Lawrence Livermore Laboratory

DERIVATION OF PLANT-SOIL RELATIONSHIPS FOR DOSE
ASSESSMENT ON BIKINI ATOLL

Carolyn Stockam Colsher

November 1976

This is an informal report intended primarily for internal or limited external distribution. The opinions and conclusions stated are those of the author and may or may not be those of the laboratory.

Prepared for U.S. Energy Research & Development Administration under contract No. W-7405-Eng-48.

MASTER

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DERIVATION OF PLANT-SOIL RELATIONSHIPS FOR DOSE
ASSESSMENT ON BIKINI ATOLL

Carolyn Stockam Colsher

ABSTRACT

A radiological survey of the terrestrial environment of Bikini and Eneu Islands (Bikini Atoll) was conducted in June 1975 to evaluate the potential radiation dose to the returning Bikini population. This report presents measurements of the radionuclide concentration in soil profiles and in dominant species of edible and nonedible indicator plants and describes the use of these data to derive relationships to predict the plant uptake of radionuclides from soil.

Soil-plant concentration factors together with leaf-leaf and fruit-leaf concentration ratios for indicator and edible plant species from the same area are calculated to quantitatively assess and compare the uptake of ^{90}Sr , ^{137}Cs , and $^{239,240}\text{Pu}$. In general, the concentration factors for ^{137}Cs in terrestrial vegetation are greater than those for ^{90}Sr and the concentration factors for both these nuclides exceed those for $^{239,240}\text{Pu}$ by ten to one hundred-fold. Uptake of ^{90}Sr and $^{239,240}\text{Pu}$ by fruit is less than that by mature leaves; however the opposite is true for ^{137}Cs . The relative contribution of the individual plant species to the internal dose to man varies with the nuclide. The use of concentration factors and concentration ratios to predict nuclide concentrations in fruit from those in soil or leaves is prescribed.

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

MASTER

INTRODUCTION

Since the completion of nuclear testing on Bikini Atoll in 1958, periodic environmental surveys have been conducted to evaluate the radiological status of the atoll. The early surveys and the recent survey and assessment at Enewetak Atoll indicate that concentrations of radionuclides in certain terrestrial foods were relatively high and suggest that the terrestrial foodchain would be a major exposure pathway.^{1,2,3,4} In June 1975, Bikini Atoll was resurveyed to determine the residual radioactivity in the terrestrial environments of Bikini and Eneu Islands, the two main islands of the atoll (Fig. 1). The 1975 survey included measurement of environmental gamma-ray exposure rates and the collection and analysis of samples of soil, ground water, cistern water, and vegetation to assess the internal dose via various foodchain pathways. The dose from external gamma exposure and the radionuclide concentrations in cistern and ground water have been reported.^{5,6}

This report describes the soil and vegetation studies of the 1975 survey and the derivation of relationships for prediction of the uptake of nuclides from soil by plants on Bikini Atoll with the collected data. Soil-plant concentration factors and regression equations together with leaf-leaf and leaf-fruit concentrations ratios are calculated for ^{90}Sr , ^{137}Cs , and $^{239,240}\text{Pu}$ in edible and indicator plants and in soil from the associated sampling site. A method for predicting the nuclide concentrations in edible plants at a given location from nuclide concentrations in soil at the same location is developed from evaluation of these data. The predicted nuclide concentrations in edible plants subsequently serve as inputs for prediction of the internal dose from ingested terrestrial foods. These dose levels will be presented in a separate report.⁷

At Bikini Atoll the uptake of radioactive material from soil by plants is the principal source of foodchain contamination. Soil is thus both the convenient and logical starting point for prediction of radionuclide concentration in terrestrial plants. Soil-plant concentration factors (CF) or soil-plant regression equations are the most commonly used approaches for quantitative comparison of the capacity of different plant species and various plant organs to accumulate radioisotopes through soil-root uptake.⁸ Such factors are useful for converting measured environmental concentrations into the potential dose from the soil-plant pathway. Where soil samples are not available, correlations between concentrations in leaves and fruit of a

Fig. 1. Map of Bikini Atoll.

particular plant species or between concentrations in leaves of indicator and edible plant species allow prediction of plant uptake from the soil.

The longer-lived fission and activation products are of primary concern at Bikini Atoll. Previous studies showed that because of their long half-lives and large inventories, ^{90}Sr , ^{137}Cs , and $^{239,240}\text{Pu}$ contribute nearly all the population dose from the terrestrial pathway.^{1,9,10} In addition, ^{60}Co and ^{241}Am are often studied, ^{60}Co because of its ubiquitousness and its dominant role in the marine pathway and ^{241}Am because of the potential for a significant increase in its inventory from the decay of ^{241}Pu . In this study, the major emphasis will be on ^{90}Sr , ^{137}Cs , and $^{239,240}\text{Pu}$; the results obtained for ^{60}Co and ^{241}Am will not be considered.

METHODS

Environmental Sampling and Laboratory Analysis

Soil and vegetation samples were collected at various locations on Bikini and Eneu Islands for the terrestrial sampling program (Fig. 2). Leaves, fruit, roots, litter, and stems of edible (pandanus, breadfruit, coconut, papaya, banana, and squash) and nonedible indicator (Scaevola and Messerschmidia) plants were collected where available. An attempt was made to take at least one soil profile directly next to the roots of each plant sampled. Whenever possible, three soil profiles were taken per plant to assess the variability of radioactivity in the root zone. (For a detailed description of soil and vegetation sampling techniques see Ref. 1, p. 93 for soil and p. 236 for vegetation.) Soil profiles for the terrestrial program were sampled to a depth of 25 to 105 cm at increments of 5 cm in the upper part of the profile and 10 to 20 cm throughout the rest of the profile. Samples were analyzed by gamma spectroscopy with a Ge (Li) detector system, followed by destructive wet chemistry analysis for those nuclides not detectable by the first method.¹¹ Concentrations of the radioisotopes listed in Table 1 were determined and reported in pCi/g dry weight or as the minimum detection limit.

Fig. 2. Sampling sites. A) Bikini Island terrestrial sampling program.
B) Eneu Island terrestrial sampling program.

Table 1. List of radionuclides considered.

^{40}K	^{125}Sb	^{228}Ra
^{55}Fe	^{137}Cs	^{235}U
^{60}Co	^{133}Ba	^{238}Pu
^{90}Sr	^{144}Ce	^{239}Pu
^{106}Ru	^{152}Eu	^{240}Pu
$^{102\text{m}}\text{Rh}$	^{155}Eu	^{241}Pu
$^{110\text{m}}\text{Ag}$	^{207}Bi	^{241}Am

Data Analysis

Because they contribute most to the dose from ingestion of terrestrial foods, ^{90}Sr , ^{137}Cs , and $^{239,240}\text{Pu}$ were selected for detailed analysis.^{10,11,12} Concentration factors (CF) were calculated for these elements with concentrations measured in plant samples and the average concentration measured in the associated 0 to 25 cm soil profile. We define the concentration factor as

$$\frac{\text{pCi/g dry plant}}{\text{pCi/g dry soil}}$$

The use of a 0 to 25 cm soil profile that encompasses a large fraction of the effective absorptive root zone rather than the 0 to 55 cm profile that encompasses the entire root zone reduced the variability in average soil concentrations (Table 2A). Concentration factors calculated on the basis of the average soil concentration in the upper 25 cm of the profile were somewhat greater but did not differ substantially from those based upon deeper profiles (Table 2B). All concentration factors reported in this paper are therefore those derived from 0 to 25 cm soil concentrations.

Table 2A. Average radionuclide concentrations. Soil profiles 0 to 25 cm and deeper.

Location ^a	Average soil concentration, pCi/g dry weight			
	⁹⁰ Sr	¹³⁷ Cs	²³⁹ Pu	²⁴⁰ Pu
T0001 (0-25) ^b	81	45	4.3	4.7
(0-40)	70	27	1.6	1.8
T0051 (0-25)	202	150	9.2	10
(0-45)	207	165	9.3	10
T0061 (0-25)	42	28	1.4	1.6
(0-55)	150	85	5.1	5.7
T0062 (0-25)	67	31	2.3	2.5
(0-45)	80	37	1.3	1.5
T0081 (0-25)	126	43	2.2	2.5
(0-45)	70	15	0.53	0.64
T0121 (0-25)	89	50	2.0	2.2
(0-55)	34	25	0.52	0.60
T0161 (0-25)	27	34	1.5	1.7
(0-55)	30	25	1.09	1.22
T0181 (0-25)	94	13	2.4	2.83
(0-55)	62	5.0	0.56	0.70
T0191 (0-25)	36	23	0.99	1.18
(0-55)	28	17.5	0.87	1.01
T0241 (0-25)	3.7	3.3	0.42	0.46
(0-45)	4.7	2.8	0.49	0.47
T0251 (0-25)	7.3	7.9	0.24	0.27
(0-45)	9.8	5.7	0.42	0.45
T0261 (0-25)	7.8	4.6	0.41	0.47
(0-45)	6.8	1.8	0.23	0.38
T0271 (0-25)	1.0	0.88	0.12	0.14
(0-45)	0.62	0.40	—	—
T0301 (0-25)	16	10	1.1	1.2
(0-45)	20	12	1.6	1.5

^aSample locations are shown in Fig. 2.

^bDepth of profile in centimeters.

Table 2B. Soil-plant concentration factors calculated from 0-25 cm and deeper soil profiles.

Location ^a		Soil-mature leaf concentration factor ^b			
		⁹⁰ Sr	¹³⁷ Cs	²³⁹ Pu	²⁴⁰ Pu
T0001	(0-25)	1.0	17	0.014	0.015
	(0-40)	1.2	29	0.038	0.012
T0051	(0-25)	0.94	0.30	0.050	0.0053
	(0-40)	0.92	0.27	0.50	0.0052
T0061	(0-25)	5.3	2.5	0.043	0.045
	(0-55)	0.15	0.82	0.012	0.013
T0062	(0-25)	2.8	2.2	0.049	0.045
	(0-55)	3.3	1.9	0.028	0.013
T0081	(0-25)	1.4	0.79	0.019	0.049
	(0-45)	2.4	2.30	0.078	0.029
T0121	(0-25)	1.2	2.9	0.030	0.021
	(0-55)	2.5	5.9	0.066	0.084
T0161	(0-25)	0.22	13	0.018	0.014
	(0-55)	0.19	18	0.024	0.054
T0181	(0-25)	0.11	35	0.012	0.018
	(0-55)	0.17	9.3	0.051	0.024
T0191 (litter)	(0-25)	0.56	17	0.025	0.013
	(0-55)	0.72	23	0.029	0.051
T0241	(0-25)	0.30	1.1	—	—
	(0-45)	0.19	1.3	—	—
T0251	(0-25)	0.16	3.9	0.010	0.013
	(0-45)	0.12	5.4	0.0059	0.069
T0261	(0-25)	0.099	2.6	—	—
	(0-45)	0.20	6.6	—	—
T0271	(0-25)	—	16	—	—
	(0-45)	—	36	—	—
T0301	(0-25)	0.11	2.3	—	—
	(0-45)	0.085	2.0	—	—

^aSample locations are shown in Fig. 2.

^bpCi/g dry leaf ÷ pCi/g dry soil.

The average soil concentration was calculated as the weighted geometric mean of the separate concentrations measured at various increments throughout the 0 to 25 cm profile. The USEPA technique of setting concentration values less than the minimum detection limit equal to the minimum detection limit was used. Where sample size was sufficiently large, soil concentrations were plotted against concentrations in plants from the same sampling site and the results analyzed with linear regression methods. The results of the linear regression analysis were considered to be statistically significant at the 0.1 level of a standard F test. For each combination of nuclide, plant part, and species considered, statistically significant regression equations were compared to the median of the calculated concentration factors and a single representative concentration factor assigned.

Predictions of radionuclide levels in foodstuffs can be made from concentration factors if measured soil concentrations are available; however, concentration ratios are needed if the only available data are from mature leaf samples. Concentration ratios are defined as the ratio of the concentration in fruit to that in leaves of the same species or the ratio of the concentration in the leaves of one species to that in the leaves of another species. Preliminary ratios were developed for all species available from the 1975 Bikini survey; however, these results were not analyzed statistically because of the small numbers of samples involved.

RESULTS AND DISCUSSION

More samples are available from the 1975 Bikini Survey than from any previous survey (see Table 3). However even on Bikini, the most thoroughly sampled island of the atoll, there are generally not enough specimens to justify statistical analysis. Mature coconut leaves and pooled mature Messerschmidia and Scaevola leaves are the only exceptions. In general, plant-soil relationships seen in the 1975 survey confirm the results of previous surveys; however, they are often statistically insignificant. Statistically insignificant results often occur if the number of samples considered is small even if the relationships under study are extremely significant since in such cases sampling errors dominate the explanatory variables. Although a statistical analysis of larger numbers of samples is necessary to verify the results, general plant-soil relationships developed in this study are recommended for use in subsequent dose assessments.

Table 3. Number of vegetation and soil samples analyzed in various Bikini surveys.

Species, organ	Number of samples					
	^{90}Sr		^{137}Cs		$^{239,240}\text{Pu}$	
	64-74 ^a Survey	75 ^b Survey	64-74 Survey	75 Survey	64-74 Survey	75 Survey
Pandanus leaves ^c		6(6) ^d		6(6)		5(5)
Pandanus fruit	6	1(1)	4	1(1)	0	1(1)
Papaya leaves		8(4)		8(4)		8(4)
Papaya fruit		4(4)		4(4)	0	4(4)
Breadfruit, leaves		2(2)		2(2)		2(2)
Breadfruit	0	1(1)	0	1(1)	0	1(1)
Banana leaves		3(3)		3(3)		3(3)
Coconut leaves		22(8)		22(8)		22(8)
Coconut fruit	5	6(6)	48	6(6)	0	6(6)
Scaevola leaves		8(2)		8(2)		8(2)
Scaevola fruiting- body		1(1)		1(1)		1(1)
Messerschmidia, leaves		6(3)		6(3)		6(3)
Soil profiles	5	42	22	42	0	42
Soil (top 15 cm)	21	196	176	196	0	196

^aData from 1974 Bikini Draft (unpublished).

^bData from this report.

^cLeaves include both mature and young specimens.

^d() indicates number of samples out of total that have directly associated soil profiles.

Concentration Factors

Soil profiles with uniform patterns of nuclide migration are seldom found at Bikini Atoll because of the complete disruption of the upper soil layers by clearing, construction, and testing over the past 30 years and by more recent agricultural practices. To determine the soil nuclide concentration available to the root system of a specific plant, it is therefore necessary to sample soil profiles located in direct proximity to the root system. The two replicate groups of soil profiles sampled showed minimal variation regardless of the side of the plant on which they were located (Table 4), while profiles in the general area but not exactly at the same location were highly variable (Table 5).

Table 4. Radionuclide concentrations in replicate soil profiles.

Location ^a	Average 0 to 25 cm soil concentration, pCi/g dry weight			
	⁹⁰ Sr	¹³⁷ Cs	²³⁹ Pu	²⁴⁰ Pu
T0001	81	45	4.3	4.7
T0002	92	29	4.6	5.1
T0003	100	44	5.0	5.5
T0061	42	28	1.4	1.6
T0062	68	31	2.6	2.5

^aSampling sites shown in Fig. 2.

Table 5. Radionuclide concentrations in soil profiles: same general area.

Location ^a	Average 0 to 25 cm soil concentration, pCi/g dry weight			
	⁹⁰ Sr	¹³⁷ Cs	²³⁹ Pu	²⁴⁰ Pu
Group 1				
T0091	81	55	2.5	2.8
T0101	32	35	0.27	0.29
T0111	81	87	3.3	3.7
T0121	89	50	2.0	2.2
T0131	86	13	0.53	0.64
Group 2				
T0031	6.8	8.6	0.18	0.20
T0041	35	26	0.58	0.69
T0051	202	150	9.2	10
T0061	42	28	1.4	1.6
T0071	127	86	4.6	5.1

^aSampling sites shown in Fig. 2.

Table 6 presents the range and median values of concentration factors calculated for vegetation and soil sampled at the same location, while Table 7 compares the information in Table 6 with the same information for concentration factors calculated for mature Scaevola and coconut leaf samples for which no soil samples from the same location were available. Mature Scaevola and coconut leaves were selected for comparative purposes because they provide the largest number of samples in both categories. A comparison of the ranges in Table 7 shows the importance of using plant-soil data from the same location. Concentration factors calculated from unassociated plant and soil factors showed up to a 1000-fold difference for ¹³⁷Cs uptake by mature Scaevola leaves while those calculated from associated data showed a ten-fold or less difference. These results agree with the wide range of concentration factors calculated in previous surveys from unassociated plant and soil samples.^{1,4} Since the range of concentration factors in only two combinations of nuclide, plant part, and species from the associated soil-plant data (pooled Scaevola and Messerschmidia leaves for ¹³⁷Cs and papaya leaves for ²³⁹Pu) varied by more than 20-fold (Table 8), the median concentration factors derived from the associated data were chosen for use in our predictive model.

Table 6. Soil-to-plant uptake of selected radionuclides. Plants and soil sampled at the same location.

Table 6A. ^{90}Sr and ^{137}Cs .

Plant species, organ	No. of samples	Concentration factors, pCi/g dry plant ÷ pCi/g dry soil						
		^{90}Sr			^{137}Cs			
		Min.	Max.	Median	No. of samples	Min.	Max.	Median
Scaevola, mature leaves	2	0.24	0.41	0.33	2	1.3	14	7.4
Messerschmidia, mature leaves	3	0.48	0.86	0.52	3	2.1	50	3.7
Pooled Scaevola & Messerschmidia, mature leaves	5	0.24	0.86	0.48	5	1.3	50	3.7
Coconut, mature leaves	7	0.09	0.38	0.16	8	1.1	16	3.0
Coconut, fruit	2	0.024	<0.018		2	1.4	3.6	2.5
Coconut, meat	2	<0.019	0.026		2	7.3	9.8	8.6
Coconut, milk ^a	2	<0.0084	<0.012		2	0.90	1.4	
Pandanus, mature leaves	5	0.71	2.4	0.91	5	2.9	25	15
Pandanus, green fruit	1			0.53	1			0.054
Papaya, mature leaves	4	0.62	4.0	1.3	4	0.30	5.9	3.1
Papaya, fruit	4	0.12	0.85	0.43	4	1.9	18	8.2
Breadfruit, mature leaves	2	1.4	2.3	1.8	2	0.79	2.4	1.6
Breadfruit, mature fruit	1			0.76	1			7.0
Danana, mature leaves	2	0.48	1.1	0.73	2	0.33	0.54	0.42
Squash, whole plant	1			3.4	1			26
Squash, seeds	1			0.15	1			56

^a Coconut milk was measured and reported in pCi/ml wet weight, which was assumed to equal pCi/g wet weight for calculation of the concentration factor. Thus the CF for coconut milk has the units: $\frac{\text{pCi/g wet plant}}{\text{pCi/g dry soil}}$

Table 6B. ^{239}Pu and ^{240}Pu .

Concentration factors, pCi/g dry plant $\div$ pCi/g dry soil								
Species, organ	No. of samples	^{239}Pu			No. of samples	^{240}Pu		
		Min.	Max.	Median		Min.	Max.	Median
Scaevola, mature leaves	1			0.0047	1			0.0051
Messerschmidia, mature leaves	2	0.024	0.11	0.067	2	0.045	0.12	0.081
Pooled Scaevola & Messerschmidia, mature leaves	3	0.0047	0.11	0.024	3	0.0051	0.12	0.045
Coconut, mature leaves	4	0.010	0.022	0.015	4	0.011	0.021	0.015
Pandanus, mature leaves	4	0.0044	0.030	0.016	4	0.0043	0.015	0.014
Papaya, mature leaves	4	0.0012	0.037	0.037	4	0.0053	0.042	0.026
Papaya, fruit	2	0.0012	0.0021	0.0017	2	0.0013	0.0023	0.0018
Breadfruit, mature leaves	2	0.0063	0.019	0.013	2	0.021	0.063	0.042
Banana, mature leaves	2	0.0017	0.0054	0.0036	2	0.0018	0.0066	0.0042

Table 7. Soil-mature leaf concentration factors. Calculated from associated and unassociated data.^a

Species	Concentration factors, pCi/g dry plant ÷ pCi/g dry soil							
	Associated				Unassociated			
	No. of samples	Min.	Max.	Median	No. of samples	Min.	Max.	Median
⁹⁰ Sr								
Scaevola	2	0.24	0.41	0.33	4	0.048	4.3	1.8
Coconut	7	0.099	0.38	0.16	15	0.041	0.74	0.29
¹³⁷ Cs								
Scaevola	2	1.3	14	7.5	4	0.073	39	7.7
Coconut	8	1.1	16	3.0	15	0.53	18	2.6
²³⁹ Pu								
Coconut	4	0.011	0.022	0.015	12	0.0036	0.14	0.016
²⁴⁰ Pu								
Coconut	4	0.011	0.021	0.015	12	0.0021	0.15	0.016

^a Associated indicates plant and soil data sampled from the same site. Unassociated indicates plant and soil data sampled from different sites in the same general area.

Table 8. Ratio of maximum to minimum associated^a soil-plant concentration factors.

Species, organ	Maximum-minimum ratio			
	⁹⁰ Sr	¹³⁷ Cs	²³⁹ Pu	²⁴⁰ Pu
<u>Scaevola</u> , mature leaves	1.7	11	-	-
<u>Messerschmidia</u> , mature leaves	1.8	24	4.9	2.6
Pooled <u>Scaevola</u> and <u>Messerschmidia</u> , mature leaves	3.6	39	23	23
Pandanus, mature leaves	3.3	8.4	6.9	3.6
Coconut, mature leaves	3.8	14	2.1	1.8
Coconut, fruit	<7.2	2.6	-	-
Papaya, mature leaves	6.5	20	29	7.9
Papaya, fruit	7.4	9.5	1.7	1.8
Banana, mature leaves	2.3	1.6	3.2	3.8
Breadfruit, mature leaves	1.7	3.0	3.0	2.9

^aAssociated indicates plant and soil data sampled from the same site.

There are several reasons why some variability in calculated concentration factors persists even with plant and soil data sampled at the same location. Possible factors include differences in the physiochemical properties of the radionuclides under consideration, in soil type and chemical characteristics, in soil management and irrigation practices, and in the physiology, age, and prior history of the plants sampled. It is impossible to identify the specific cause of each variation, but the variation can be reduced by carefully controlled sampling techniques and increased number of samples. Where fruit data were unavailable, concentration factors calculated from mature leaf data were selected as the basis for predicting concentrations in food available to the returning Bikini population. Mature leaf concentration factors used in conjunction with correlations developed between various species and between

leaves and fruit of the same species make it possible to predict concentrations in fruit from measured concentrations in leaves of edible or nonedible indicator plants.

As discussed in the introduction and methods section of this paper, results are only reported for ^{90}Sr , ^{137}Cs , and $^{239,240}\text{Pu}$. As predicted from previous studies, the most effectively transferred radionuclide in the terrestrial environment is ^{137}Cs , even though ^{90}Sr is often present in larger quantities in the soil material of the atoll. This can be partly explained by the differential solubilities of ^{90}Sr and ^{137}Cs . Strontium-90 appears to be tied up as insoluble carbonates in the Atoll soil thereby being unavailable to the plant, while ^{137}Cs is more soluble in the Atoll soil since there is no clay in this soil to fix it. Although ^{137}Cs is leached through the soil at a faster rate than ^{90}Sr , it is absorbed and accumulated in organified soil horizons where there is a proliferation of plant roots and is thus still more available for uptake by plants than ^{90}Sr .¹² Because of its similarity to potassium, the available ^{137}Cs is taken up by plants and incorporated into organic matter.

The concentration factors discussed later for the most part reflect the relationship discussed above between ^{90}Sr and ^{137}Cs uptake. For all fruit and pandanus, coconut, Scaevola and Messerschmidia leaves, for CFs were observed for ^{90}Sr as compared to ^{137}Cs . However the leaves of papaya, banana, and breadfruit showed CFs for ^{90}Sr as high or higher than those for ^{137}Cs . Concentration factors for $^{239,240}\text{Pu}$ were generally 0.1 to 0.001 of those for ^{90}Sr or ^{137}Cs . Although they were often measured in soil, ^{60}Co , ^{241}Pu , and ^{241}Am were only occasionally detected in vegetation. For this reason, concentration factors for the latter three nuclides were not calculated.

The specific concentration factors assigned to each species are discussed in the following section. Concentration factors were assigned solely on the basis of the median calculated concentration factors except in the case of coconut and pooled Scaevola and Messerschmidia leaves. For these cases enough samples were available to justify analysis by linear regression methods, so that the regression results were compared with the median calculated concentration factor and a representative value chosen for use in our models. The relationships between the amount of uptake by different species will be considered in the section on concentration ratios.

Coconut: Since more coconut trees are available on Bikini and Eneu Islands than any other species, coconut was the most extensively sampled plant in the 1975 survey. Despite the large numbers of trees, few were bearing fruit, so most of the samples consisted of leaves. Regression analysis comparing mature coconut leaves and soil sampled from the same location showed correlations significant at the 0.1 to 0.05 level for ^{90}Sr , the 0.005 level for ^{137}Cs , and the 0.1 level for $^{239,240}\text{Pu}$ (Figs. 3, 4, 5). Combining the results of this regression analysis with the median calculated concentration factors (Table 9) led to final concentration factors of 0.16 for ^{90}Sr , 3.0 for ^{137}Cs , and 0.015 for $^{239,240}\text{Pu}$ for mature coconut leaves.

Table 9. Summary table of median soil-plant concentration factors.

Species	Concentration factor, pCi/g dry plant ÷ pCi/g soil					
	^{90}Sr		^{137}Cs		$^{239,240}\text{Pu}$	
	Mature leaves	Fruit	Mature leaves	Fruit	Mature leaves	Fruit
Pooled <u>Scaevola</u> & <u>Messerschmidia</u>	0.48	—	3.7	—	0.035	—
Coconut	0.16	0.024	3.0	2.5	0.015	—
Pandanus	0.91	0.50	15	5.4	—	—
Papaya	1.3	0.43	3.1	8.2	0.016	0.0018
Breadfruit	1.8	0.76	1.6	7.0	0.0273	—
Banana	0.73	0.058 ^a	0.42	—	0.0039	0.00028 ^a
Squash	3.41 ^b	0.15 ^c	26 ^b	56 ^c	—	—

^a1974 Unpublished BNL plant and soil data from the same vicinity.¹⁴

^bWhole plant.

^cSeeds.

Fig. 3. Correlation between ^{90}Sr concentration in mature coconut leaves and ^{90}Sr concentration in the soil.

Fig. 4. Correlation between ^{137}Cs concentration in mature coconut leaves and ^{137}Cs concentration in the soil.

Fig. 5. Correlation between $^{239,240}\text{Pu}$ concentrations in mature coconut leaves and $^{239,240}\text{Pu}$ concentrations in the soil.

Concentrations in both coconut meat and coconut milk were analyzed for two samples from Bikini. When compared on a wet/wet or dry/dry basis there were no conclusive differences in the radionuclide concentrations in coconut meat and coconut milk sampled at the same location. (The results are reported in wet weight for coconut milk and dry weight for coconut meat; so for comparative purposes, coconut milk was assumed to be 95% water and coconut meat 50% water following the example of The Enewetak survey.¹) In the Enewetak survey it was assumed that ^{90}Sr and ^{137}Cs concentrations in fresh coconut meat and fresh coconut milk were equal because the 1972 Enewetak data also showed no consistent differences in their uptake. Since the concentration factors calculated from the Bikini data (Table 6) are within the range of those from the Enewetak survey,¹ we have assigned a concentration factor of 0.024 for ^{90}Sr and 2.5 for ^{137}Cs to both the meat and milk of coconut until more conclusive data become available.

Pandanus

Although the number of samples of mature pandanus leaves was insufficient for statistical analysis, the concentration factors calculated from associated leaf-soil data for Bikini are within the range of those from Enewetak. The median concentration factors of 0.91 for ^{90}Sr and 15.2 for ^{137}Cs were therefore assigned to mature pandanus leaves. The concentration factor calculated for the one green pandanus fruit available from the Bikini survey (0.50 for ^{90}Sr and 5.4 for ^{137}Cs) is comparable to those from previous surveys and was therefore used.

Breadfruit

Since breadfruit were not available on Enewetak Atoll, data from the two samples collected during the 1975 Bikini survey for the first time provided directly measured concentration factors. As expected from the 1972 Bikini survey¹³ and the stable-element analysis of potassium and calcium in the Enewetak survey,¹ uptake of ^{90}Sr and ^{137}Cs by breadfruit is high and comparable to that by pandanus. Preliminary concentration factors of 1.8 for ^{90}Sr , 1.6 for ^{137}Cs , and 0.027 for $^{239,240}\text{Pu}$ were calculated for mature breadfruit leaves. The concentration factors for the one mature fruit sampled from this species were 0.76 for ^{90}Sr and 7.0 for ^{137}Cs .

Papaya

The ratio of maximum to minimum concentration factors calculated for mature papaya leaves is small so that median concentration factors of 1.3 for ^{90}Sr , 3.1 for ^{137}Cs , and 0.016 for $^{239,240}\text{Pu}$ are assigned. Concentration factors of 0.43 for ^{90}Sr , 8.2 for ^{137}Cs , and 0.0018 for $^{239,240}\text{Pu}$ were calculated for the four papaya fruit available.

Banana

The only data on radionuclide concentrations in banana from the 1975 Bikini survey is for mature leaves. The two samples available suggest tentative concentration factors of 0.73 for ^{90}Sr , 0.42 for ^{137}Cs , and 0.0039 for $^{239,240}\text{Pu}$ in mature banana leaves. Unpublished data from the Brookhaven Bikini survey on banana fruit and soil samples from the same area yield concentration factors of <0.058 for ^{90}Sr and <0.00028 for $^{239,240}\text{Pu}$.¹⁴ Since there are currently no data available on concentration factors for ^{137}Cs in bananas, we have assigned the conservative value of the ^{137}Cs concentration factor for mature banana leaves to banana fruit.

Messerschmidia and Scaevola

As discussed in the Enewetak survey, data from these two indicator plants showed a significant correlation between leaves and soil on both an individual and a pooled basis. The number of samples from the Bikini survey did not warrant individual statistical analysis of these species, but the pooled data showed a correlation between leaves and soil significant at the 0.1 level for ^{90}Sr (Fig. 6) although not for ^{137}Cs (Fig. 7). However ^{137}Cs did show a significant correlation between leaves and soil in the Enewetak results and would probably do so for Bikini if the number of samples was larger as discussed earlier in this section. Based on the median calculation concentration factor and the results of the regression analysis, concentration factors of 0.49 for ^{90}Sr , 3.7 for ^{137}Cs , and 0.035 for $^{239,240}\text{Pu}$ were assigned to mature Scaevola and Messerschmidia leaves.

Squash

The 1975 survey provided one sample of summer squash and its seeds. This was the first time that measured radionuclide concentrations in garden vegetables from Bikini Atoll have been available. Squash uptake of ^{90}Sr

Fig. 6. Correlation between ^{90}Sr concentration in mature Scaevola and Messerschmidia leaves and ^{90}Sr concentration in the soil..

Fig. 7. Correlation between ^{137}Cs concentration in mature Scaevola and Messerschmidia leaves and ^{137}Cs concentration in the soil.

and ^{137}Cs was greater than that of any other plant sampled. Other workers have also noted high concentrations of ^{137}Cs in garden vegetables as compared to other edible and indicator plants. Lynch *et al.*⁹ noted that in field studies the ^{137}Cs concentration in lettuce leaves was ten times greater than the concentrations measured in other edible portions of food plants. Walker *et al.*¹⁵ in their laboratory experiments on the uptake of ^{137}Cs by squash reported ^{137}Cs concentrations in squash that were higher than those measured in Messerschmidia, Scaevola and pandanus grown in the same Rongelap Atoll soil. From Walker's experiments it appears that the concentrations in squash can be reduced to levels comparable to those found in other edible plants by the application of fertilizer.

Concentration Ratios

Radionuclides that are taken up through roots from the soil are either retained in the roots or transported to above-ground plant organs. At Bikini the concentrations in above-ground plant organs of any particular species were comparable to the concentrations retained in the roots of the species for ^{90}Sr but lower for ^{137}Cs and $^{239,240}\text{Pu}$ (Table 10). In addition, there are differences in uptake among the various above-ground plant organs. Within any one species, concentrations in nonedible plant parts like leaves are generally greater than those in edible plant parts like fruit for ^{90}Sr and $^{239,240}\text{Pu}$ but lower for ^{137}Cs (Table 11).

Since leaves are more often available for sampling than fruit, fruit-leaf concentration ratios were calculated to allow prediction of fruit concentrations from those measured in leaves of the same species (Table 11). The small number of samples made it impossible to statistically evaluate these ratios, but this will be done as more data becomes available. Leaf-leaf and fruit-fruit concentration ratios between different species were also calculated to allow prediction of fruit concentrations of one species from concentrations measured in fruit or leaves of another species. These ratios show that distribution patterns of each nuclide are consistent within a particular species. However, when comparing different species, the importance of the contribution of each nuclide to the internal dose to man varies.

Table 10. Comparison of soil-root and soil-leaf concentration factors.

Species	Concentration factor, pCi/g dry plant ÷ pCi/g dry soil					
	⁹⁰ Sr		¹³⁷ Cs		^{239,240} Pu	
	Roots	Leaves	Roots	Leaves	Roots	Leaves
Pandanus	0.88	1.0	23	17	0.44	0.015
	0.77	1.2	6.1	2.9	0.45	0.022
<u>Messerschmidia</u>	0.59	0.48	33	50	0.44	0.035
Coconut	0.16	0.11	3.4	2.3	0.085	ND
	0.89	ND ^b	16	0.88	0.11	ND
	0.30	0.30	5.7	1.1	0.081	ND
	0.89	ND	5.0	ND	0.38	ND
Banana	0.42 ^a	1.1	0.026	0.54	0.027	0.0060

^aRoot and crown.^bBelow minimum detection limits.

The fruit-fruit and fruit-leaf concentration ratios were developed from a comparison of the concentration factors of three groups of plants (plants within each group were sampled in close proximity to each other) (Table 12) and from comparisons of the median concentration ratios of all associated plant-soil samples (Table 13). Analysis of the concentration ratios for mature leaves and fruit suggests that some species concentrate the radionuclides to a much greater extent than others. The order of ⁹⁰Sr concentration by mature leaves from highest to lowest uptake seems to be breadfruit and papaya > pandanus and banana > Scaevola and Messerschmidia > coconut. Fruit shows a similar pattern, breadfruit > pandanus, papaya and banana > coconut (Table 13A and 13D). These results agree with those of Welander.¹⁰

Table 11. Fruit-leaf concentration ratios.

Species	Nuclide	Concentration in fruit, pCi/g dry	Concentration in mature leaf, pCi/g dry	Concentration ratio
Pandanus	^{90}Sr	40 ^a	87	0.50
	^{137}Cs	2.7	146	0.02
Breadfruit	^{90}Sr	62	190	0.33
	^{137}Cs	383	133	3.0
Coconut fruit	^{90}Sr	0.79	12	0.06
	^{137}Cs	60	7.1	4.0
	^{90}Sr	1.9	2.9	—
	^{137}Cs	14	9.7	—
		54	15	—
Coconut meat/ milk	^{90}Sr	0.41/0.18	1.7	0.33
	^{137}Cs	76/9.3	24	3.0
		95/14	15	—
Papaya	^{90}Sr	18	264	0.20
		22 ^a	22	—
		49	191	—
		47	221	—
		161 ^a	189	5.0
	^{137}Cs	865 ^b	156	—
		282	45	—
		303	70	—
		0.014 ^b	0.049	0.03
		0.0023	0.067	—

^aGreen fruit.^bFallen fruit.

Table 12. Associated soil-plant concentration factors: Species sampled from the same location.

Species, organ	Concentration factor, pCi/g dry plant ÷ pCi/g dry soil		
	^{90}Sr	^{137}Cs	$^{239,240}\text{Pu}$
Group 1 ^a			
Papaya, mature leaves	1.6	3.9	0.012
Papaya, mature leaves	0.6	5.9	0.037
Papaya, mature leaves	0.9	0.30	0.0051
Papaya, mature leaves	4.0	2.4	0.027
Banana, mature leaves	0.48	0.33	0.0017
Banana, mature leaves	1.1	0.41	0.0060
Group 2 ^b			
Breadfruit, mature leaves	2.3	2.4	0.063
Pandanus, mature leaves	1.2	2.9	0.022
Messerschmidia, mature leaves	0.48	87	0.035
Messerschmidia, mature leaves	0.52	3.7	-
Scaevola, mature leaves	0.24	1.3	0.0049
Scaevola, mature leaves	0.41	13	-
Breadfruit, fruit	0.76	7.0	-
Pandanus, fruit (green)	0.53	5.4	-
Scaevola, fruit	0.14	1.4	0.00096
Group 3 ^c			
Scaevola, mature leaves	4.3	39	0.024
Coconut, mature leaves	0.67	14	0.026
Coconut, mature leaves	0.27	7.3	0.020

^aGroup 1 samples include T0010, T0030, T0040, T0050, T0060, and T0070.

^bGroup 2 samples include T0090, T0100, T0110, T0120, and T0130.

^cGroup 3 samples include T0150 and T0160.

Table 13A. Leaf-leaf concentration ratios of ^{90}Sr for different species.

Species	Leaf-leaf concentration ratio						
	Breadfruit	Papaya	Pandanus	Banana	Messerschmidia	Scaevola	Coconut
Breadfruit	1.0	1.5	2.0	2.5	3.5	6.0	12
Papaya	0.66	1.0	1.3	1.7	2.5	4.0	8.0
Pandanus	0.50	0.77	1.0	1.3	1.8	3.0	6.0
Banana	0.40	0.59	0.77	1.0	1.4	2.2	4.4
Messerschmidia	0.29	0.40	0.56	0.71	1.0	1.6	3.2
Scaevola	0.17	0.25	0.33	0.45	0.63	1.0	2
Coconut	0.08	0.12	0.17	0.23	0.31	0.50	1.0

Table 13B. Leaf-leaf concentration ratios of ^{137}Cs for different species.

Species	Leaf-leaf concentration ratio						
	Pandanus	Scaevola	Messerschmidia	Coconut	Papaya	Breadfruit	Banana
Pandanus	1.0	2.0	4.0	5.0	5.0	10	35
Scaevola	0.50	1.0	2.0	2.5	2.5	5.0	18
Messerschmidia	0.25	0.50	1.0	1.3	1.3	2.4	8.8
Coconut	0.20	0.40	0.80	1.0	1.0	2.0	7.0
Papaya	0.20	0.40	0.80	1.0	1.0	2.0	7.5
Breadfruit	0.10	0.20	0.40	0.50	0.50	1.0	3.8
Banana	0.03	0.06	0.12	0.14	0.13	0.26	1.0

Table 13C. Leaf-leaf concentration ratios of $^{239,240}\text{Pu}$ for different species.

Species	Leaf-leaf concentration ratio			
	<u>Messerschmidia</u>	Breadfruit ^a	Papaya	<u>Scaevola</u> ^b
<u>Messerschmidia</u>	1.0	4.5	10	15
Breadfruit ^a	0.22	1.0	2.2	3.3
Papaya	0.10	0.45	1.0	1.5
<u>Scaevola</u> ^b	0.07	0.30	0.67	1.0

^aGroup also includes pandanus and coconut.

^bGroup also includes banana.

Table 13D. Fruit-fruit concentration ratios of ^{90}Sr for different species.

Species	Fruit-fruit concentration ratio		
	Breadfruit	Pandanus, papaya	Coconut
Breadfruit	1.0	1.5	3.0
Pandanus, papaya	0.67	1.0	2.0
Coconut	0.33	0.50	1.0

Table 13E. Fruit-fruit concentration ratio of ^{137}Cs for different species.

Species	Fruit-fruit concentration ratio			
	Papaya	Breadfruit	Pandanus	Coconut
Papaya	1.0	1.3	1.6	3.2
Breadfruit	0.75	1.0	1.4	2.8
Pandanus	0.63	0.71	1.0	2.0
Coconut	0.30	0.36	0.50	1.0

The relative uptake of ^{137}Cs by various species differs slightly from that for ^{90}Sr . For ^{137}Cs in mature leaves, an appropriate ordering appears to be pandanus > Scaevola > Messerschmidia, coconut and papaya > breadfruit > banana while a comparison of ^{137}Cs uptake by fruit yields the pattern, papaya > pandanus and breadfruit > coconut (Table 13B and 13E). The data on uptake of $^{239,240}\text{Pu}$ by mature leaves is much more limited than those for ^{90}Sr and ^{137}Cs , but preliminary results suggest the order Messerschmidia > breadfruit > pandanus and coconut > papaya > Scaevola and banana (Table 13C). Although no concentration ratios were calculated, the uptake of ^{90}Sr and ^{137}Cs by unfertilized summer squash exceeds that of any of the other edible plants sampled.

SUMMARY AND CONCLUSIONS

In the past, concentrations in terrestrial foodstuffs at Bikini Atoll were predicted from soil concentrations measured in the field and concentration factors derived from the literature. This approach was a consequence of the limited vegetation sampling programs of the early surveys. The terrestrial sampling program of the 1974 and 1975 Bikini surveys included sufficient vegetation samples to allow preliminary prediction of concentrations in nearly all components of the postulated Bikini diet. These predicted

concentrations were based on soil-plant concentration factors and fruit-leaf, leaf-leaf, or fruit-fruit concentration ratios calculated from measured field data. The predicted concentrations compared favorably with available measured concentrations. A more extensive survey of Bikini Atoll with larger sample sizes is needed to verify these preliminary results on a statistical basis. In the meantime, future concentrations in foodstuffs from Bikini can be predicted from our concentration factors if measured soil concentrations are available and from our concentration ratios if soil data are unavailable. Estimation of the dose commitment expected from various projected lifestyles using our predicted concentrations will be reported in a subsequent paper.

This report identified ^{90}Sr and ^{137}Cs followed by $^{239,240}\text{Pu}$ as the radionuclides that are predominant in the terrestrial foodchain and that will therefore contribute most to the internal dose to the organs and tissues of man from this pathway. In general within a given species, ^{137}Cs uptake by fruit and leaves is ten times greater than ^{90}Sr uptake, which in turn exceeds $^{239,240}\text{Pu}$ uptake by ten to one hundred times. Uptake by mature leaves of papaya, banana, and breadfruit varies slightly from this general pattern, because in these cases measured uptake of ^{90}Sr is equal to that of ^{137}Cs . However, more samples are needed to verify the pervasiveness of these exceptions to the overall patterns observed. The distribution of ^{90}Sr , ^{137}Cs , and $^{239,240}\text{Pu}$ in fruit and leaves follows similar patterns in the various species studied. Uptake of ^{90}Sr and $^{239,240}\text{Pu}$ by mature leaves is two to ten times greater than that by fruit. The ^{137}Cs uptake measured in this study showed a different trend with uptake by fruit exceeding that by mature leaves by two to five times.

Although the radionuclides studied showed consistent patterns of relative uptake in most species, the relative importance of each species to the internal dose to man depends on the particular nuclide and the proportion of the diet contributed by the species. A comparison of the uptake of ^{90}Sr and ^{137}Cs by the various edible plant parts studied showed unfertilized summer squash having the highest uptake and coconut fruit the lowest. The uptake of ^{90}Cs by fruit of papaya, breadfruit, banana, and pandanus is to varying degrees greater than that by coconut fruit and leaves, but ^{137}Cs uptake by mature leaves follows a different pattern. Pandanus is the only edible species whose mature leaf uptake of ^{137}Cs exceeds that of coconut leaves.

All other species have smaller uptakes of ^{137}Cs with banana leaves having the smallest. The uptake of $^{239,240}\text{Pu}$ by the mature leaves of all species is comparable with the exception of bananas whose uptake was much lower. In general the relative order of uptake is: squash in the high range; breadfruit, pandanus, and papaya in the intermediate range; and banana and coconut in the low range of the scale with slight variations depending on the nuclide. A more quantitative ordering can be made when greater numbers of plants are sampled in future surveys.

ACKNOWLEDGEMENT

I am deeply indebted to the various people who participated in the field operations and analytical portions of the survey that provided the data on which this paper is based. I wish to express special appreciation to Bill Robison, Yook Ng, and John Holdren for their invaluable comments and criticism, to Bill Phillips for computational support, to John Koshiver for statistical help and to Ora Lowe for her technical assistance.

REFERENCES

1. *Enewetak Radiological Survey*, Vols. 1-3, U.S. Atomic Energy Commission, Nevada Operations Office, Las Vegas, Nevada, Rept. NVO-140 (1973).
2. E.E. Held, *Radiological Resurvey of Animals, Soils and Groundwater at Bikini Atoll, 1969-70*, U.S. Atomic Energy Commission, Rept. NVO-269-8 (Rev. 1) (1971).
3. P.A. Gustafson, *Radiological Report on Bikini Atoll*, Argonne National Laboratory Rept., Chicago, Illinois (1968).
4. W.L. Robison, Lawrence Livermore Laboratory, private communication (1974).
5. P.H. Gudiksen, T.R. Crites, and W.L. Robison, *External Dose Estimates for Future Bikini Atoll Inhabitants*, Lawrence Livermore Laboratory, Rept. UCRL-51879 (Rev. 1) (1976).
6. V.E. Noshkin, K.M. Wong, R.J. Eagle, and G. Brown, *Preliminary Evaluation of the Radiological Quality of the Water on Bikini and Eneu Islands*, Lawrence Livermore Laboratory, Rept. UCRL-51971 (1976).
7. W.L. Robison, *Dose Assessment at Bikini Atoll*, Lawrence Livermore Laboratory, Rept. in preparation (1976).
8. J.F. Gamble, S.C. Snedaker and Associates, *Bioenvironmental and Radiological Feasibility Studies. Atlantic-Pacific Interoceanic Canal Final Report-Agricultural Ecology*, Battelle Memorial Institute, Richland, Washington, Rept. BMI 821.02 (1969).
9. O.D.T. Lynch, Jr., T.F. McGraw, V.A. Nelson, and W.E. Moore, *Radiological Resurvey of Food, Soil, Air and Ground Water at Bikini Atoll, 1972*, U.S. Energy Research and Development Administration Publ. 34 (1975).
10. A.D. Welander, "Distribution of Radionuclides in the Environment of Eniwetok and Bikini Atolls, August 1964" in *Symposium on Radioecology*, D.J. Nelson and F.C. Guand, Eds. U.S. Atomic Energy Commission, Rept. CONF-670503 (1969).
11. M.E. Mount, W.L. Robison, S.E. Thompson, and K.O. Hamby, A.L. Prindle, and H.B. Levy, *Analytical Program - 1975 Bikini Radiological Survey*, Lawrence Livermore Laboratory, Rept., in preparation (1976).
12. R.M. Kennady, *The Soils of Rongelap Atoll*, M.S. thesis, University of Washington, Seattle, Wn. (1962).
13. N.A. Greenhouse and T.F. McCraw, *Marshall Islands Radiological Followup*, Brookhaven National Laboratory, Rept. BNL-20767 (1976).

14. N.A. Greenhouse, Brookhaven National Laboratory, personal communication (1974).
15. R.B. Walker, E.E. Held, and S.P. Cessel, "Radiocesium in Plants Grown on Rongelap Atoll Soils," *Recent Adv. Bot.*, 88(2), 1363 (1961).

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research & Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights.

NOTICE

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Energy Research & Development Administration to the exclusion of others that may be suitable.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price: Printed Copy \$; Microfiche \$3.00

Page Range	Domestic Price	Page Range	Domestic Price
001-025	\$ 3.50	326-350	10.00
026-050	4.00	351-375	10.50
051-075	4.50	376-400	10.75
076-100	5.00	401-425	11.00
101-125	5.50	426-450	11.75
126-150	6.00	451-475	12.00
151-175	6.75	476-500	12.50
176-200	7.50	501-525	12.75
201-225	7.75	526-550	13.00
226-250	8.00	551-575	13.50
251-275	9.00	576-600	13.75
276-300	9.25	601-up	*
301-325	9.75		

*Add \$2.50 for each additional 100 page increment from 601 to 1,000 pages;
add \$4.50 for each additional 100 page increment over 1,000 pages.

Technical Information Department

LAWRENCE LIVERMORE LABORATORY

University of California | Livermore, California | 94550