>a</sup>		
Domestic Meat	0.020	0.020
Pandanus Fruit	n.s. <sup>b</sup>	0.0039
Breadfruit	n.s.	0.0039 <sup>c</sup>
Wild Birds	0.0235	0.0235
Bird Eggs	0.00065	0.00065
Arrowroot <sup>b</sup>	n.s.	n.s.
Coconut Meat	0.0016	0.0016
Coconut Milk	0.016 <sup>d</sup>	0.016 <sup>d</sup>
Coconut Crabs	0.0027	0.0027
Island Group		
Janet		
Domestic Meat	0.043	0.043
Pandanus Fruit	n.s.	0.026
Breadfruit	n.s.	0.026 <sup>e</sup>
Wild Birds	0.0033	0.0033
Bird Eggs	0.0148	0.0148
Arrowroot <sup>b</sup>	n.s.	n.s.
Coconut Meat	n.s.	0.026 <sup>e</sup>
Coconut Milk	n.s.	0.26 <sup>d</sup>
Coconut Crabs	n.s.	n.s.

<sup>a</sup>The concentration for Alvin-Keith are based on measurements; those for Janet are based primarily on concentration factors and levels in soil.

<sup>b</sup>The abbreviation n.s. signifies not available. Although arrowroot can be expected in the diet beginning 1982, it can be expected to contribute relatively very little plutonium to the terrestrial diet and no concentration has been listed.

<sup>c</sup>The concentration is assumed to be that in pandanus leaves.

<sup>d</sup>The dry wt concentration in coconut milk is assumed to be 10 times that in coconut meat.

## EVALUATION OF PLUTONIUM AT ENEWETAK ATOLL

Table 9. Rate of ingestion of plutonium from terrestrial and aquatic foods

	Ingestion Rate, pCi/day		
	Assuming Diet at Time of Return Jan. 1, 1974	Assuming 10-yr Postreturn Diet Jan. 1, 1974	Assuming 10-yr Postreturn Diet Jan. 1, 1982
<b>Island Group</b>			
Alvin-Keith			
Fish	44	44	
Domestic Meat	0.32	0.54	
Pandanus Fruit			0.16
Breadfruit			0.18
Wild Birds	0.70	0.14	
Bird Eggs	0.003	0.002	
Coconut Meat	0.16	0.16	
Coconut Milk	0.06	0.24	
Coconut Crabs	0.023	0.023	
TOTAL	45.3	45.1	0.33
<b>Island Group</b>			
Janet			
Fish	44	44	
Domestic Meat	0.69	1.2	
Pandanus Fruit			1.0
Breadfruit			1.2
Wild Birds	0.10	0.020	
Bird Eggs	0.074	0.037	
Coconut Meat			2.6
Coconut Milk			3.8
TOTAL	44.9	45.2	8.6

return and for the 10-yr post-return diet. The total rate of ingestion assuming the diet at the time of return, which considers only those food items that are available at the time of return, has been used to estimate 5- and 10-yr integral dosages. The total rate of ingestion assuming the 10-yr post-return diet has been used to estimate the 30- and 70-yr integral dosages. Fish and other marine foods are seen to contribute the bulk of the plutonium to the diet. The daily rates of plutonium ingestion in Table 9 would greatly exceed that for residents of New York, whose ingestion rate of plutonium was estimated to be 1.5 pCi/yr in 1972 (BENNETT, 1974b).

Table 10. Uptake and retention parameters for  $^{239}\text{Pu}$ 

	Bone	Liver
$E$ (MeV)	270	53
$f_{\text{man}}$	$1.35 \times 10^{-5}$	$1.2 \times 10^{-5}$
$M$ (g)	3000	1800
$\lambda_{\text{man}}$ ( $\text{day}^{-1}$ )	$1.91 \times 10^{-5}$	$4.76 \times 10^{-5}$
$\lambda_r$ ( $\text{day}^{-1}$ )	$7.79 \times 10^{-8}$	$7.79 \times 10^{-8}$

Doses were calculated assuming that the radionuclide concentrations in foods decrease with time by radioactive decay alone. Uptake and retention in human organs, organ mass and the energy absorbed in tissue per disintegration were adapted from ICRP (1959, 1972) reports or from the more recent literature (see Table 10). The integrated dose via food chain was determined from the equation below:

$$\text{Dose (rem)} = \frac{KEI f_{\text{man}} C_0}{M(\lambda_{\text{man}} - \lambda_r)} \times \left[ \frac{1 - e^{-\lambda_r t}}{\lambda_r} - \frac{1 - e^{-\lambda_{\text{man}} t}}{\lambda_{\text{man}}} \right]$$

where

$$K = 5.1 \times 10^{-8} \frac{\text{dis/g/rem}}{\text{pCi/MeV/day}}$$

$E$  = disintegration energy, MeV (includes RBE and  $n$  factors)

$I$  = food intake, g/day

$f_{\text{man}}$  = fraction of nuclide ingested reaching the organ of reference

$C_0$  = initial concentration of nuclide in food product, pCi/g

$M$  = mass of the organ of reference, g

$\lambda_{\text{man}}$  = effective elimination rate of nuclide from organ of reference,  $\text{day}^{-1}$

$\lambda_r$  = radioactive decay constant,  $\text{day}^{-1}$

$t$  = time, day.

Dosages to bone and liver from ingestion of plutonium for island groups Alvin-Keith and Janet integrated over 5, 10, 30 and 70 yr were computed using the rates of ingestion of Table 9. The predicted 5- and 10-yr dosages from terrestrial foods for Alvin-Keith (Table 11) exceed those for Janet. These dosages assume the diet at the time of return. The greater dosage for Alvin-Keith can be explained by the absence of coconut and coconut crabs in the diet from Janet and by the greater concentrations of plutonium in the birds from Alvin-Keith. The 30- and 70-yr dosages for Janet exceed those for Alvin-Keith, as one would expect on the basis of greater plutonium contamination of the terrestrial environment on Janet. For both island groups marine foods can be expected to contribute far greater dosages than terrestrial foods. The 30- and 70-yr dosages from marine

Table 11. Summary of predicted integral dosages from ingestion of plutonium

A. Terrestrial Foods								
	Integral Dose, rem							
	5 yr		10 yr		30 yr		70 yr	
	Bone	Liver	Bone	Liver	Bone	Liver	Bone	Liver
Alvin-Keith	7.8(-5)	3.8(-5)	3.1(-4)	1.5(-4)	2.9(-3)	1.2(-3)	0.016	5.6(-3)
Janet	5.2(-5)	2.5(-5)	2.1(-4)	9.8(-5)	1.2(-2)	5.5(-3)	0.082	0.033
B. Marine Foods								
All Groups	2.7(-3)	1.3(-3)	1.0(-2)	5.0(-3)	0.091	0.041	0.45	0.18

foods for Janet would be 5-10 times greater, the dosages from marine foods for Alvin-Keith and the 5- and 10-yr dosages from marine foods for Janet would be 30-50 times greater than the corresponding dosages from terrestrial foods.

*Dosage via all pathways*

Table 12 shows the predicted 30-yr dosages from plutonium to the three major receptor organs (lung, liver and bone) via the three relevant exposure pathways. The major pathway for plutonium for living patterns involving residence and agriculture on the southern islands is the marine pathway, followed by the terrestrial and inhalation pathways. The 30-yr dosages via inhalation for Alvin-Keith are about 1 mrem or less and are therefore comparable to or less than the estimated dose commitments to a

New Yorker through the year 2000 from inhalation of plutonium from world-wide fallout (BENNETT, 1974a). The 30-yr dosages to liver and bone from terrestrial foods for the southern islands are relatively low, approx 1-3 mrem, but they exceed the 30-yr dose commitments to a New Yorker via ingestion by 2 to 3 orders-of-magnitude (BENNETT, 1974b). The dosages via marine foods, which contribute most to the total dosages are greater still. For living patterns involving residence and agriculture on Janet and other northern islands, the major pathway for plutonium is the inhalation pathway followed by the marine and terrestrial pathways. The 30-yr dosages via inhalation exceed those for Alvin-Keith by more than 2 orders-of-magnitude. The 30-yr dosages via terrestrial foods exceed those for Alvin-Keith by about a factor of five.

Table 12. The plutonium 30-yr integral dose to bone, liver and lung via the three exposure pathways

Living Pattern	Plutonium 30-Year Integral Dose, Rem											
	Marine			Terrestrial			Inhalation			Total		
	Bone	Liver	Lung	Bone	Liver	Lung	Bone	Liver	Lung	Bone	Liver	Lung
I	0.091	0.041	-	2.9(-3)	1.2(-3)	-	7(-4)	4(-4)	9(-4)	0.095	0.043	9(-4)
II	0.091	0.041	-	1.2(-2)	5.5(-3)	-	0.10	0.056	0.13	0.20	0.15	0.13
Living Pattern	Village Island			Agriculture			Visitation					
I	Bhavetah-Parry			Alvin-Keith			Southern Is.					
II	Janet			Janet			Northern Is.					

Table 11. Summary of predicted integral dosages from ingestion of plutonium

A. Terrestrial Foods								
	Integral Dose, rem							
	5 Yr		10 yr		30 yr		70 yr	
	Bone	Liver	Bone	Liver	Bone	Liver	Bone	Liver
Alvin-Keith	7.8(-5)	3.8(-5)	3.1(-4)	1.5(-4)	2.9(-3)	1.2(-3)	0.016	5.6(-3)
Janet	5.2(-5)	2.5(-5)	2.1(-4)	9.8(-5)	1.2(-2)	5.5(-3)	0.082	0.033
B. Marine Foods								
All Groups	2.7(-3)	1.3(-3)	1.0(-2)	5.0(-3)	0.091	0.041	0.45	0.18

foods for Janet would be 5-10 times greater, the dosages from marine foods for Alvin-Keith and the 5- and 10-yr dosages from marine foods for Janet would be 30-50 times greater than the corresponding dosages from terrestrial foods.

*Dosage via all pathways*

Table 12 shows the predicted 30-yr dosages from plutonium to the three major receptor organs (lung, liver and bone) via the three relevant exposure pathways. The major pathway for plutonium for living patterns involving residence and agriculture on the southern islands is the marine pathway, followed by the terrestrial and inhalation pathways. The 30-yr dosages via inhalation for Alvin-Keith are about 1 mrem or less and are therefore comparable to or less than the estimated dose commitments to a

New Yorker through the year 2000 from inhalation of plutonium from world-wide fallout (BENNETT, 1974a). The 30-yr dosages to liver and bone from terrestrial foods for the southern islands are relatively low, approx 1-3 mrem, but they exceed the 30-yr dose commitments to a New Yorker via ingestion by 2 to 3 orders-of-magnitude (BENNETT, 1974b). The dosages via marine foods, which contribute most to the total dosages are greater still. For living patterns involving residence and agriculture on Janet and other northern islands, the major pathway for plutonium is the inhalation pathway followed by the marine and terrestrial pathways. The 30-yr dosages via inhalation exceed those for Alvin-Keith by more than 2 orders-of-magnitude. The 30-yr dosages via terrestrial foods exceed those for Alvin-Keith by about a factor of five.

Table 12. The plutonium 30-yr integral dose to bone, liver and lung via the three exposure pathways

Plutonium 30-Year Integral Dose, Rem												
UNMODIFIED CONDITIONS												
Living Pattern	Marine			Terrestrial			Inhalation			Total		
	Bone	Liver	Lung	Bone	Liver	Lung	Bone	Liver	Lung	Bone	Liver	Lung
I	0.091	0.041	-	2.9(-3)	1.2(-3)	-	7(-4)	4(-4)	9(-4)	0.095	0.043	9(-4)
II	0.091	0.041	-	1.2(-2)	5.5(-3)	-	0.10	0.056	0.13	0.20	0.15	0.13
Living Pattern	Village Island			Agriculture			Visitation					
I	Snowhak-Parry			Alvin-Keith			Southern Is.					
II	Janet			Janet			Northern Is.					

## EVALUATION OF PLUTONIUM AT ENEWETAK ATOLL

Table 13. Major contributions of radionuclides to the 30-yr integral dose to bone and liver

Nuclide	30-yr Integral Dose, Rem					
	Marine		Terrestrial		Inhalation	
	Bone	Liver	Bone	Liver	Bone	Liver
<sup>60</sup> Co	0.017	0.18	6.2(-4)	6.6(-3)		
<sup>90</sup> Sr	0.77	4.8(-4)	2.2	1.4(-3)		
<sup>137</sup> Cs	0.030	0.030	0.18	0.18		
<sup>239,240</sup> Pu	0.091	0.041	2.9(-3)	1.2(-3)	7(-4)	4(-4)
Total	0.91	0.25	2.4	0.19	7(-4)	4(-4)

Total dose to bone all pathways<sup>b</sup> = 4.1 rem  
 Total dose to liver all pathways<sup>b</sup> = 1.3 rem

<sup>a</sup>See Table 12 for a description of the living patterns.

<sup>b</sup>The total dose via all pathways includes 30-yr external gamma doses of 0.83 rem for Alvin-Keith and 4.0 rem for Janet.

Living Pattern II<sup>a</sup>

Nuclide	Marine		Terrestrial		Inhalation	
	Bone	Liver	Bone	Liver	Bone	Liver
<sup>60</sup> Co	0.017	0.18	3.0(-4)	0.032		
<sup>90</sup> Sr	0.77	4.8(-4)	74	0.046		
<sup>137</sup> Cs	0.030	0.030	8.0	8.0		
<sup>239,240</sup> Pu	0.091	0.040	0.012	5.5(-3)	0.10	0.056
Total	0.91	0.25	82	8.1	0.10	0.056

Total dose to bone all pathways<sup>b</sup> = 87 rem  
 Total dose to liver all pathways<sup>b</sup> = 12 rem

<sup>a</sup>See Table 12 for a description of the living patterns.

<sup>b</sup>The total dose via all pathways includes 30-yr external gamma doses of 0.83 rem for Alvin-Keith and 4.0 rem for Janet.

Although plutonium would contribute more than 95% of the total dosages via inhalation (NVO, 1973), this pathway is not the greatest contributor to the total dosage via all pathways (Table 13). For most living patterns, the relative ranking of the pathways from the standpoint of their contributions to the total dose would be (1) terrestrial food chain, (2) external gamma dose, (3) marine food chain, (4) inhalation. For the pathways ranking above inhalation nuclides other than plutonium would contribute most to the dosages. Thus <sup>90</sup>Sr and <sup>137</sup>Cs would contribute most via the terrestrial food chain, while <sup>60</sup>Co would make a smaller contribution, comparable to that of <sup>239,240</sup>Pu. For the marine food chain <sup>90</sup>Sr would contribute most to the bone dose and <sup>60</sup>Co, <sup>137</sup>Cs and <sup>239,240</sup>Pu would make more or less comparable contributions to the liver dose. Essentially the entire external gamma dose can

be attributed to the presence of <sup>137</sup>Cs and <sup>60</sup>Co. The potential dosage from plutonium via all pathways is low relative to that from <sup>90</sup>Sr, <sup>137</sup>Cs and <sup>60</sup>Co. Remedial measures that may be designed to limit the dose via the terrestrial food chain or the external dose commitment will have very little impact on the plutonium dose via the marine food and inhalation pathways (NVO, 1973). It must be remembered that by virtue of its very long half-life, plutonium will still remain in the Atoll environment after the other major radionuclides have decayed away.

## REFERENCES

- AARKROG A., 1971, *Health Phys.* 20, 31.  
 BENNETT B. G., 1974a, USAEC Rept. HASL-278, Pt. 1, p. 41 (New York: USAEC HASL).  
 BENNETT B. G., 1974b, USAEC Rept. HASL-286, Pt. 1, p. 36 (New York: USAEC HASL).