Status Report:

Dose Reassessment for Populations on Rongelap and Utirik following exposure to fallout from the BRAVO incident (March 1, 1954).

Introduction:

Incidences of thyroid nodules, benign and malignant, in the exposed populations of Utirik and Rongelap has indicated critical differences in correspondence between nodule incidence and thyroid dose for the populations (Table 1). The estimated external dose received from the time fallout began to the time of evacuation shows that the Rongelap population received an external dose (175 rads) which was about 13 times that for the Utirik population (14 rads), and the thyroid dose was about 10 times larger, whereas the incidence of thyroid nodules in the two populations were not significantly different.

A preliminary study has indicated that the critical area of investigation that could shed light is the period during fallout and evacuation for both the islands. In addition, the fact that the Utirik population returned within 120 days following evacuation, whereas the Rongelap population returned only after three years, requires that we look closely at the Utirik population in terms of a longer exposure period, both internal and external. Further studies would, therefore, have to concentrate on the reexamination of all available data in reports issued by various agencies during that period, consultations with scientific personnel involved at that time, identifying the areas of uncertainty, and using appropriate computer programs to analyze the data. The end result will enable us to look for correlations between the incidence of thyroid nodules and the reassessed dose estimates.

Objective:

To examine the external and internal dose estimates to the Rongelap and Utirik populations following the "Bravo" test in order to:

a. increase the confidence in the reported values
b. test the hypothesis that radiation effects can be translated into meaningful dose estimates
c. look for correlationship between the thyroid cancer cases and the reassessment dose estimates (if any).

Method of Study:

1. Literature Search: This would require examining the various research reports such as:

   a. Weapon Test (WT)
   b. Naval Research Defense Laboratory (NRDL) Reports
   c. Reports from various other laboratories (University of Washington, etc).

2. Personnel Contacts: Efforts will be made to contact as many of the scientists and technical persons, who were involved in the early years for information on measurement techniques and analytical procedures.

TABLE 1

THYROID TUMOR RISK VS DOSE

(Cases/10^6/rad/yr)

GROUP	Yrs. of Follow-up	Children (Age < 10 at exposure) Thyroid Dose Average	Children BENIGN*	Children CANCER	Adults (Age > 10 at exposure) Thyroid Dose Average	Adults BENIGN*	Adults CANCER
Rongelap	22	1010	33	2.4	379	16	6.4
Ailingnae	22	382	40		135	142	
Utirik	22	83		9.5	30	8	26.4
All	22	317	29	3.5	139	14	10.5
Rochester[16]	17	335	64	5.5			
Ann Arbor[16]	17	20	24	2.2	-	-	
UNSCEAR[17]	17	100 - 300		0.5 - 1.5			
ABCC[18]	20	20 - 1000		1.3 (all ages)			

*Corrected for control incidence.

Reference BNL-21924 - Summary of Thyroid Findings in Marshallese 22 Years After Exposure to Radioactive Fallout - Robert A. Conard

APPROXIMATE GAMMA DOSE RATES AT THREE FEET ABOVE THE GROUND ON D+1 (One Day after Detonation)

(Roentgens Per Hour)

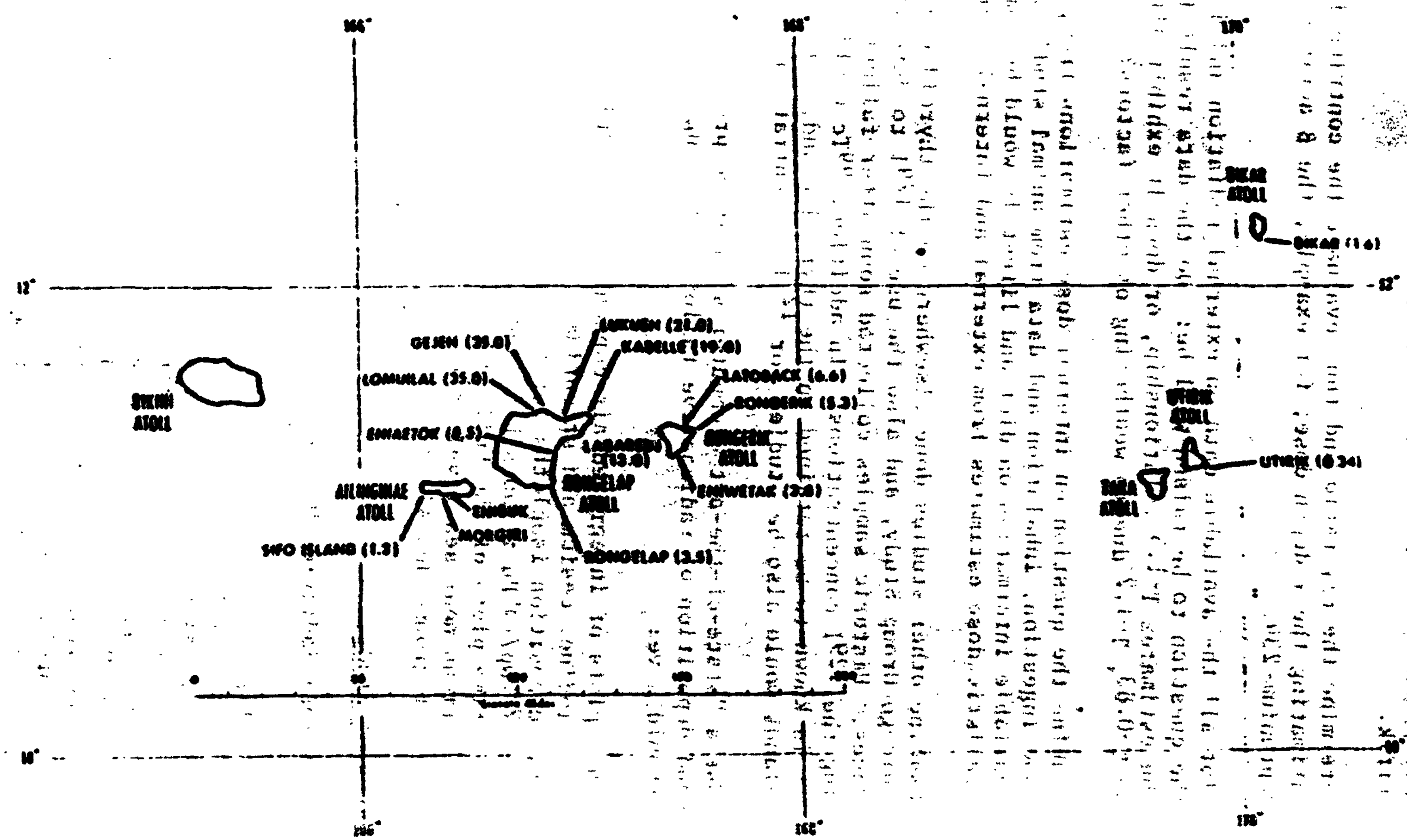

Figure 1.

3. Use of film badge data at Rongerik to quantify the fallout building curve upslope and downslope, and to extrapolate this information to Rongelap and Utirik.

4. Determine the β/γ ratio and thus evaluate the contribution of β dose in estimating the γ depth dose; for example, the β activity dose due to Neptunium-239.

5. Plot all the available data on external radiation and determine decay factors. The question to be raised will be: Do the data result in a curve similar to the estimates $T^{-1.5}$ relationship, or does it exhibit different values, such as $T^{-0.83}$, $T^{-1.2}$ due to weathering or other factors?

6. Examine the question on internal dose estimations from, urine analysis, food ingestion, inhalation and data from animal studies. In this process all available information on diet and lifestyle would be compiled so as to derive realistic dose estimates from external and internal sources.

7. Examine other studies done elsewhere on the thyroid nodules, for example; the Chicago Group Study, and also the use of ^{129}I to determine the early thyroid doses. Historic samples collected soon after fallout will be used in determining the ^{129}I concentrations. In addition, ^{99}Tc would also be determined since it is known to be retained in the thyroid gland. If possible, excised thyroid glands would also be studied for ^{129}I concentrations.

8. Use a "state-of-the-art" computer simulation program to determine the transport and deposition of radioactive fallout following the BRAVO test. This study should give:

   a. plots of integrated air concentration isopleths for fission products iodine, cesium and strontium
   b. deposition isopleths for the aforementioned fission products, plus $^{239}Np/^{239}Pu$ if possible, and
   c. time plots of the buildup and decline of airborne fallout concentrations near sea level at the points of interest, and/or the building of ground deposited fallout.

<u>Status of Study</u>:

1. <u>External Radiation Measurement</u>

   a. Figure 1 shows a plot of the gamma dose rate in roentgens per hour at three feet above ground at 24 hours after the BRAVO test explosion. Figure 2 shows the estimated total dose contours in roentgens at 96 hours after the BRAVO test explosion indicating 175 rads of whole body gamma radiation for the Rongelap inhabitants and 14 rads for the Utirik inhabitants. In view of these observations, an exhaustive search of all reports generated Tables 2 and 3 for Rongelap and Utirik respectively. This data has been plotted in Figures 3 and 4. These plots will be further examined when results from Item 8 above will be received.

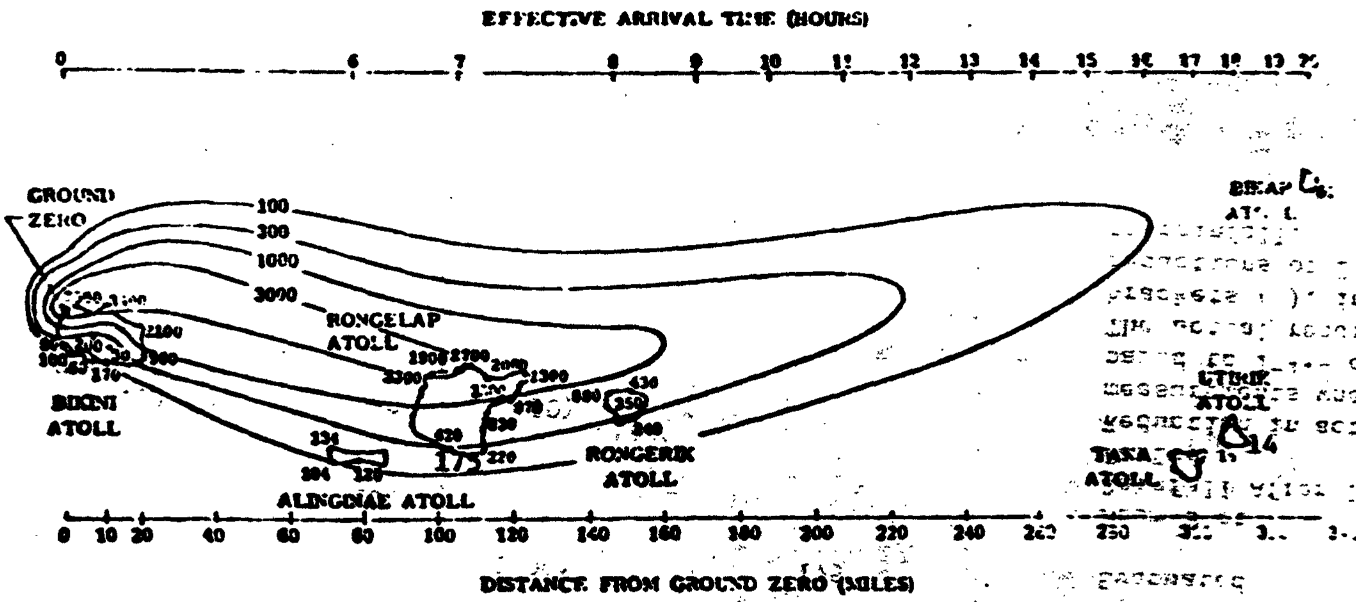

FIGURE 2

ESTIMATED TOTAL-DOSE CONTOURS IN ROENTGENS AT 96 HOURS AFTER THE BRAVO TEST EXPLOSION

Table 2

Dose Rates Consequent To The "Bravo" Shot. March 1, 1954

Rongelap - 115 Miles From GZ

Date	H + Hours	Dose Rate (mR/hour)		Total Dose (Rads)	Comments	Reference
3 1	H + 4 to H + 6				Fallout Began	2
3 2	H + 24	3500				6
		3300			Estimated	1
	H + 46					
[illegible]	(H + 48) to H + 50		(1300)	175	Evacuated	1
3 11	H + 240	200			From Plot	5
	H + 336	160			Rainfall After This Period	1
3 21 54	H + 480	80	(50)		Reduction in actual measurements when compared to $T^{-1.2}$ curne. The actual readings in brackets ( ), indicating reductions of 20-40%, due to rainfall.	1,2,4
	H + 240 to H + 600					
3 31 54	H + 720	50	(30)			1
	H + 960	38	(20)			1
4 19 54	H + 1200	30	17			1,4
		28				
	H + 1440	25	(14)			1
6 1 54	H + 2400	14	(5)			1
10 1 54	H + 4800	5	(1.5)			1
1 1 55	H + 7200	4	(0.85)			1
		3.2	(0.60)			4
	H + 8088		(0.7)			3
	H + 14400	1.5	(0.2)			4
	H + 16848		(0.09)			3
7 1 56	H + 21864		(~0.1)			1
3 2 57	H + 26288		(~0.1)			1
9 5 59	H + 48180		(0.03)			Univ. of Washington
			(0.04)			

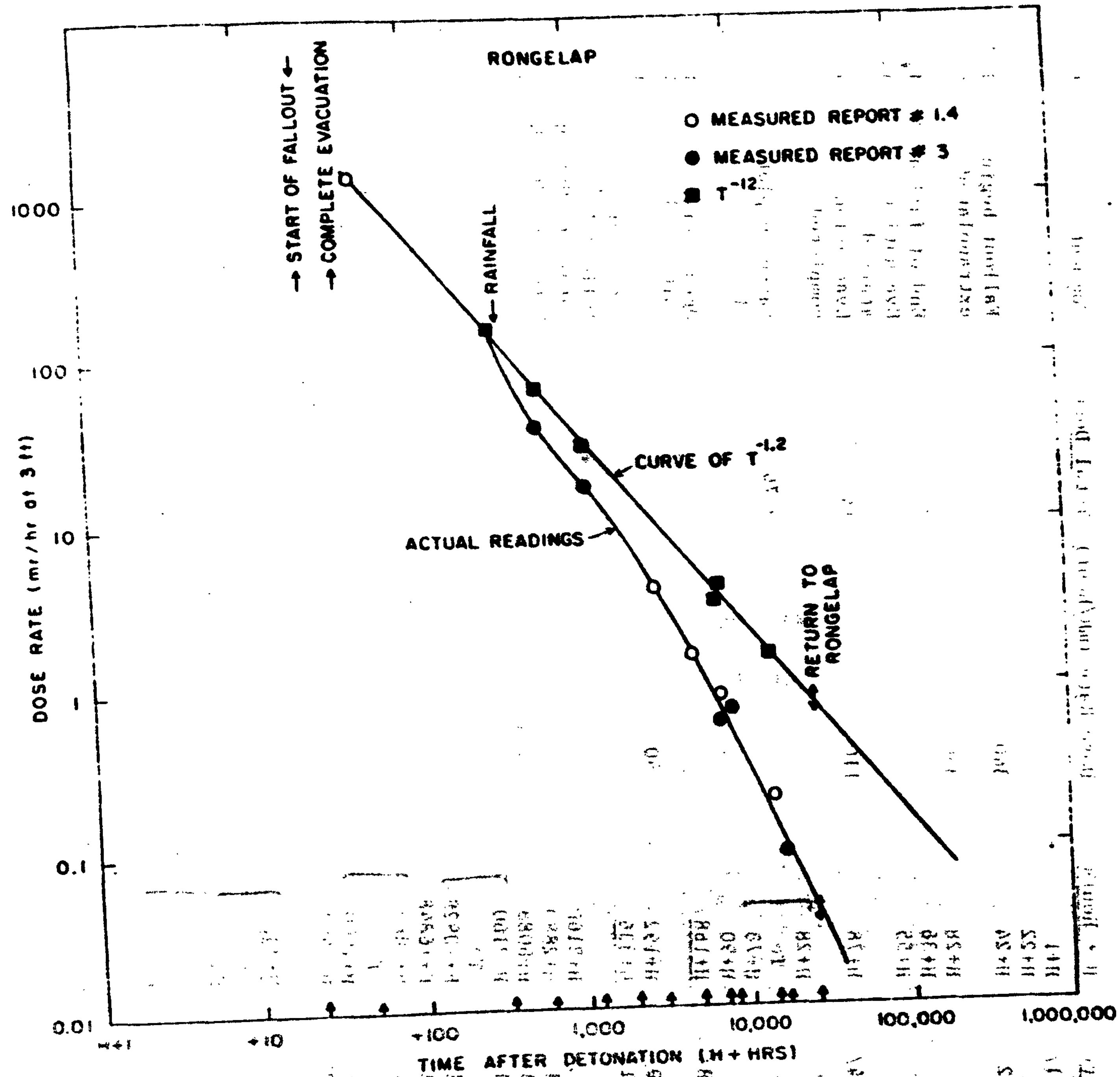

Figure 3 — Rongelap

Table 3

Dose Rates Consequent To The "Brave" Shot, March 1, 1954

Utirik - 300 miles from GZ

Date	H + Hours	Dose Rate (mR/hour)	Total Dose (R)	Comments	Refere[nces]
3/1/54	H+1				
	H+22				
3/2/54	H+24	340		Fallout begins extrapolated	1,2 4
	H+28	350			
	H+36			End of fallout	1,2
	H+55			Evacuation started	1,2
3/4/54	H+78	110	14	Evacuation completed	1,2
	H+28 To H+78		9.76	Based on plot of data	5
	H+90				
3/8/54	H+168			Decay curve follows $T^{-1.2}$	1 1
3/9/54	H+192	40			1
3/15/54	H+336			Decay curve follows $T^{-1.3}$	1
	H+2160			Return to Utirik	
7/1/54	H+2880			Return to Utirik	
2/1/55	H+8088	0.14			3
6/1/54 To 6/1/55	H+2160 To H+10928		5		4
2/1/56	H+16848	0.05			3
7/1/54 To 7/1/65	H+2880 To H+100000		3.10	Based on plot of data	5
[illegible]/25/76	H+190000	0.004		BNL data Sept 1976	
3/15/54 To α	H+336 To H+α			Decay curve follows $T^{-1.4}$	1
6/1/54 To α	H+2160 To H+α	17			4

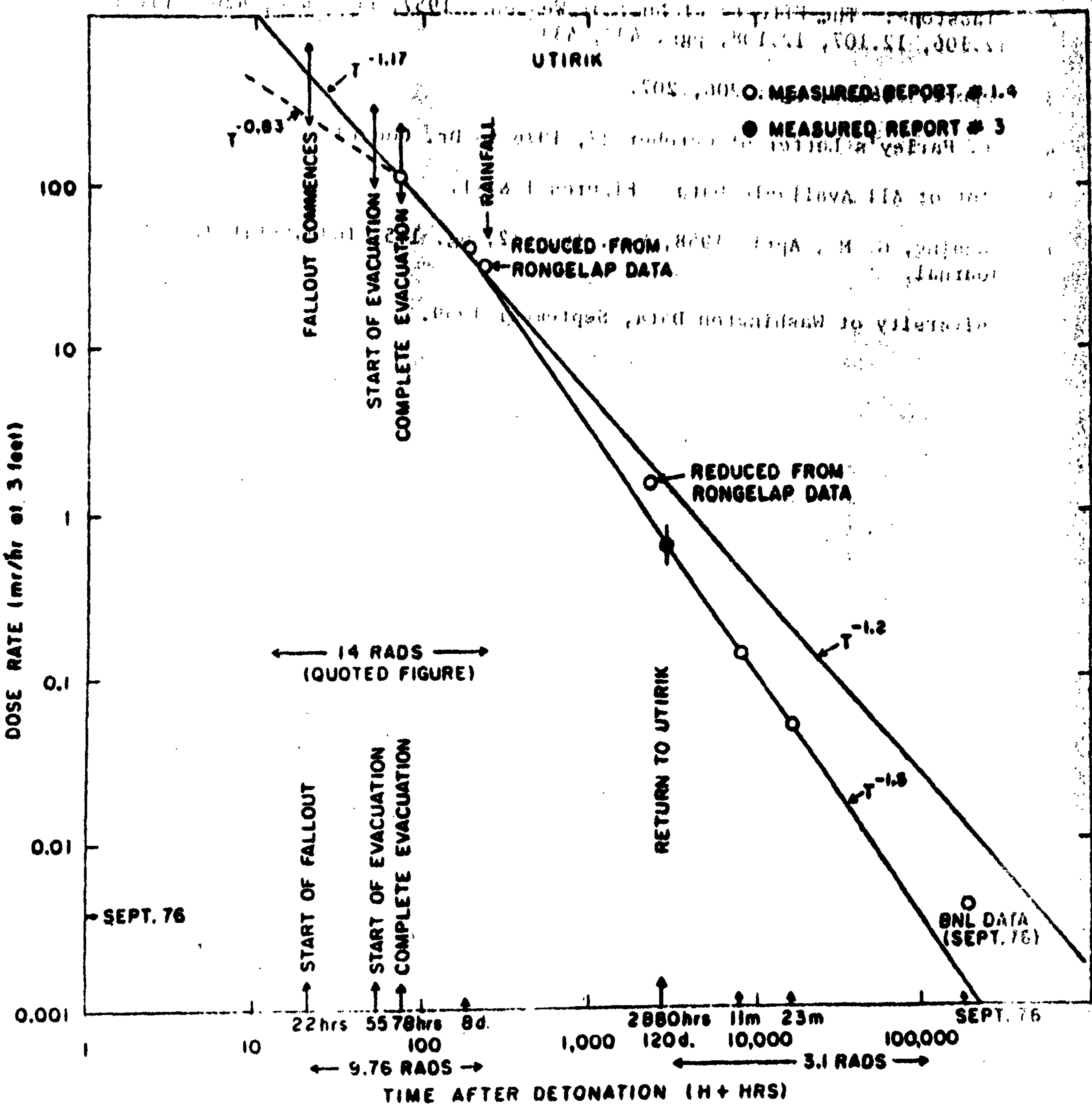

Figure 4 - Utirik

References:

1. Joint Committee Report: U. S. Congress, 1957, pgs. 173, 174, 192, 198, 222, 224.

2. Glasstone: The Effects of Nuclear Weapons, 1957, pgs. 424, 426. Figures 12.106, 12.107, 12.108, pgs. 432, 433.

3. Report: USAEC, pgs. 206, 207.

4. Dr. Harley's Letter of October 27, 1976 to Dr. Conard.

5. Plot of All Available Data - Figures I & II.

6. Dunning, G. M., April 1958, Vol. 19, #12, pg. 115, Industrial Hygiene Journal.

7. University of Washington Data, September 1959.

2. Diet and Lifestyle Study

a. All available reports concerning fallout on Ailinginae, Rongelap, Rongerik and Utirik have been examined and pertinent information has been collated into one location. The data collected concerns external radiation measurements, radionuclide concentrations in soil, water, vegetation, animals and food items. In addition, efforts are being made to collect information on whole body analysis and bioassay samples.

b. A recent diet and lifestyle study completed in November 1978 will provide a firm basis to estimate internal and external doses.

3. ^{129}I Study

a. Historic samples collected by University of Washington during the period 1954-1974 have been analyzed for ^{129}I (Table 4). These samples are also being analyzed for ^{99}Tc. Information from Item 8 (Methods of Study) will be required to correlate the findings. Additional samples from these areas (Rongelap, Ronerik, Utirik) will be analysed for ^{129}I and ^{99}Tc if required. In addition, we are exploring the possibility of analyzing "Bikini-ash"-the fallout that settled on "The Lucky Dragon". This sample should provide the most accurate description of the fallout.

4. 'State-of-the-Art' Computer Simulation

a. All available data pertaining to meteorological conditions before, during and after the BRAVO test have been collected and transmitted to Lawrence Livermore Laboratory for the computer analysis. These results should be available by February/March 1979.

b. A recent Marshall Islands Radiological survey completed in December 1978 should provide iso-dose lines for recent times. Comparison of the two plots should be very valuable in assessing 1954 observations.

5. Discussions are being continued with the scientists and technical people who were involved during Operation Castle.

Table 4

^{129}I Radiochemical Analysis Results*

DATE	I-129 ATOMS/G	PCT ERROR	I-129 ATOMS/μG	PCT ERROR	COMMENTS
32654	4.44E+10	3.4	2.77E+09	4.5	ISLAND SOIL, (SAND), TOP 1 INCH, RONGELAP-LABARDZ
71654	4.80E+10	3.6	3.88E+09	5.8	ISLAND SOIL, (SAND), ALMOST NO HUMUS), RONGELAP-KABELLE
12955	1.33E+11	4.2	3.65E+09	6.8	ISLAND SOIL, (SAND), RONGELAP-KABELLE
12555	1.53E+11	3.4	7.77E+09	6.9	ISLAND SOIL, (SAND), RONGELAP-RONGELAP
102255	2.24E+11	3.1	1.52E+10	6.5	SOIL, (SAND), SUBSAMPLE SPECIMAN A-12) RONGELAP
102255	1.73E+10	4.2	1.59E+09	5.7	SOIL, (SAND, FROM BOTTOM OF WELL), RONGELAP ATOLL
102255	2.98E+10	3.5	9.72E+08	6.1	SOIL, (SAND, SUBSAMPLE SPECIMAN A-9), RONGELAP
72456	4.73E+10	3.7	2.60E+09	6.4	MID ISLAND SOIL, (SAND 0-2"), RONGELAP-KABELLE
72356	2.02E+10	3.3	1.10E+09	6.3	SOIL, (SAND 0-2", POSS. FALLOUT CONTAM.), RONGELAP-RONGELAP
72356	1.12E+10	3.2	4.58E+08	5.6	SOIL, (SAND 0-2", MID ISLAND CLEARING), RONGELAP-RONGELAP
71857	7.60E+10	3.8	4.17E+09	6.6	ISLAND SOIL (SAND, RANDOM TOP INCH), RONGELAP-KABELLE
71757	2.13E+10	3.5	1.90E+09	4.6	SOIL (SAND, RANDOM TOP INCH, E 1/2 OF ISLAND) RONGELAP
12355	4.14E+09	7.5	1.52E+08	10.9	ISLAND SOIL (SAND) UTIRIK ATOLL
12355	9.31E+08	6.7	4.45E+07	8.3	BLACK BEACH SAND, UTIRIK ATOLL
112874	3.82E+09	3.3	2.22E+08	4.3	SURF, SOIL, 0-2.5 CM, SW TRANSECT, RONGERIK-ENEWETAK ISLAND
112874	6.13E+09	3.4	3.73E+08	5.2	SURF, SOIL, 0-2.5 CM, NE TRANSECT, RONGERIK-ENEWETAK ISLAND

*Done by PNL, Hanford, Washington

BNL 51257
UC-41
(Health and Safety - TIC-4500)

A RECONSTRUCTION OF CHRONIC DOSE EQUIVALENTS FOR RONGELAP AND UTIRIK RESIDENTS - 1954 TO 1980

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October 1980

SAFETY AND ENVIRONMENTAL PROTECTION DIVISION

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UPTON, NEW YORK 11973

Coded As 43507

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Price: Printed Copy $7.00; Microfiche $3.50

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E. T. Lessard, N. A. Greenhouse, R. P. Miltenberger

ABSTRACT

From June 1946 to August 1958, the U.S. Department of Defense and Atomic Energy Commission conducted nuclear weapons tests in the Northern Marshall Islands. BRAVO, an aboveground test in the Castle series, resulted in radioactive fallout contaminating Rongelap and Utirik Atolls. On March 3, 1954, the inhabitants of these atolls were relocated until radiation exposure rates declined to acceptable levels. Environmental and personnel radiological monitoring programs were begun in the mid 1950's by Brookhaven National Laboratory to ensure that dose equivalents received or committed remained within U.S. Federal Radiation Council Guidelines for members of the general public. Body burden and dose equivalent histories along with activity ingestion patterns post return are presented. Dosimetric methods, results, and internal dose equivalent distributions for subgroups of the population are also described.

INTRODUCTION

On March 1, 1954, at Bikini Atoll, BRAVO, the first of six nuclear weapons tests in the Castle series, was detonated. The BRAVO device caused substantial surface contamination on inhabited atolls within a 2,000 square mile area. The contaminated region was cigar shaped and included Ailinginae, Rongelap, Rongerik, and Utirik Atolls which lay east of ground zero at distances from 60 to 300 miles. The fallout on Rongelap, initially visible at H+6 hours, had thinned out to the extent that it was no longer seen at H+10 hours (G162).

On March 3, 1954, the 64 residents of Rongelap Atoll and 18 residents of Sifo Island, Ailinginae Atoll, were evacuated. On March 3 and 4, evacuation of 157 Utirik Atoll residents also took place. During the first few weeks and at least once every year from 1957 to the present, a Brookhaven National Laboratory medical team, organized by the Department of Defense and by the Atomic Energy Commission and its successor organizations, has provided medical examinations to monitor the health of the persons initially affected by the fallout from the nuclear testing program, plus a comparison population. Reports of their findings are given in Cr56, Co58, Co59, Co60, Co62, Co63, Co65, Co67, Co70, Co75, and Co80.

The Utirikese and Rongelapese returned to their home atolls in June 1954 and in June 1957 respectively. The earlier repatriation of Utirik Atoll was based on the low level of external radiation exposure measured after the initial 3 month observation period (March to June 1954). The Utirik population was not examined by a Brookhaven medical team until March, 1957, when 144 people received comprehensive physical examinations. Following the 1957, medical survey, two men, removed from Utirik for medical reasons, were whole body counted at Argonne National Laboratory and provided urine samples for radiochemical analysis of ^{137}Cs. Four persons visited Argonne from Rongelap and, in addition, pooled urine samples from both atolls were analysed radiochemically for ^{137}Cs and ^{90}Sr. Subsequent Brookhaven National Laboratory expeditions by members of the Medical Department and Safety and Environmental Protection Division utilized whole body counting and radiochemical analysis of urine and blood samples to identify and quantify the radionuclides that were present in the body. The results of these radiological measurements are given in terms of body burden in Tables 1 and 2. Throughout this paper the units of quantities are SI derived and those which are accepted for use with the SI for the time being. Thus both the Curie and the Becquerel may be used as units for the quantity activity.

The aforementioned body burden tables illustrate adult mean values for Rongelap and Utirik. An adult, as classified here, was a person over 16 years of age. The mean body mass in this age interval was 60 kilograms. The observed body mass versus age distribution is shown in Figure 1 for Rongelap residents. The same body mass versus age distribution was observed at Utirik.

Because of the paucity of measurements at Utirik, information on ^{60}Co, ^{65}Zn, and ^{55}Fe was in some instances derived from the ratio of adult mean body burdens between Rongelap and Utirik. A mean ratio of 2.6 was observed in body burdens for ^{65}Zn, ^{90}Sr, and ^{137}Cs after they reached their maximum values. The standard deviation of this ratio was 15%.

In the following analysis, personal body burden histories and residence intervals, in conjunction with contemporary dosimetric models, are used to estimate internal dose. Dosimetric distributions were constructed from the results and a summary of the derived activity ingestion rates and dose equivalents was provided for various subgroups of the population. Additionally, exposure rate history curves were constructed for each atoll for the period following the

Table 1

Rongelap Body Burdens

	Adult Males		Adult Females		Adults		
	Body Burden μCi	Number of Persons	Body Burden μCi	Number of Persons	Body Burden μCi	Number of Persons	Days Post Return Days
^{60}Co	2.9×10^{-5}	NA	1.7×10^{-5}	NA	2.3×10^{-5}	NA	1
	1.0×10^{-2}	37	7.8×10^{-3}	37	9.0×10^{-3}	74	1370
	2.5×10^{-3}	45	2.0×10^{-3}	45	2.2×10^{-3}	90	2831
^{65}Zn	4.3×10^{-2}	NA	3.8×10^{-2}	NA	4.1×10^{-2}	NA	1
	4.3×10^{-1}	30	3.8×10^{-1}	12	4.1×10^{-1}	42	306
	6.2×10^{-1}	32	5.0×10^{-1}	27	5.6×10^{-1}	59	639
	9.5×10^{-2}	38	8.5×10^{-2}	23	9.0×10^{-2}	61	1370
^{55}Fe	4.3×10^{-1}	28	4.0×10^{-1}	32	4.1×10^{-1}	60	4626
^{90}Sr	1.9×10^{-4}	NA	1.6×10^{-4}	NA	1.7×10^{-4}	NA	1
	3.7×10^{-3}	11	2.8×10^{-3}	4	3.4×10^{-3}	15	306
	5.7×10^{-3}	24	3.5×10^{-3}	16	4.8×10^{-3}	40	639
	3.7×10^{-3}	9	1.6×10^{-3}	4	3.0×10^{-3}	13	1370
	8.8×10^{-3}	12	7.9×10^{-3}	13	8.4×10^{-3}	25	2100
	7.9×10^{-3}	11	7.4×10^{-3}	7	7.7×10^{-3}	18	2466
	2.8×10^{-3}	12	4.6×10^{-3}	12	3.7×10^{-3}	24	3561
	3.9×10^{-3}	11	3.1×10^{-3}	11	3.5×10^{-3}	22	3927
	4.1×10^{-3}	11	3.3×10^{-3}	13	3.6×10^{-3}	24	4292
	1.3×10^{-3}	8	3.3×10^{-3}	11	2.5×10^{-3}	19	4657
	3.1×10^{-3}	8	2.8×10^{-3}	7	3.0×10^{-3}	15	5022
	2.0×10^{-3}	5	1.4×10^{-3}	7	1.6×10^{-3}	12	5388
	6.6×10^{-3}	4	4.2×10^{-3}	7	4.3×10^{-3}	13	5753
	3.3×10^{-3}	10	1.7×10^{-3}	6	2.8×10^{-3}	16	6118
	4.4×10^{-3}	23	NA	0	NA	NA	7579
	6.3×10^{-4}	24	4.6×10^{-4}	19	5.5×10^{-4}	43	8097
^{137}Cs	1.4×10^{-2}	NA	8.4×10^{-3}	NA	1.1×10^{-2}	NA	1
	8.7×10^{-1}	NA	5.2×10^{-1}	NA	6.8×10^{-1}	NA	306
	7.9×10^{-1}	47	4.1×10^{-1}	49	5.7×10^{-1}	96	639
	9.5×10^{-1}	37	4.7×10^{-1}	37	6.7×10^{-1}	74	1370
	9.6×10^{-1}	44	4.9×10^{-1}	45	6.8×10^{-1}	89	2831
	4.8×10^{-1}	22	3.0×10^{-1}	24	3.9×10^{-1}	46	6118
	3.0×10^{-1}	30	1.9×10^{-1}	21	2.5×10^{-1}	51	7213
	1.8×10^{-1}	19	1.5×10^{-1}	18	1.7×10^{-1}	37	8097

NA = Not available

Table 2

Utirik Body Burdens

	Adult Males		Adult Females		Adults		
	Body Burden µCi	Number of Persons	Body Burden µCi	Number of Persons	Body Burden µCi	Number of Persons	Days Post Return Days
^{60}Co							
D	4.0×10^{-3}		3.1×10^{-3}		3.5×10^{-3}		2464
D	9.7×10^{-4}		7.6×10^{-4}		8.7×10^{-4}		3924
^{65}Zn	3.5×10^{-1}*	2	-		-		
	2.7×10^{-1}	14	1.6×10^{-1}	15	2.1×10^{-1}	29	1734
D	3.7×10^{-2}		3.3×10^{-2}		3.5×10^{-2}		2464
^{55}Fe							
D	1.7×10^{-1}		1.6×10^{-1}		1.6×10^{-1}		6114
^{90}Sr							
	1.4×10^{-3}	5	2.4×10^{-3}	2	1.7×10^{-3}	7	1734
	1.2×10^{-3}	5	1.3×10^{-3}	6	1.3×10^{-3}	11	7213
	NA	12	NA	12	NA	24	8669
	1.5×10^{-4}	14	1.5×10^{-4}	17	1.5×10^{-4}	31	9225
^{137}Cs							
	4.1×10^{-1}	NA	2.7×10^{-1}	NA	3.3×10^{-1}	NA	1004
	2.9×10^{-1}	15	2.0×10^{-1}	15	2.5×10^{-1}	30	1734
	2.6×10^{-1}	9	1.3×10^{-1}	13	1.8×10^{-1}	22	7213
	1.2×10^{-1}	27	7.8×10^{-2}	21	1.0×10^{-1}	48	8309
	6.2×10^{-2}	19	4.3×10^{-2}	17	5.3×10^{-2}	36	9225

D = Ratio derived body burden
NA = Not available
* = Measured at Argonne National Laboratory

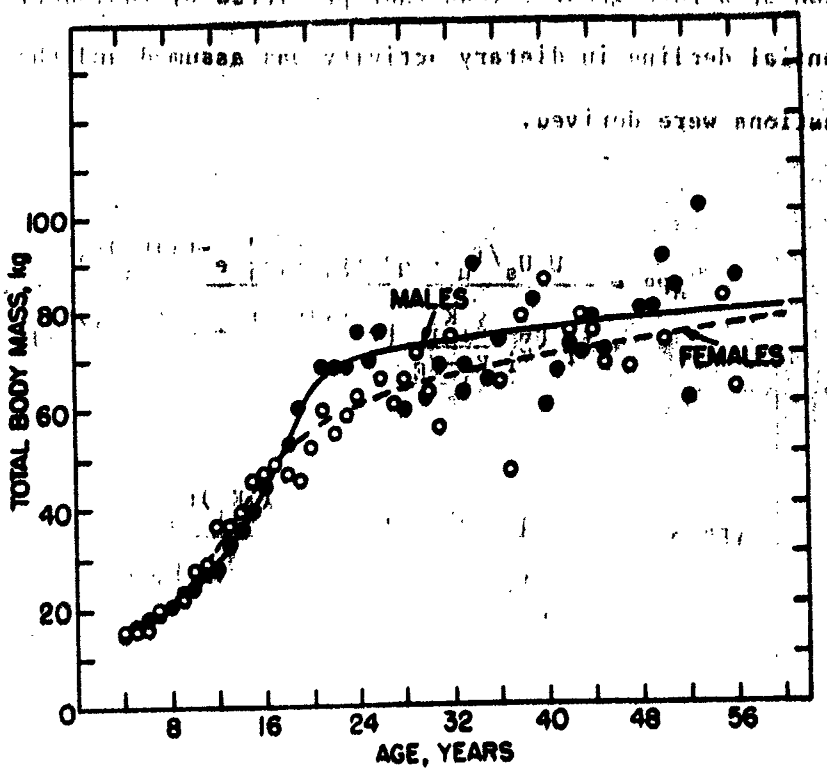

Fig. 1 Body Mass as a Function of Age for
Residents of Rongelap Atoll

BRAVO test. These data, together with appropriate conversion factors and living pattern models, provided an estimate of external dose equivalent.

METHODS

Exponentially declining activity concentrations have been observed in surface soil for ^{137}Cs, ^{129}I, and ^{90}Sr from 1954 to the present on Rongelap and Utirik Atolls. Declining activity concentrations have also been observed in vegetation at a rate greater than that predicted by radioactive decay. Thus exponential decline in dietary activity was assumed and the following general equations were derived.

$$\lambda P^{\circ} = \frac{U_0 U_s / E_U - q^{\circ} \left(\Sigma_i K_i X_i' e^{-(\lambda+K_i)t} \right)}{f_1 \left(\Sigma_i \frac{X_i K_i}{K_i - K_E} \left(e^{-(\lambda+K_E)t} - e^{-(\lambda+K_i)t} \right) \right)} \qquad (1)$$

or

$$\lambda P^{\circ} = \frac{q - q^{\circ} \left(\Sigma_i X_i' e^{-(\lambda+K_i)t} \right)}{f_1 \left(\Sigma_i \frac{X_i}{K_i - K_E} \left(e^{-(\lambda+K_E)t} - e^{-(\lambda+K_i)t} \right) \right)} \qquad (2)$$

and

$$D = f_1 \lambda P^{\circ} \Sigma_i \frac{X_i}{K_i - K_E} \left(\frac{K_i - K_E - (\lambda+K_i) e^{-(\lambda+K_E)t} + (\lambda+K_E) e^{-(K_i+\lambda)t}}{(K_E+\lambda)(K_i+\lambda)} \right)$$

$$+ q^{\circ} \Sigma_i \frac{X_i'}{\lambda+K_i} \left(1 - e^{-(\lambda+K_i)t} \right), \qquad (3)$$

where

$t \equiv$ time post onset of uptake, days,

$\lambda \equiv$ instantaneous fraction of atoms decaying per unit time, day^{-1}

$P^o \equiv$ initial atom ingestion rate, atoms day^{-1},

$K_i \equiv$ instantaneous fraction of atoms removed from compartment i by physiological mechanisms, day^{-1},

$\chi_i \equiv$ compartment i deposition fraction,

$\chi_i' \equiv$ the number of atoms in compartment i relative to the number in all compartments at the onset of declining continuous uptake, (t=0),

$U \equiv$ instantaneous urine activity concentration, Bq ℓ^{-1},

$U_s \equiv$ subject urine excretion rate, ℓ day^{-1},

$f_1 \equiv$ fraction from GI tract to blood,

$f_u \equiv$ fraction excreted by the urine pathway,

$K_E \equiv$ instantaneous fraction of atoms removed or added to the atom uptake per unit time, day^{-1}, due to factors other than radioactive decay,

$q \equiv$ instantaneous body burden, Bq,

$q^o \equiv$ body burden at the onset of uptake, Bq,

$D \equiv$ the number of disintegrations in all compartments occurring during the uptake interval, Bq days.

The development of Eqs. (1), (2), and (3) was based on the following convolution integral. At some variable time, τ, defined during a fixed uptake interval, T, the daily activity ingestion rate crossing the gastrointestinal tract to blood is given by

$$\lambda f_1 P^o e^{-(k_E+\lambda)\tau} .$$

The whole body retention at any time $t-\tau$ of the fraction of initial radioactivity inputed at time τ is

$$\Sigma_i \chi_i e^{-(\lambda+K_i)(t-\tau)}$$

Thus, the instantaneous activity at time $t-\tau$ that remains following input during $d\tau$ is

$$\lambda f_1 P^\circ e^{-(K_g+\lambda)\tau} \Sigma_i \chi_i e^{-(\lambda+K_i)(t-\tau)}$$

It follows that the instantaneous activity at time $t-\tau$ that remains following input during T is

$$\int_0^T \lambda f_1 P^\circ e^{-(K_g+\lambda)\tau} \Sigma_i \chi_i e^{-(\lambda+K_i)(t-\tau)} d\tau \, ,$$

The solution of the integral yields a general expression that depends on the user defining t. For example, if t is the fixed uptake interval, T, plus an additional fixed post uptake interval, Ø, then the body burden at T + Ø is given by

$$\frac{\lambda P^\circ f_1 \, \Sigma_i \chi_i \left(e^{-(\lambda+K_g)T} - e^{-(\lambda+K_i)T}\right) e^{-(\lambda+K_i)\,\emptyset}}{K_i - K_g}$$

As previously stated, Eq. (2) applied at Rongelap and Utirik, it was for the situation that variable time t was the uptake interval. Additionally, persons who returned to the atolls in June 1954 and June 1957 did so with an initial body burden, q°. The behavior of this contribution to body burden, q, was embodied in the q° term of Eq. (2). A similar model was used to relate urine activity concentration to body burden. Equation 3 was obtained by integrating Eq. (2).

Equations (1) and (2) were used to determine the instantaneous fraction of atoms removed or added to the atom uptake per unit time, K_E, and then the initial daily activity ingestion rate required to produce the measured or derived body burden. Equation (3) was used to determine the number of disintegrations that occurred in the body during the residence interval of an individual living on Rongelap or Utirik Atoll.

If the mean residence time in the diet is much much longer than the residence interval, then constant continuous uptake is achieved. Equations (1) and (2) can be converted to the constant continuous equations by replacing K_E with $-\lambda$. Single uptake expressions are obtained by setting F^o equal to zero. In some cases only radioactive decay may remove the nuclide from dietary items; for these cases K_E would equal zero. In the case of the former Bikini residents, the maturing of coconut trees during residence on Bikini Atoll caused a continuously increasing dietary uptake of ^{137}Cs. Thus, K_E was found to have a negative value. In the case of Rongelap and Utirik, K_E was found to have a positive value for ^{137}Cs, ^{65}Zn, ^{60}Co, and ^{90}Sr. This indicated that in addition to radioactive decay, some other removal mechanism decreased the radioactivity in dietary items during the residence interval. For the nuclide ^{55}Fe, only one measurement was published by the BNL Medical Program (Be72); thus an estimate of K_E was not possible.

K_E was determined by using Eq. (1) or (2) and the population subgroup mean body burden or urine activity concentration. Portions of these bioassay data are illustrated for adult males and females in Figures 2 to 6. Two consecutive urine or body burden data points were used to eliminate the unknown ingestion

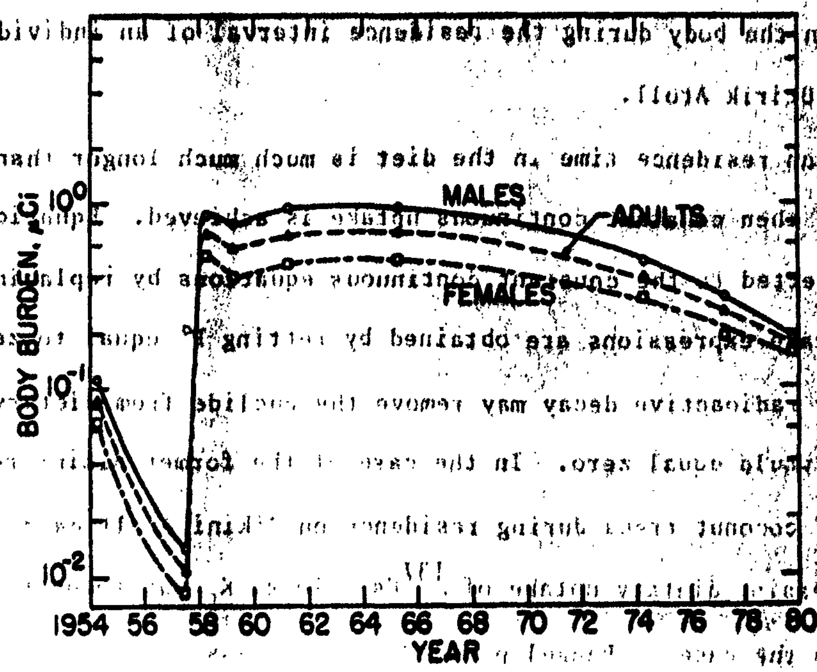

Fig. 2 Mean Adult ^{137}Cs Body Burden History at Rongelap Atoll

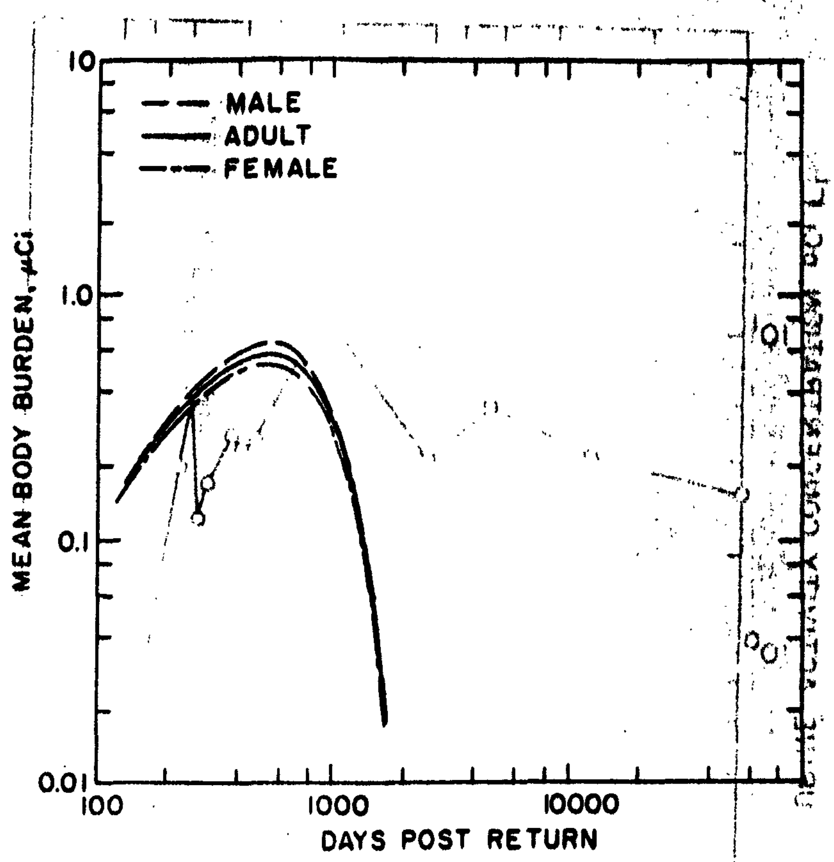

Fig. 3 Mean Adult ^{65}Zn Body Burden History at Rongelap Atoll

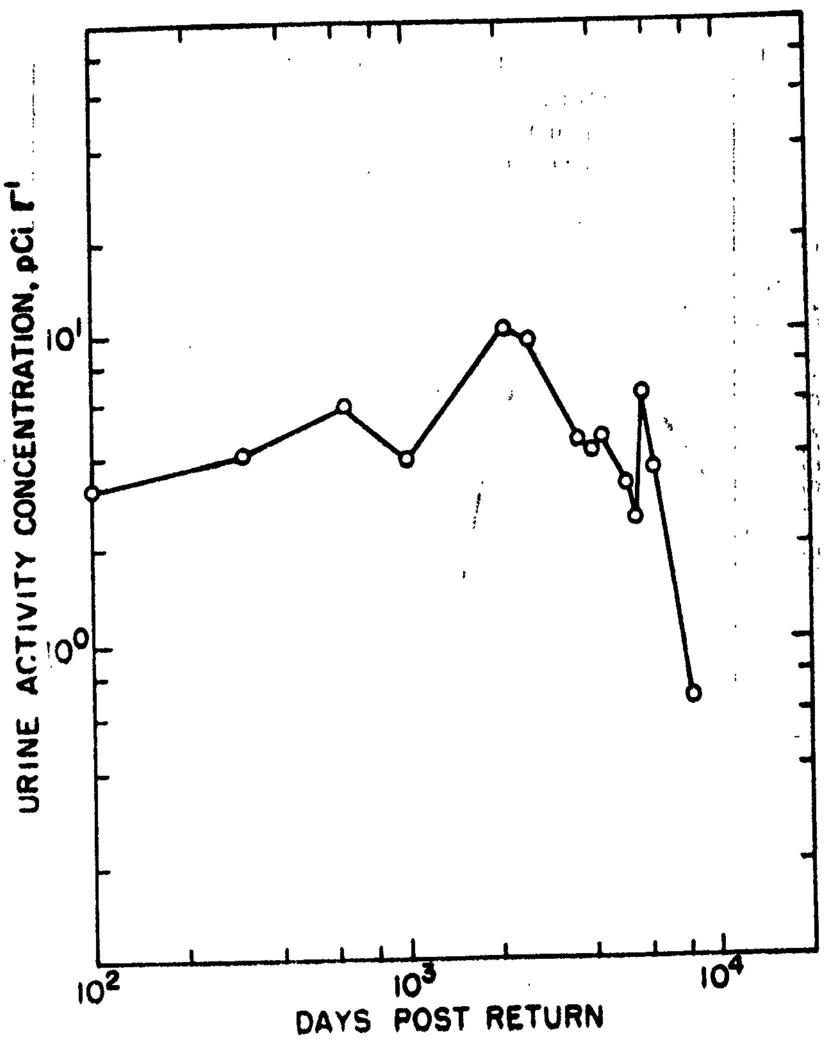

Fig. 4 Mean Adult ^{90}Sr Urine Activity Concentration History at Rongelap Atoll

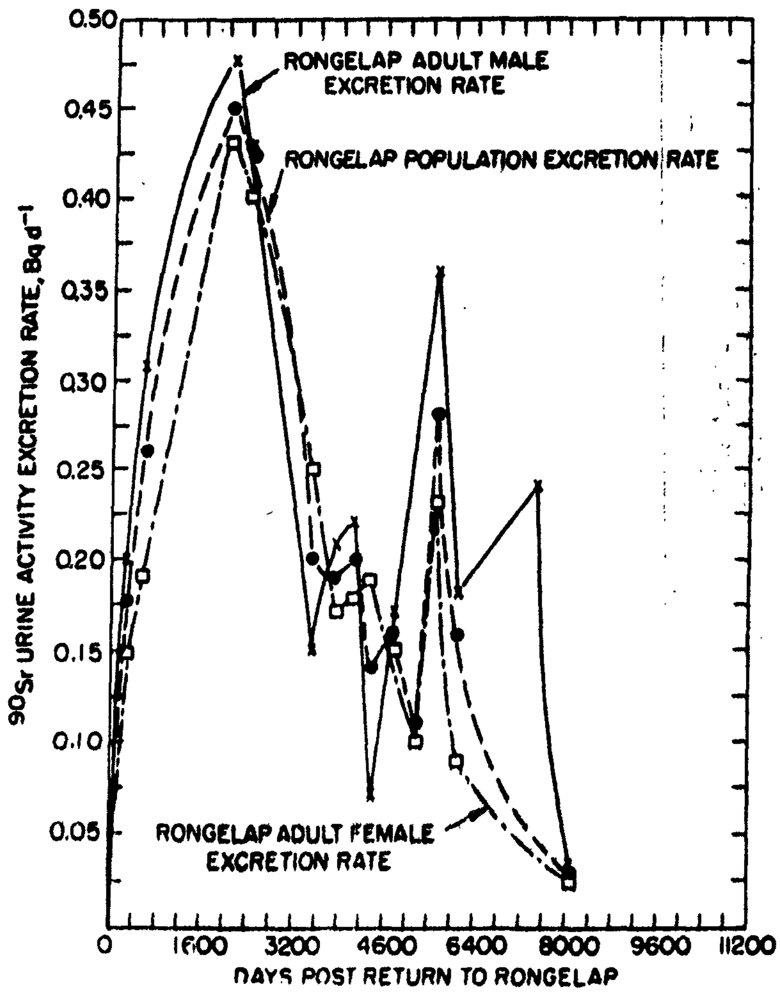

Fig. 5 Mean Adult ^{90}Sr Urine Activity Excretion Rate at Rongelap Atoll

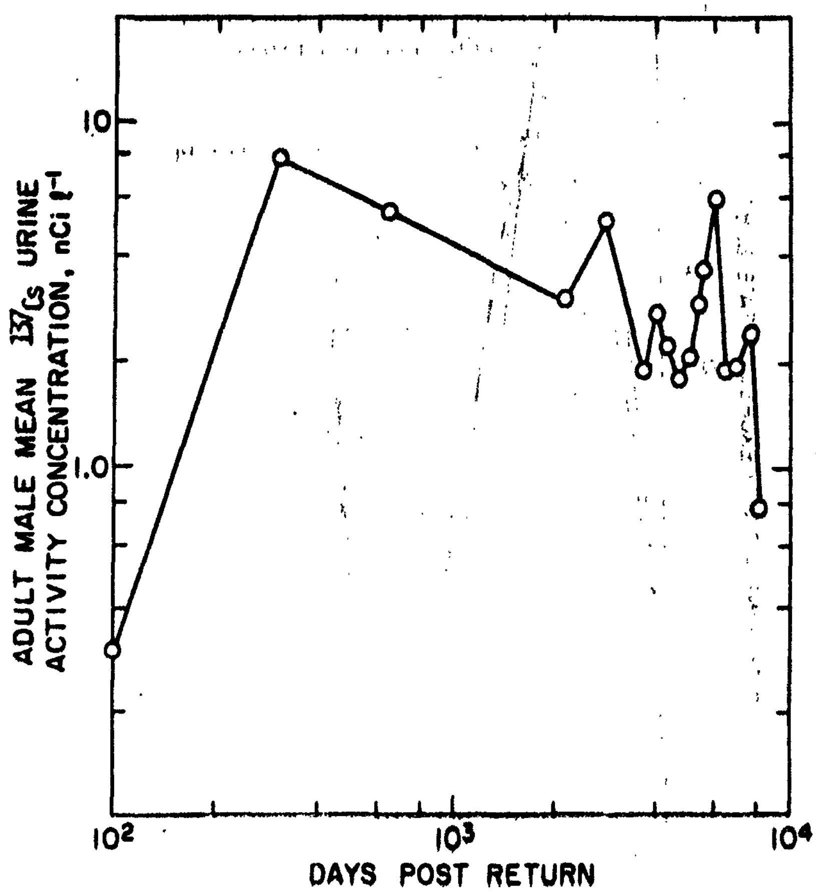

Fig. 6 Mean Adult Male ^{137}Cs Urine Activity Concentration History at Rongelap Atoll

rate from the equation. This method yields n-1 estimates of K_E where n was the number of data points. An average value of K_E was assigned for each nuclide, and the results for the Rongelap and Utirik populations are given in Table 3. For the evaluation of K_E from Eq. 1 and 2, radiological and physiological parameters were obtained from the open literature (ICRP59, ICRP68, ICRP69, ICRP79, Ki78). A representative sample of these parameters is presented in Table 4.

Table 3

Summary of Dietary Rate Constants (K_E, d^{-1})

	^{60}Co	^{90}Sr	^{65}Zn	^{137}Cs
Rongelap Adults				
Males	1.5×10^{-3}	1.8×10^{-4}	3.1×10^{-3}	1.4×10^{-4}
Females	1.6×10^{-3}	4.1×10^{-4}	3.5×10^{-3}	1.4×10^{-4}
Adults	1.5×10^{-3}	1.9×10^{-4}	3.1×10^{-3}	1.4×10^{-4}
Utirik Adults				
Males	N.D.	4.6×10^{-4}	N.D.	1.4×10^{-4}
Females	N.D.	4.0×10^{-4}	N.D.	1.4×10^{-4}
Adults	N.D.	4.2×10^{-4}	N.D.	1.4×10^{-4}

N.D. ≡ No data sufficient for analysis.

The values of K_E were similar for males and females and for reside[illegible] Rongelap and Utirik. For ^{90}Sr on Rongelap a factor of 2 difference betw[illegible] values was observed for males and females. The female parameter for Ron[illegible] Atoll compares with that obtained from the Utirik data. A paired t-test Rongelap male and female data indicates that the male/female difference [illegible] highly probable and therefore not significant. This difference leads t[illegible]

Table 6

Total Body Dosimetric and Physiologic Data

Nuclide $^{A}_{Z}X$	Compartment Deposition Fraction X_i	Compartment Removal Rate Constant K_i d^{-1}	GI Tract to Blood Transfer f_1	Fraction Excreted in Urine f_u	Decay Constant λ d^{-1}	Significant Progeny $^{A}_{Z}X$	Branching Ratio
$^{137}_{55}Cs$	0.13 0.87	0.50 0.0051	1.0	0.90	6.3×10^{-5}	$^{137m}_{56}Ba$	0.946
$^{65}_{30}Zn$	0.25 0.75	0.058 0.0022	0.35	0.25	2.8×10^{-3}	$^{65*}_{29}Cu$	0.49
$^{90}_{38}Sr$	0.89 0.059 0.051	0.21 7.1×10^{-4} 1.0×10^{-4}	0.20	0.85	6.5×10^{-5}	$^{90}_{39}Y$ $^{90*}_{40}Zr$	1.0 0.0002
$^{60}_{27}Co$	0.5 0.3 0.1 0.1	1.4 0.12 0.012 8.7×10^{-4}	0.05	0.70	3.6×10^{-4}	$^{60*}_{28}Ni$	1.0
$^{55}_{26}Fe$	1.0	3.5×10^{-4}	0.1	0.0	7.0×10^{-3}		

bimodal activity ingestion rate distribution for ^{90}Sr in the Rongelap population.

Data for ^{60}Co and ^{65}Zn were not sufficient for analysis for the Utirik Atoll residents. Values for K_E observed at Rongelap were assigned to Utirik males and females and body burden histories for population subgroups were reconstructed using Eq. 1 or 2. Figures 7 and 8 illustrate the derived mean adult body burdens for all significant nuclides studied on Rongelap and Utirik. This method provides a best fit of the data shown in Figures 2 through 6, and provides a body burden history during the early years post return at Utirik, a time when body burden measurements were not made. Actual data points are also plotted to demonstrate the fit.

The curves shown for ^{55}Fe in Figures 7 and 8 were obtained by setting K_E equal to zero. This underestimated the initial body burdens and overestimated future ones. Since ^{55}Fe contributed less than 1.0% to the total dose equivalent, an arbitrary assignment of K_E based on observed values for the other nuclides was not attempted. During 1974, another series of blood samples was obtained from Rongelap and Utirik (Co75). Analysis for ^{55}Fe has yet to be reported. A recalculation of ^{55}Fe body burden and its impact on early dose equivalent rates will be conducted when the data is made available. A substantial change in dose equivalent is not to be expected.

Figure 4 and Figure 6 illustrate the observed adult histories of ^{90}Sr and ^{137}Cs mean urine activity concentrations. Mean values for adult males or all adults were plotted. Measured values for ^{137}Cs body burdens were also shown in Figure 7. A much smoother curve was plotted in Figure 7 and it was determined that the collection and analysis technique for urine samples introduced the additional variations. On the basis of this observation for ^{137}Cs, a smooth body

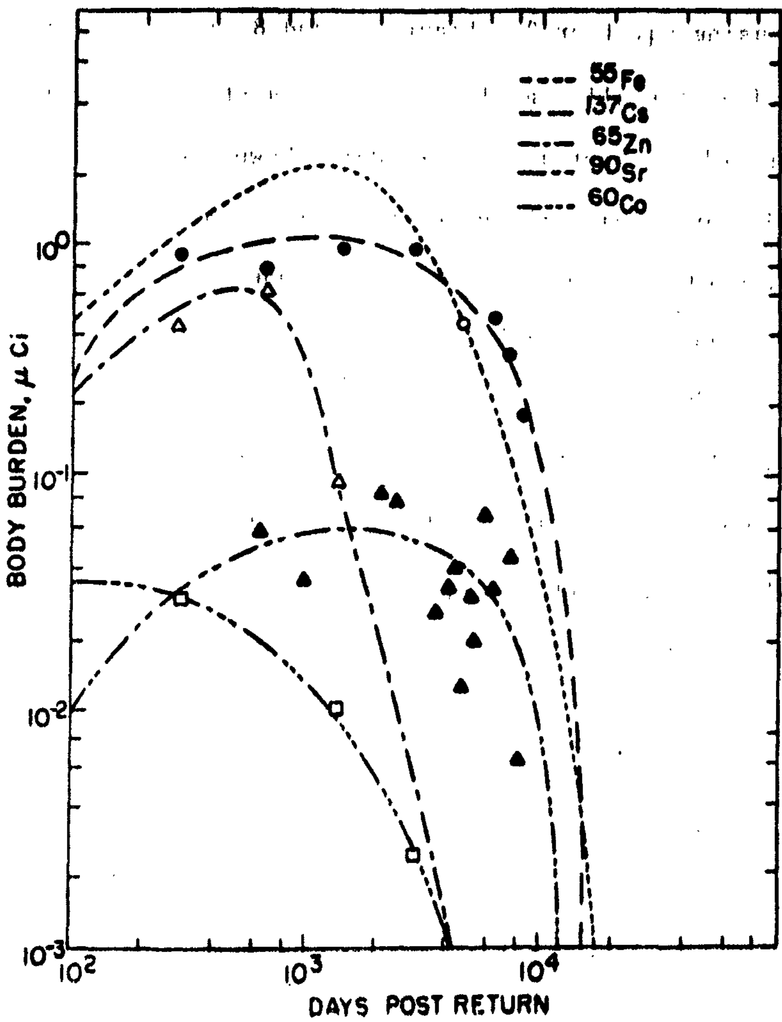

Fig. 7 Composite Nuclide Body Burden History For Adults at Rongelap Atoll

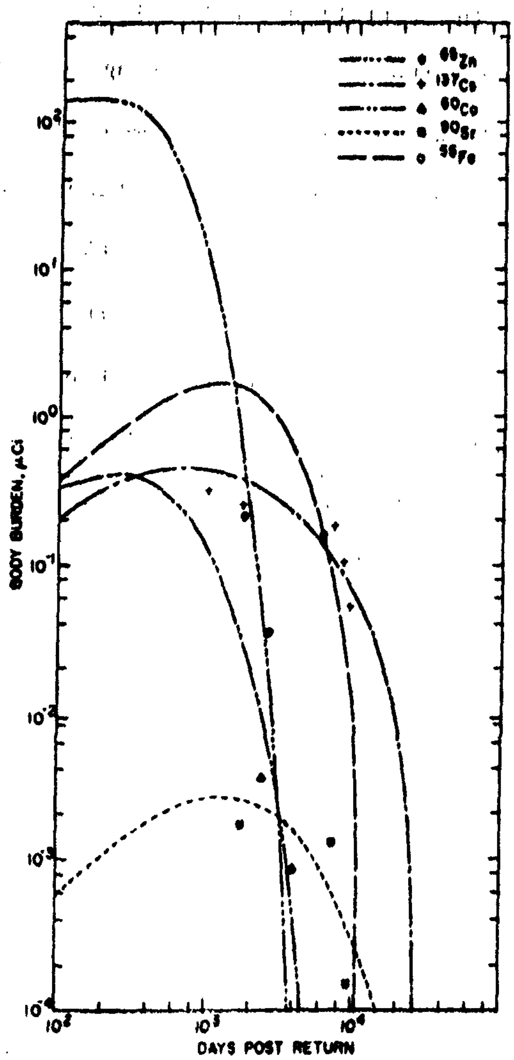

Fig. 8 Composite Nuclide Body Burden History For Adults at Utirik Atoll

burden curve for ^{90}Sr, reconstructed from raw data and Eq. 1, was considered a more accurate history. A detailed presentation of the greater variation in radiochemical analysis of urine versus direct body burden measurements can be found in Mi81.

Figure 9 illustrates the variation exhibited in the body burden of 5 randomly chosen subjects over the 25 year monitoring period. These individual variations may have had a dramatic impact on the mean data. In Figure 2, which illustrates the adult male, adult female, and adult population mean ^{137}Cs body burden for the 25 year exposure period, a decrease followed by an increase was seen during the years 1958 through 1963. Although the Castle BRAVO test initially contaminated Rongelap in March 1954, it had been proposed that the Hardtack Phase I series added to this an amount of contamination equal to that responsible for the Figure 2 body burden pattern (Co63). Figure 9 suggests that most individuals counted in those years had body burdens which remained the same or declined; however, one individual's burden (#881 M) rose and fell quite differently from the others. Several factors could have contributed to this variation from the mean such as departure and return to the atoll, sickness, the dietary contribution of imported foods, etc. Since the mean values are based on small numbers of persons who were chosen at random, it is conceivable that individuals like 881 M influenced the mean body burdens to a greater degree than recontamination of the inhabited atolls. The impact of the individual body burden pattern on the true mean value is moot since body burdens of all individuals were not monitored consistently throughout their residence intervals except in the few cases exhibited in Figure 9.

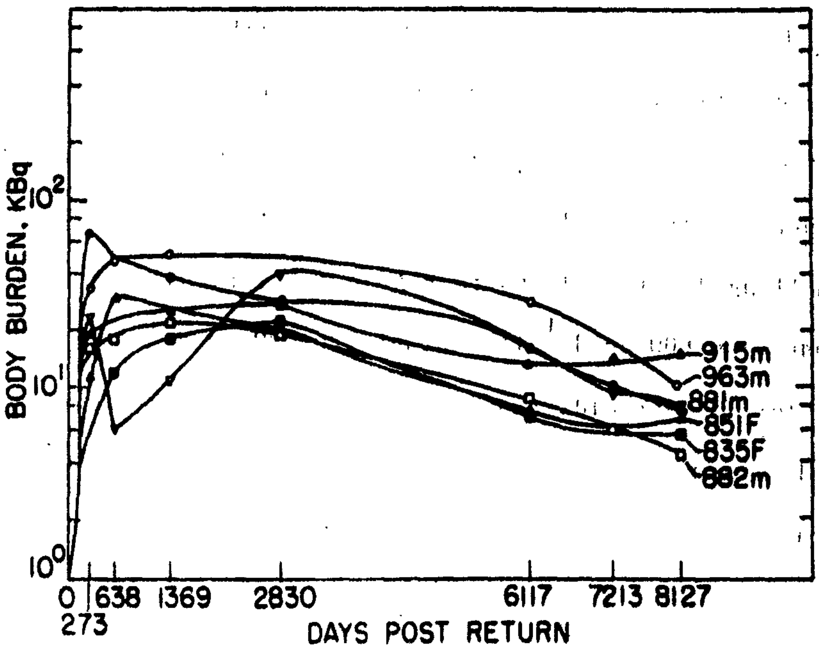

Fig 9 Individual Male and Female Body Burden Histories Randomly Chosen From The Rongelap Atoll Population

RESULTS AND DISCUSSION

Daily Activity Ingestion Rates

Daily activity ingestion rates were calculated for dosimetrically significant nuclides post return. An exponential decline was proposed for the ingestion rate within a population subgroup and initial reference values are given in Figures 10 through 14 (June 1, 1957, was assigned as a return date to Rongelap). Figure 10 demonstrates the differences in ingestion of ^{137}Cs for various population subgroups. This undulating pattern was exhibited by ^{137}Cs, ^{90}Sr, and ^{65}Zn, nuclides for which sufficient data existed for analysis.

Differences in ingestion rates of the stable element at the same geographic location have been shown to occur among members of a population (ICRP 23). Age dependent diet studies for ingestion of Cs for urban Japan have values varying from 11 $\mu g\ d^{-1}$ for adults to 8.6 $\mu g\ d^{-1}$ for children. Sr in a western type diet rose from 600 $\mu g\ d^{-1}$ for infants to 690 $\mu g\ d^{-1}$ for 5 year olds to 3,600 $\mu g\ d^{-1}$ for 13 year olds and fell to a mean of 1,900 $\mu g\ d^{-1}$ for adults. Zn in the United Kingdom rose from 2 to 40 $mg\ d^{-1}$, the higher value of Zn being observed in adult tea drinkers. Fe ingestion in a western type diet has a minimum at age 3 and maxima at ages 1 and 20 years. Co is ingested at a rate of 20 $\mu g\ d^{-1}$ for Japanese adults and half this amount for children. The Marshallese population also exhibits dietary changes as a function of age. The authors of the Marshall Islands Diet and Living Pattern Study (Na80) observed coconut sap being used as a major food supplement for infants, and later in adult life as a major source of daily fluid intake. Since coconuts and coconut tree sap provided the major source of ^{137}Cs on Bikini Atoll (Le80, Mi80), the shape of Figure 10 was in agreement with the observed diet pattern.

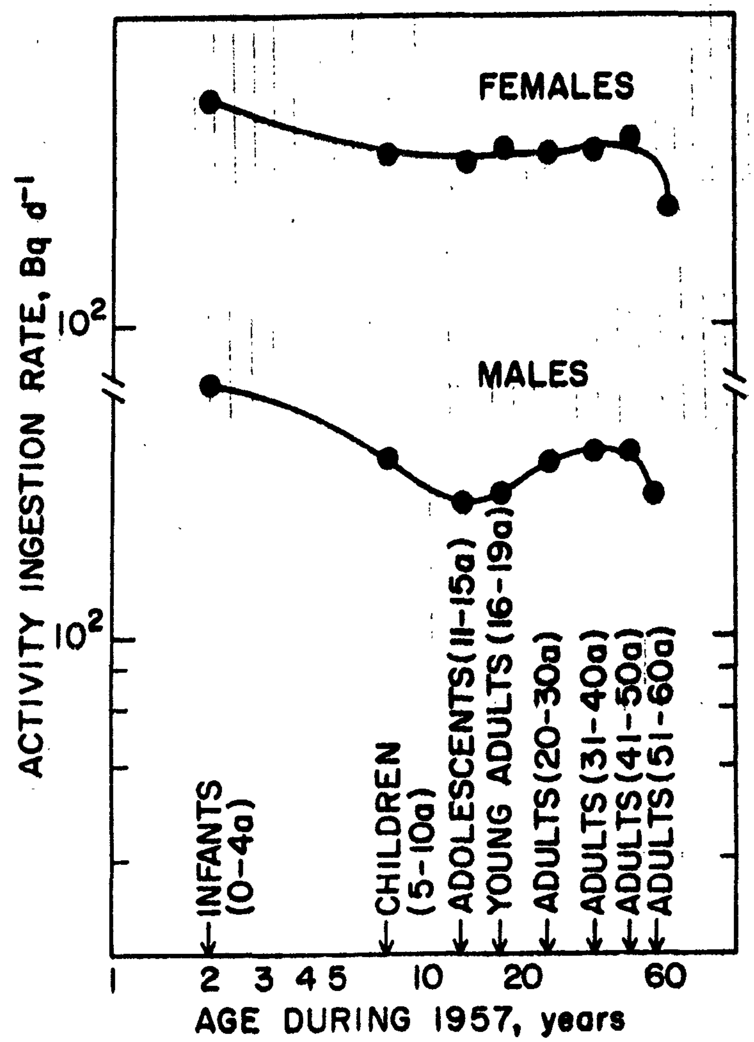

Fig. 10 Age and Sex Group Mean Values For ^{137}Cs Activity Ingestion Rate Referenced To Mid 1957 for Rongelap Atoll

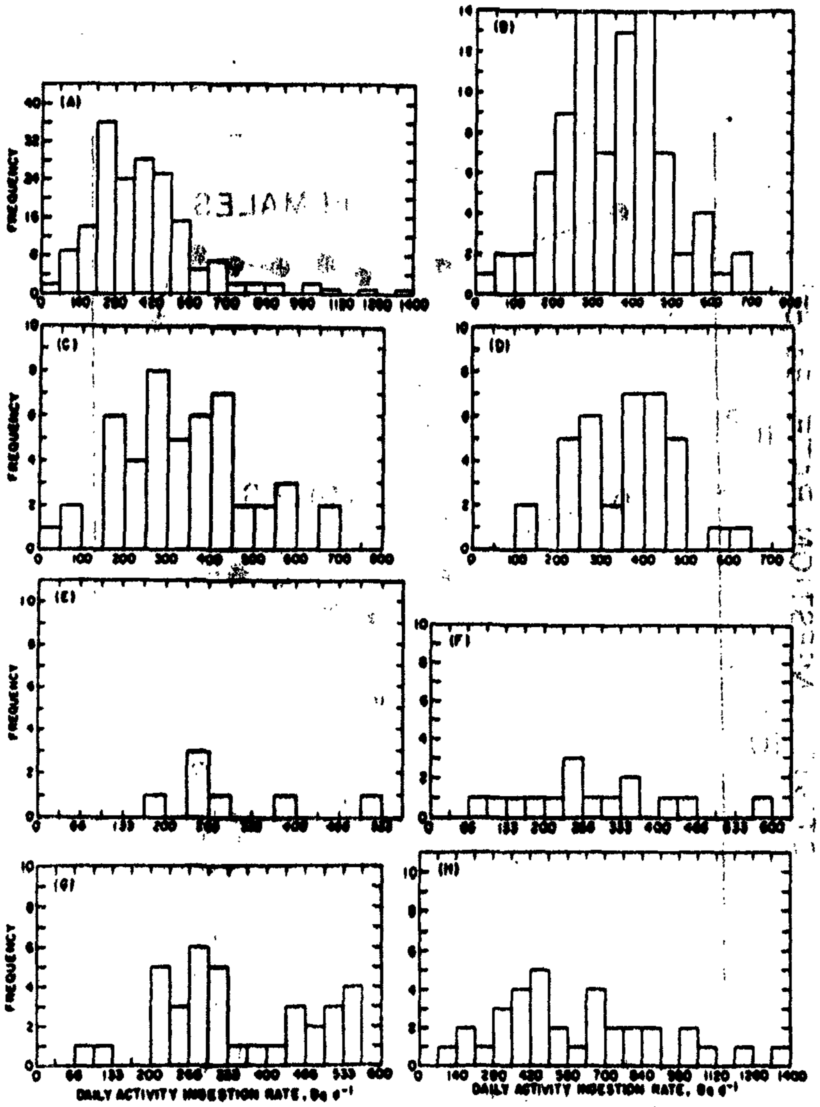

Fig. 11 ^{137}Cs Daily Activity Ingestion Rate For (A) All Residents (B) Adults (C) Adult Males (D) Adult Females (E) Young Adults (F) Adolescents (G) Children and (H) Infants on Rongelap - Referenced to June 1957

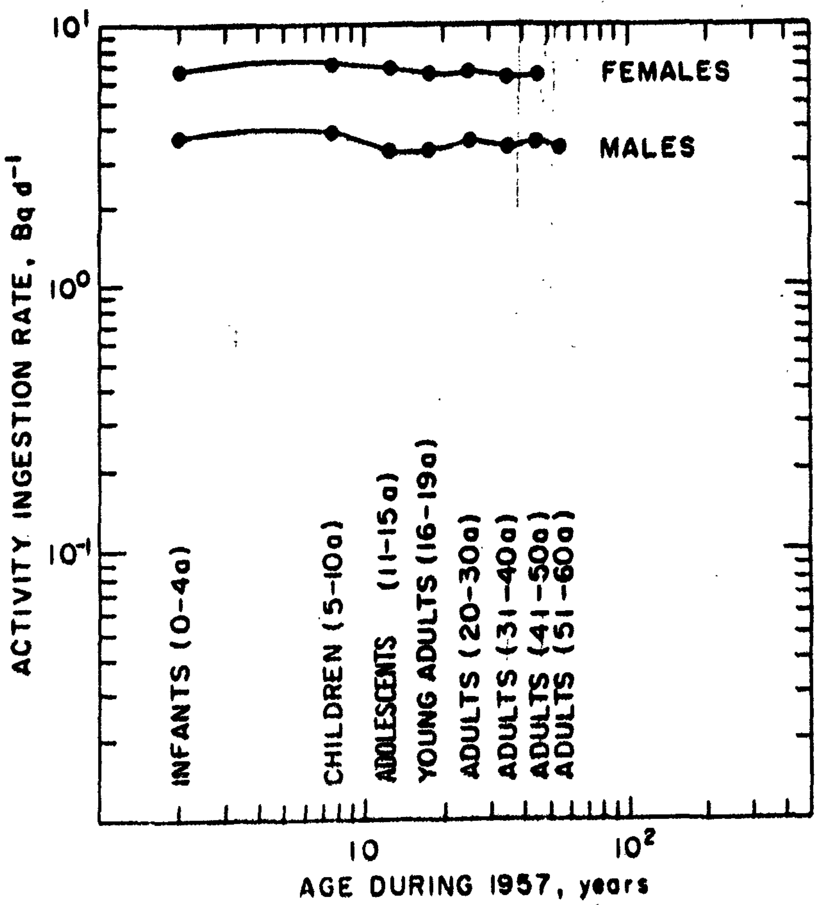

Fig. 12 Age and Sex Group Mean Values For ^{90}Sr Activity Ingestion Rate Referenced To Mid 1957 For Rongelap Atoll

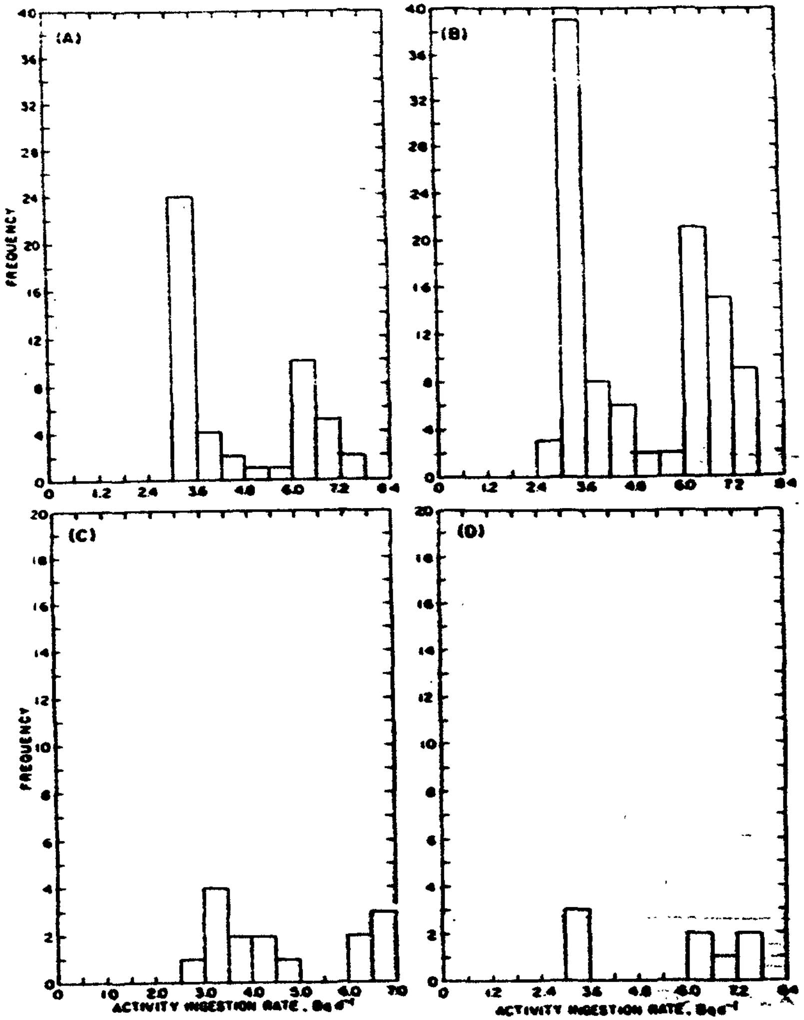

Fig. 13a ^{90}Sr Daily Activity Ingestion Rate For (A) Adults (B) All Residents (C) Infants and (D) Adolescents on Rongelap

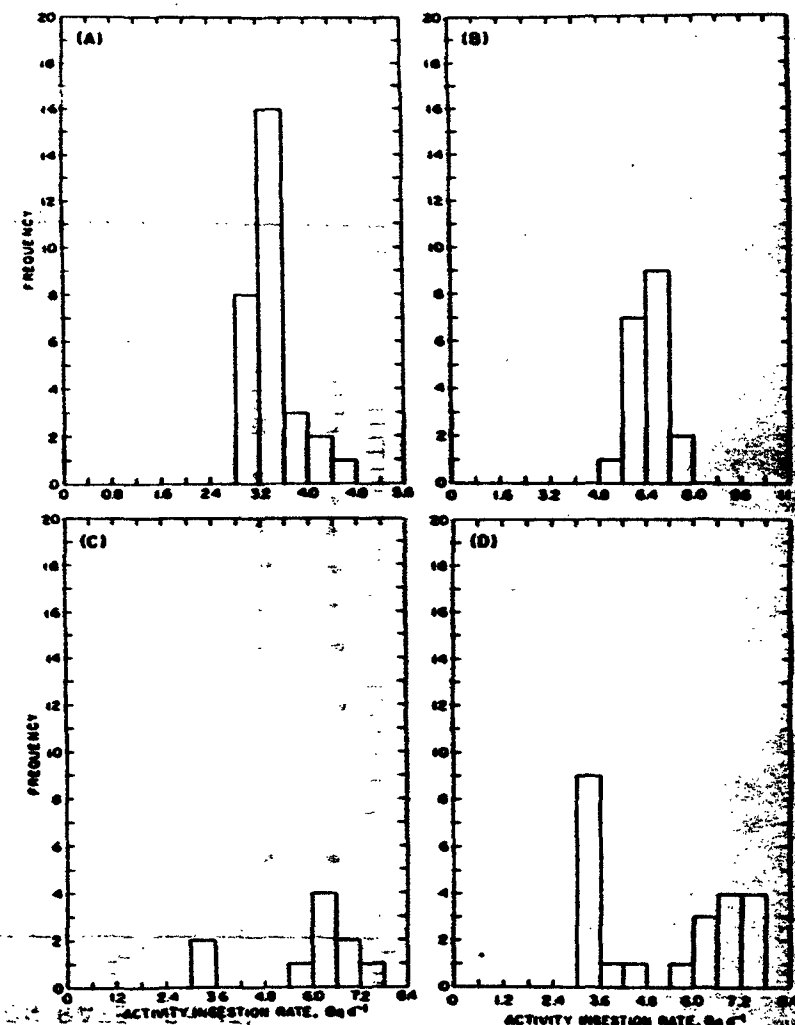

Fig. 13b ^{90}Sr Daily Activity Ingestion Rate for (A) Adult Males (B) Adult Females (C) Young Adults and (D) Children on Rongelap

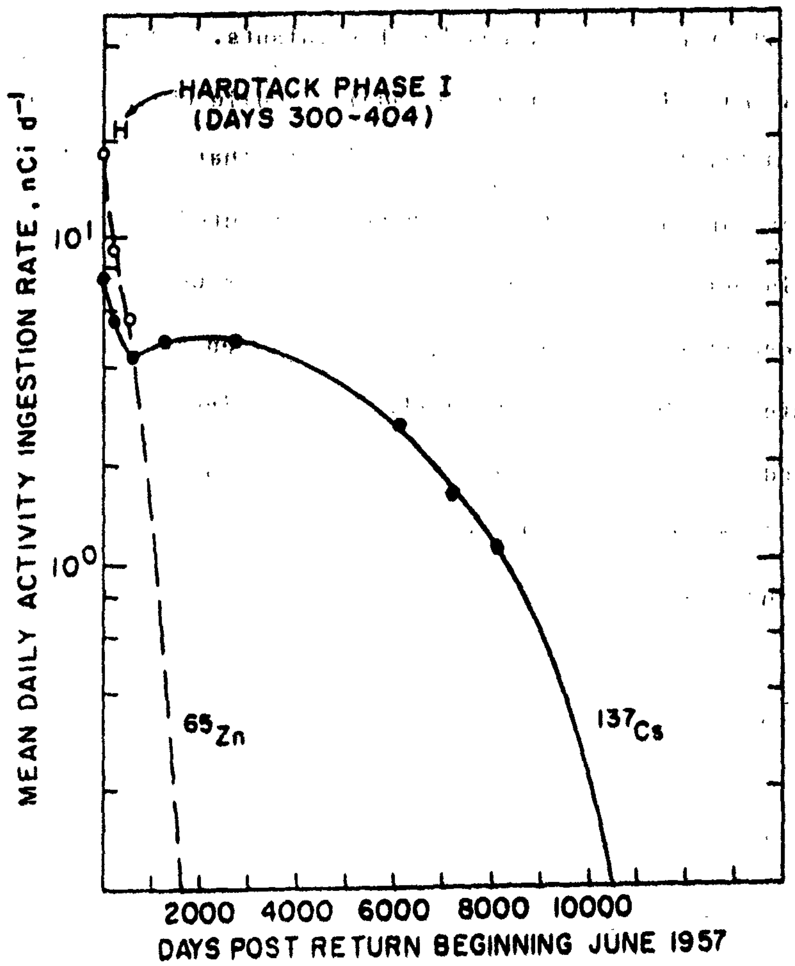

Fig. 14 Adult Mean Daily Activity Ingestion Rate For ^{137}Cs and ^{65}Zn at Rongelap Referenced to Mid-1957

Figure 11 shows the individual data calculated for ^{137}Cs for all Rongelap residents and is referenced to June 1, 1957. The individual maximum ^{137}Cs daily activity ingestion rate was approximately 4 times the population mean value. The standard deviation observed for the adult activity ingestion rate distribution was 41% of the mean value, 39% of the mean value for young adults, 48% for adolescents, 38% for children, and 54% for infants. Adolescents and infants exhibited a broader distribution than adults, while children showed a fractional variation in activity ingestion rate similar to that of adults. Breast feeding versus coconut sap supplements would have contributed to the greater variation observed in infants. Adolescents and young adults were the population subgroups which have been observed to move frequently between atolls. This mobility would lead to greater variations in the daily activity ingestion rates relative to those observed in the more stationary population subgroups.

Figure 12 also exhibited a wave pattern; however, a distinct difference between males and females was indicated. This difference arose from the use of values for K_E listed in Table 3 which were derived from urine data for male and female residents at Rongelap Atoll. Its major impact was on the dose equivalent rate, not on the total dose equivalent; and its effect was to cause the dose equivalent rate for males to rise and decline more rapidly than for females.

Figures 13a and 13b summarize the individual data for ^{90}Sr for all Rongelap residents and were referenced to June 1, 1957. A bimodal shape was observed for the distributions which contained both sexes, again reflecting the difference in the ^{90}Sr dietary rate constants. Data from urine bioassay indicated that the observed difference between the male and female values for K_E was not significant. A t-test was performed for consecutive urine measurement data during the 23 year residence interval. The results indicate that because of urine activity concentration variability, there was a 60% probability that the male value for K_E would be different from the female value by the factor observed. Thus differences in the derived activity ingestion rates and dose equivalents were not significant.

Figure 14 shows a semi-log plot of the ^{65}Zn and ^{137}Cs activity ingestion rate histories for adults on Rongelap. A curve was drawn between points, and the appearance of an increasing ^{137}Cs ingestion rate during the 1960's indicated the possibility of another contaminating event. The Hardtack Phase I series was conducted just prior to the observed increase in the curve and fallout from the Cactus, Yellow Wood, and Hickory experiments detonated at Bikini and Enewetak would have reached Rongelap. However, several observations fail to support the conclusion that recontamination was significant. These are as follows: 1) the increase in ^{137}Cs ingestion rate was not in conjunction with an increase of ^{65}Zn; however, since ^{65}Zn is an activation product it may have not been produced in the same proportions. 2) The peak ^{137}Cs body burden at Utirik occurred nearly three years after the initiating event, Castle BRAVO, while the peak body burden at Rongelap followed six years after the potentially contaminating experiments of the Hardtack series in 1958. 3) The activity ingestion rate at Utirik demonstrated a continuously declining pattern versus the humped pattern observed at Rongelap. This occurred even though there was an equal external exposure rate history following the Hardtack series as measured by the U.S. Public Health Service on both Rongelap and Utirik (Un59). 4) The peak exposure rate on Rongelap following the Hardtack series was 10,000 times less than the peak exposure rate following BRAVO. These facts suggest that the Hardtack series was not a major factor influencing the Rongelap body burden patterns. Thus it is postulated that body burden variations were caused by travel away from the atoll or sickness and other factors. Regardless of the cause of individual differences from the mean, a smooth description of the body burden and activity ingestion rate for the population could be adopted. On this basis a declining continuous uptake model was used.

Internal Dose Equivalent Rates

The approximate instantaneous dose equivalent rates for the total body were determined from the body burden data illustrated in Figures 7 and 8 and from the following equation

$$\dot{H} = qI, \tag{4}$$

where

$\dot{H} \equiv$ the total body dose equivalent rate, mRem y^{-1},

$I \equiv$ equilibrium dose equivalent rate to the total body per unit body burden, mRem y^{-1} μCi^{-1},

$q \equiv$ instanteous body burden, μCi.

The approximate nature of the estimate was due to the assumption that th radioactive atoms were distributed among the body tissues as they would be following constant continuous uptake for periods of time much greater than the me residence time for the total body. In the case of ^{90}Sr, 86% of equilibrium w assumed. These assumptions were not used in the estimate of the total dose equivalent. In addition, since mean adult body burdens were computed, a fact of 1.2 was needed to adjust for differences in body mass relative to a 70 kil gram adult. Table 5 lists values of I which were determined from information given in ICRP59 and corrected for body mass differences.

Table 5

Total Body Equilibrium Dose Equivalent Rate per Unit Body Burden

$^{A}_{Z}X$	I, mRem y^{-1} μCi^{-1}
$^{55}_{26}Fe$	2×10^{0}
$^{60}_{27}Co$	6×10^{2}
$^{65}_{30}Zn$	1×10^{2}
$^{90}_{38}Sr$	3×10^{2}
$^{137}_{55}Cs$	2×10^{2}

Figure 15 illustrates the relative contribution to the composite dose equivalent rate for each dosimetrically significant internally deposited nuclide. For the average Rongelap adult, the residence interval begins June 1, 1957; however, many adults were reported to have resettled during the next 3 to 6 months (Co80b). The composite dose equivalent rate indicated that a broad maximum of approximately several hundred millirem per year persisted for several hundred days. Most of the dose rate is attributable to the ^{137}Cs component Cesium dominated over the entire post return period and would be of prime concern for populations returning to a contaminated environment years after a fission type initiating event.

Figure 16 illustrates two possibilities for the Utirik dose equivalent rate resulting from the ^{65}Zn body burden history during the first three years post-return. The higher body burden resulted from use of the two measured ^{65}Zn

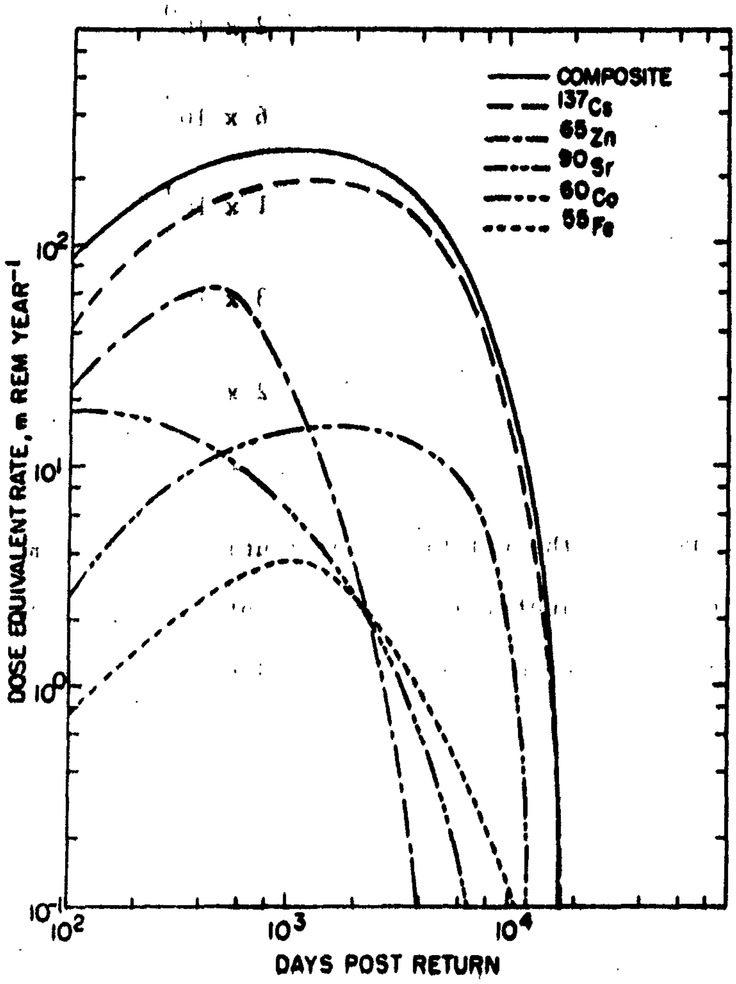

Fig. 15 Adult Mean Total Body Dose Equivalent Rate at Rongelap Atoll Post Mid 1957

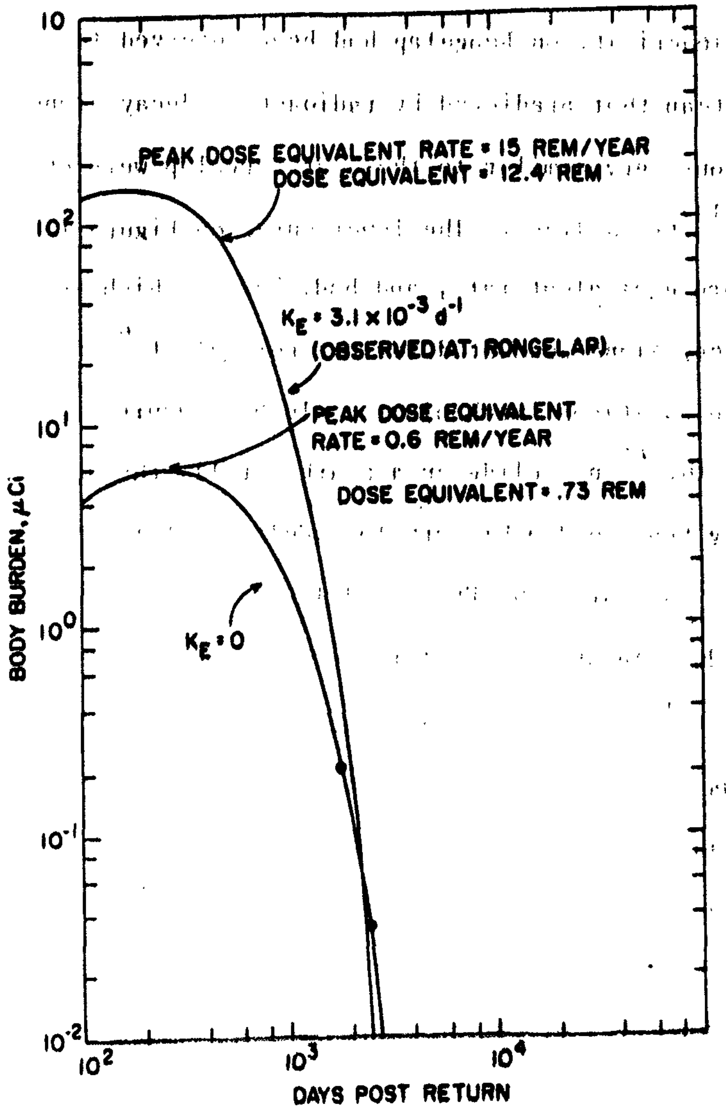

Fig. 16 Mean Adult ^{65}Zn Body Burden, Peak Dose Equivalent Rate and Dose Equivalent For Utirik Atoll

body burden means for adults on Utirik and the observed K_E rate constant from Rongelap. It was observed on Rongelap that .031% of ^{65}Zn was removed from the diet pathway each day in addition to radioactive decay. Additionally, reduction in dietary radioactivity on Rongelap had been observed for ^{137}Cs, ^{90}Sr, and ^{60}Co to be greater than that predicted by radioactive decay alone. Instantaneous reduction fractions very similar to those at Rongelap were observed at Utirik for the ^{90}Sr, and ^{137}Cs nuclides. The lower curve on Figure 16 reflects the dose equivalent, dose equivalent rate, and body burden which would have occurred had radioactive decay alone accounted for the removal of ^{65}Zn from the Utirik environment. Since additional mechanisms could be measured for other nuclides at Utirik and for the ^{65}Zn nuclide on a nearby atoll, the upper curve was chosen as the most likely body burden history for adults post return to Utirik Atoll.

Figure 17 indicates the Utirik adult mean total body dose equivalent rate for each nuclide. An obvious difference relative to the Rongelap history exists; ^{65}Zn not ^{137}Cs was the major nuclide contributing to the dose equivalent rate. This was due to the Utirik population returning 3 to 4 months after the initial contaminating event, and the Rongelap population returning after 3 years. The age of the fallout had a dramatic influence on the importance of each nuclide contributing to the internal dose equivalent. In fact ^{60}Co and ^{65}Zn played major roles during the first 3 years, a time interval that corresponded to the period during which field whole body counting facilities were being developed at Brookhaven National Laboratory and when medical examinations for people on Utirik Atoll were not done. Additionally, pooled and/or individual radiochemical analysis of urine was not performed during this period. The impact of ^{65}Zn and ^{60}Co was such that even if the least conservative rate

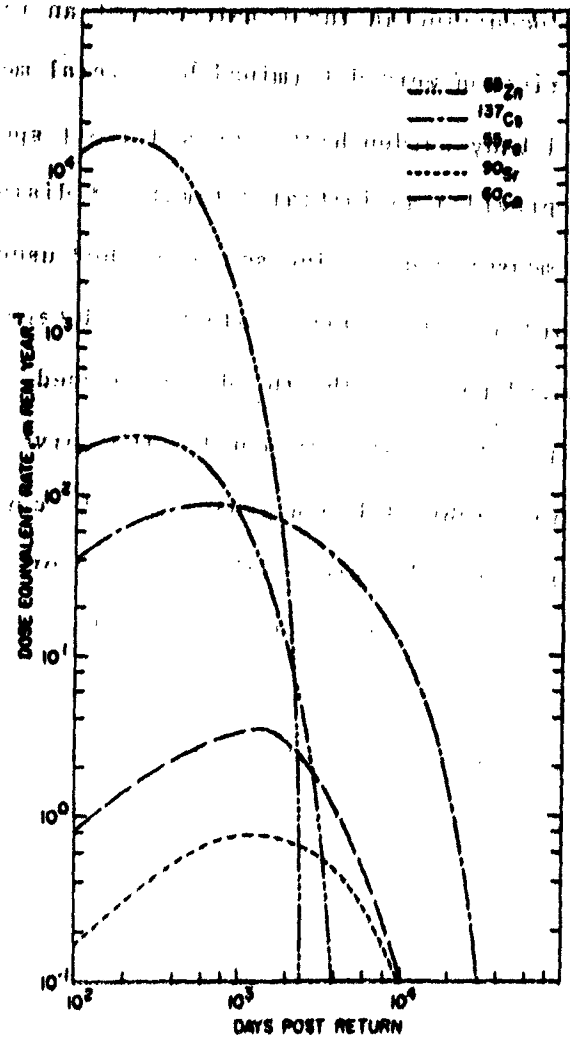

Fig. 17 Adult Mean Total Body Dose Equivalent Rate at Utirik Atoll Post Mid 1954

constant (K_E=0) was used for Zn, the dose equivalent rate for the average adult was in excess of Federal Radiation Council Guidelines for the first 2 years following the return to Utirik.

Internal Dose Equivalents

Disintegrations occurring in the total body of an individual during residence following repatriation were determined by several methods. Equation (3), together with personal body-burden histories and atoll specific K_E rate constants from Table 3, provided an initial estimate of disintegrations between consecutive body burden measurements. The second method used was a log-log plot of the subject's body burden history and an algebraic determination of area between two consecutive measured points. The third method used a linear plot of the subject's body burden history. The area under the curve was cut and weighed and compared to a standard weight of known area. Quality control procedures required that all three methods agree within ±10% before a subject was assigned his or her total body disintegrations during residence post return. In general, the methods compared to within ±5%.

After the total number of disintegrations occurring in a subject's body was assigned, they were apportioned among the body organs according to the following equation

$$F = \frac{f_2' \; \Sigma_i A_i B_i \; (\Sigma_i C_i D_i + \ln 2/\lambda)}{\Sigma_i C_i D_i (\Sigma_i A_i B_i + \ln 2/\lambda)} \quad , \qquad (5)$$

where

F ≡ the fraction of total body disintegrations occurring in the organ of interest,

A_i ≡ organ compartment deposition fraction for the element,

B_i ≡ organ compartment biological half time for the element,

C_i ≡ total body compartment deposition fraction for the element,

D_i ≡ total body compartment biological half time for the element,

f_2' ≡ fraction of the element from blood to organ of reference.

Equation (5) applied where significant decay occurred at the deposition site, and not during transit or re-transit to the organ of interest. Values for compartment deposition fractions and compartment half times were obtained from Ki78. Values for the remaining quantities were from ICRP59.

The dose equivalents to a specific organ or the total body were determined by using the source to target dose equivalent per unit cumulated activity parameters from Ki78. The total target dose equivalent was obtained by summation of the dosimetric contributions from all source organs. Several important modifications to the general procedure were made in order to compute individual dosimetric results. For each person, the source to target dose equivalent per unit cumulated activity was weighted by the ratio of a standard man's body mass relative to the actual mean body mass during the interval for which the dose equivalent was determined. In the case of ^{137}Cs, the long term biological removal rate constant for the Marshallese population was highly dependent upon body mass (Mi81). Appropriate modifications to Eq. (2), (3), and (5) were made to reflect this dependence. Finally, for ^{90}Sr deposition in bone, 28% of the source to target dose equivalent per unit cumulated activity was assumed from cancellous bone and 72% from cortical bone.

Figure 18 demonstrates the mean dose equivalent from ^{137}Cs for various age and sex groupings. The residence interval was from 1957 to 1980 for this population. The adolescents and persons above 50 years of age in 1957 maintained the lowest dose equivalent. Persons who died during this period were not included

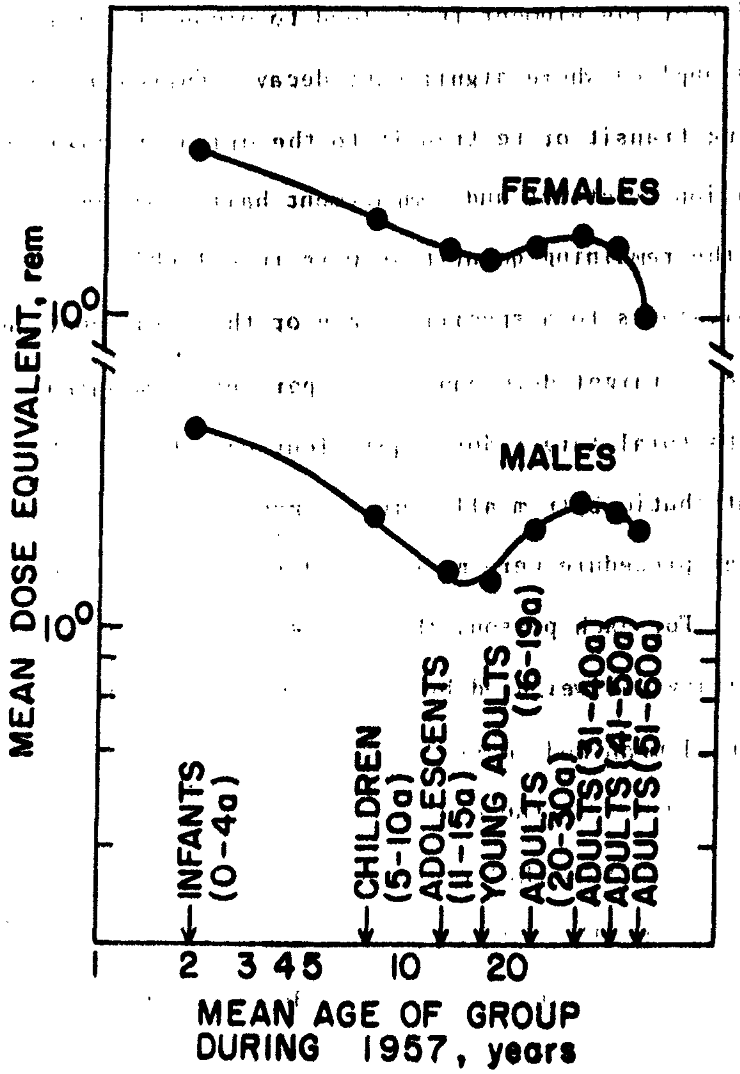

Fig. 18 ^{137}Cs Mean Dose Equivalent For Various Mid 1957 Age Groups for the Interval 1957 to 1980 at Rongelap Atoll in the figure nor were they included in any dosimetric distributions for any of the nuclides. Thus all persons considered, regardless of initial age in 1957, experienced a 23 year exposure interval.

Figure 19 shows dose equivalent distributions according to age and sex for ^{137}Cs among the Rongelapese. The shape or the population distribution was skewed with a mean of 1.7 Rem and a maximum of 9.0 Rem. Thus the maximum was 5.3 times the mean value for ^{137}Cs on Rongelap. An examination of the subgroup distributions reveals that persons who were infants at the time of rehabitation at Rongelap also were the recipients of the higher doses. This was due to the combined effects of lower average body mass, a higher average ingestion rate, and more rapid turnover of ^{137}Cs than that for adults or even children. The parameter having the greatest impact on the infant dose equivalent was body mass. The standard deviation for the adult male distribution was 49% of the mean dose equivalent, for adult females 43% of the mean dose equivalent, and for adolescents 47%. Within a subgroup, the maximum observed dose equivalent was approximately twice the mean value for all distributions considered here.

Figure 20 shows mean dose equivalents as a function of returning age groups for ^{65}Zn on Rongelap. Adolescents, young adults, and adults 50 and up were the groups receiving lower total dose equivalents, while children and middle aged persons received higher dose equivalents during the residence interval. Measured ^{65}Zn data for persons who were infants at the return date were not reported in the publications by Conard et al.

Figure 21 shows the dosimetric distributions observed for members of the Rongelap population for ^{65}Zn. Again the population overall exhibited a skewed distribution of dose with a maximum value nearly three times the mean. Children demonstrated higher doses than persons who were adults during the entire 23

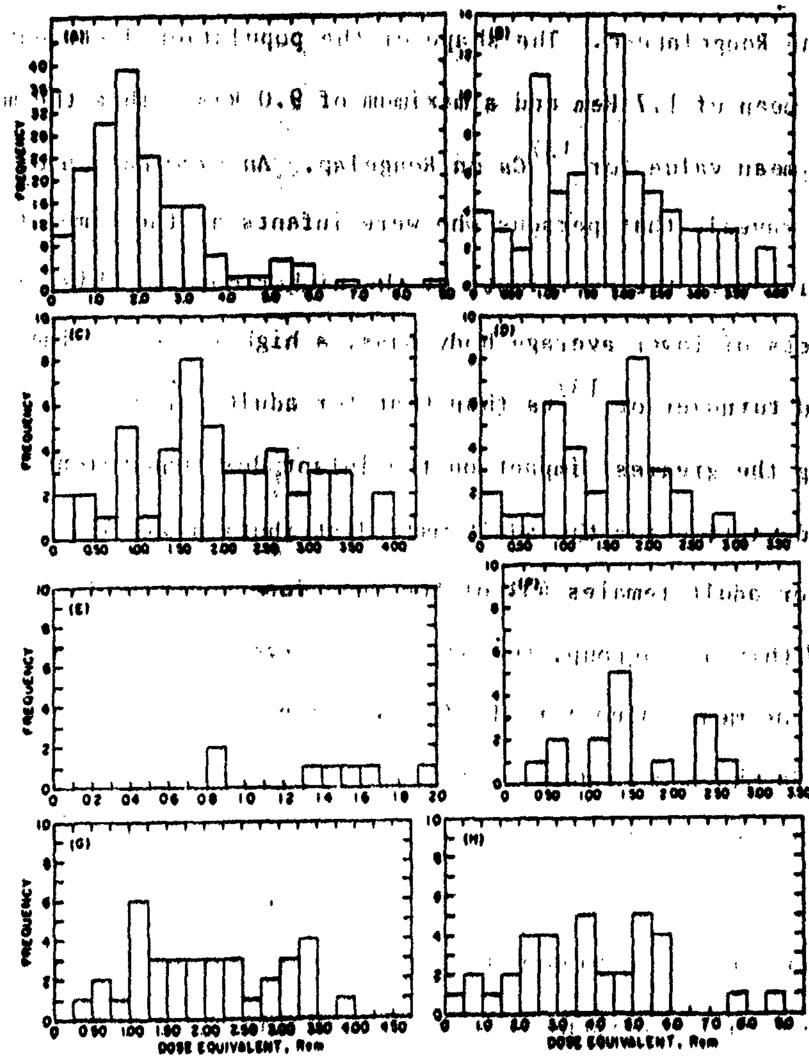

Fig. 19 ^{137}Cs Dose Equivalent to (A) All Residents (B) Adults (C) Adult Males (D) Adult Females (E) Young Adults (F) Adolescents (G) Children and (H) Infants on Rongelap

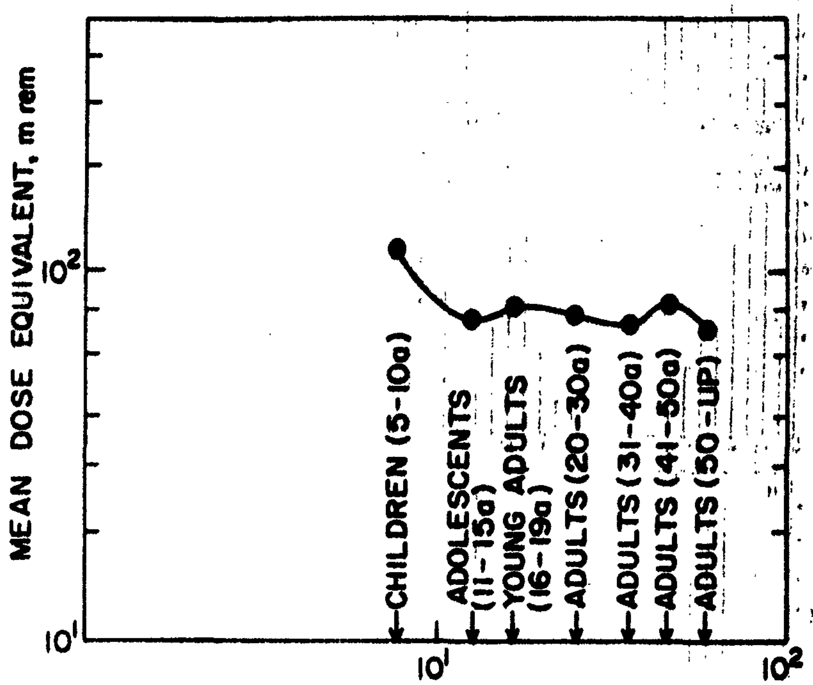

Fig. 20 ^{65}Zn Mean Dose Equivalent for Various Mid 1957 Age Groups for the Interval 1957 to 1980 at Rongelap Atoll

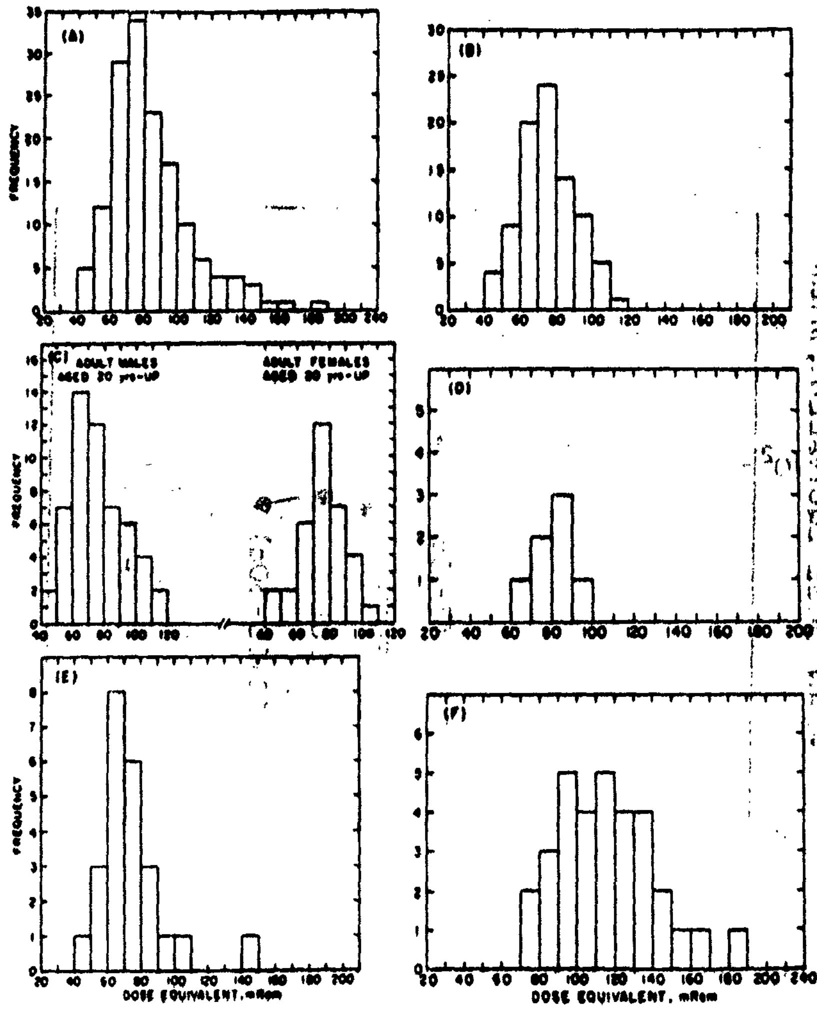

Fig 21 ^{65}Zn Dose Equivalent to (A) All Residents (B) Adults (C) Adult Males and Females (D) Adolescents (E) Children and (F) Infants on Rongelap Atoll year period. The standard deviation was in general 30% of the mean value for all age and sex subgroup distributions. This less pronounced variation may be due to the fact that ^{65}Zn measurements took place over a 3 year interval while ^{90}Sr and ^{137}Cs occurred over a 23 year interval and thus was contained in a more homogeneous population than were the longer lived nuclides.

Figures 22 and 23a and 23b summarize the ^{90}Sr dose equivalent results for individuals at Rongelap.

In this analysis, only the ingestion pathway was considered important. Some radioactivity would enter the body via the resuspension and direct inhalation pathways. It is known that for a given soil concentration of the stable naturally occurring analogs to the radionuclides considered here, the ratios of food and fluid intake to blood relative to airborne intake to blood, are as follows:

Co > 3000	Zn > 130
Fe > 550	Sr > 10,000
Cs > 400	

Thus, dietary intake of radioactive material is the principal pathway leading to internal deposition. This applies to most nuclides in the environment, however, there are notable exceptions including I, U, and Pu.

External Exposure

A value of .73 rads in tissue of interest per röntgen, measured in air at one meter above the surface, was used to convert exposure in air to absorbed dose in tissue. The source was assumed to be an exponential distribution of ^{137}Cs activity with depth in soil, typical of aged fallout (Be70). Because of the multidirectional nature of the source, variation of absorbed dose with depth of organ was minimal. Additionally, external doses were adjusted for living pat-

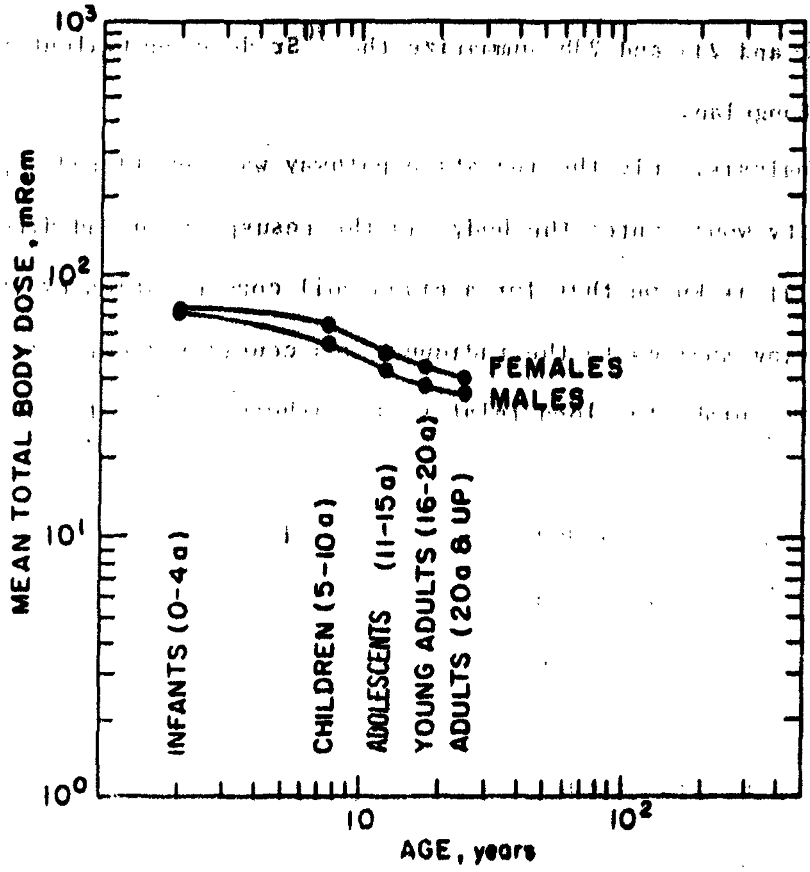

Fig. 22 Age and Sex Groups Mean Values for ^{90}Sr Dose Equivalent For The Interval 1957 to 1980 at Rongelap Atoll

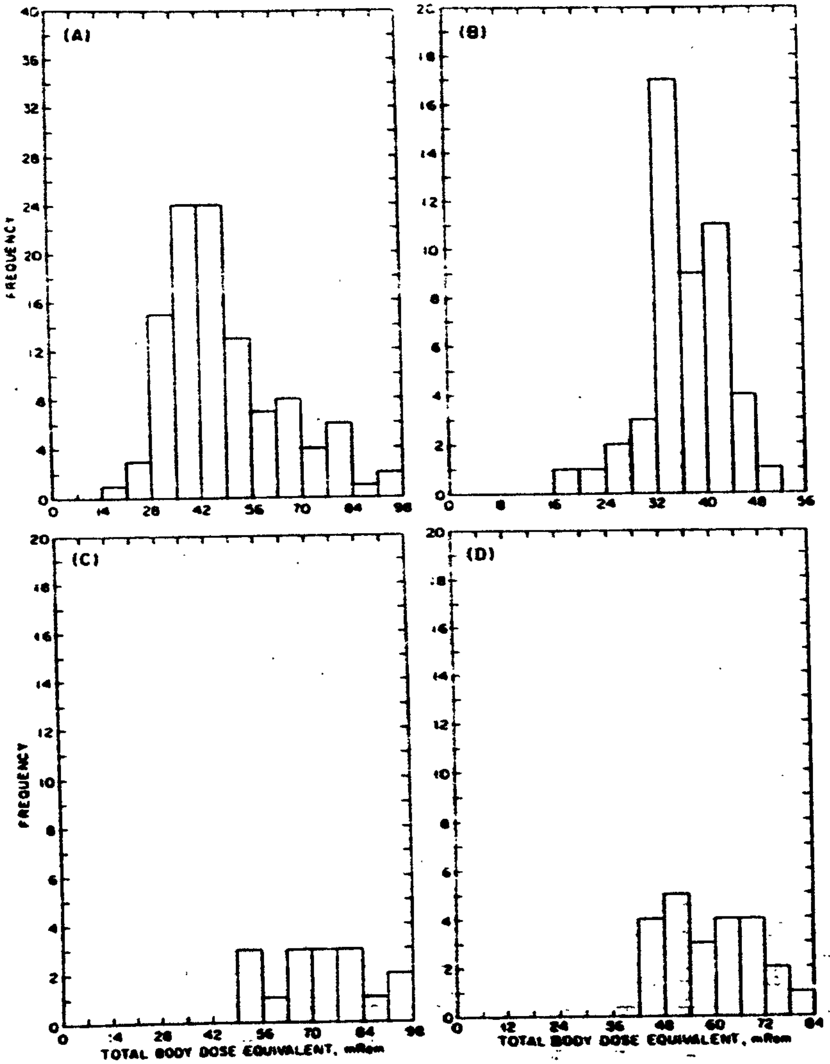

Fig. 23a ^{90}Sr Dose Equivalent for (A) All Residents (B) Adults (C) Infants and (D) Children on Rongelap

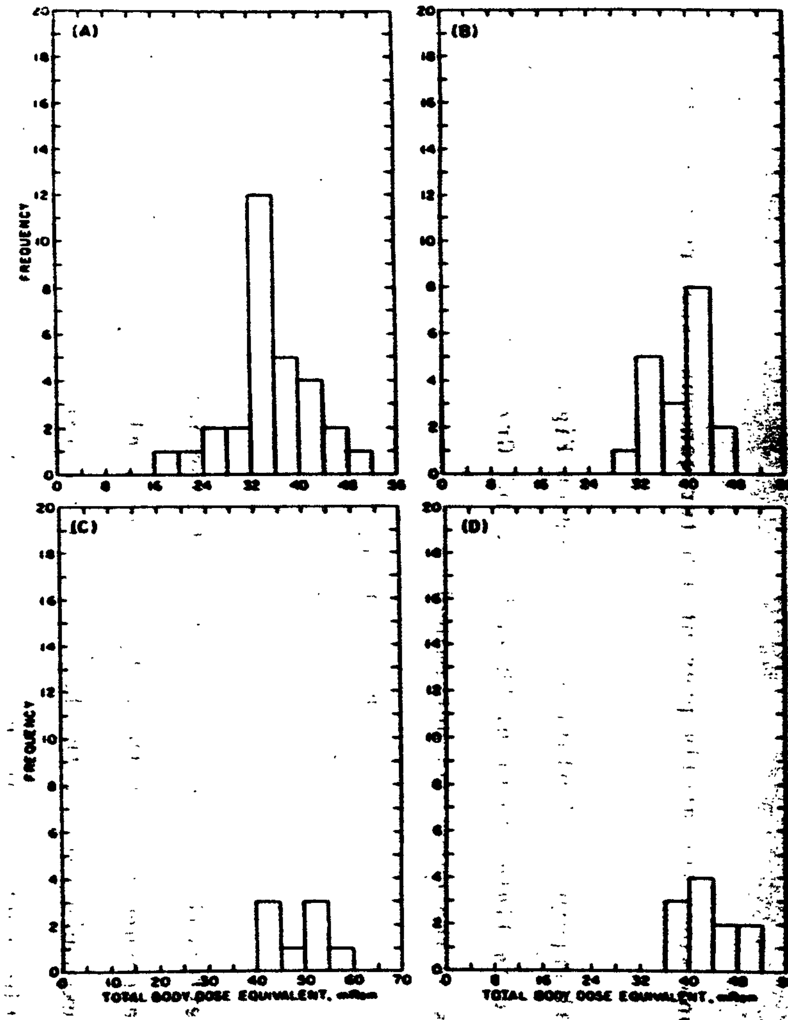

Fig. 23b ^{90}Sr Dose Equivalent for (A) Adult Males (B) Adult Females (C) Adolescents and (D) Young Adults on Rongelap tern variations since the atolls present a heterogeneous exposure rate environment (Gr77).

External exposure calculations are based on Figures 24 to 26 which were derived from data listed in Cr56, Sh57, Un59, and Gr77. The area under straight line portions of the curve was determined by

$$X = \frac{R_2 t_2 - R_1 t_1}{n + 1} \tag{6}$$

where

X ≡ external exposure during straight line interval, mR,

R_2 ≡ exposure rate at the end of the interval, mRh^{-1},

R_1 ≡ exposure rate at the beginning of the interval, mRh^{-1},

t_2 ≡ time post detonation at the end of interval, hours,

t_1 ≡ time post detonation at the beginning of interval, hours,

n ≡ slope of a straight line.

Data from 11 detonations during May, June, and July of 1958 (Sh57) indicated a mean fallout deposition exponent of 18.8. This mean value was observed at Utirik, Rongelap, Parry, and Wotho and was applied to early time post detonation of BRAVO to obtain the initial increasing exposure rate history shown on Figures 24 and 26. This method yielded a fallout deposition period of 5.5 hours on Rongelap and 12 hours on Utirik. This time compares well with the original observations reported by the Marshallese and by U.S. Navy personnel stationed in the area (Sh57). Initial dose equivalents on "acute doses" are developed in greater detail in another report.

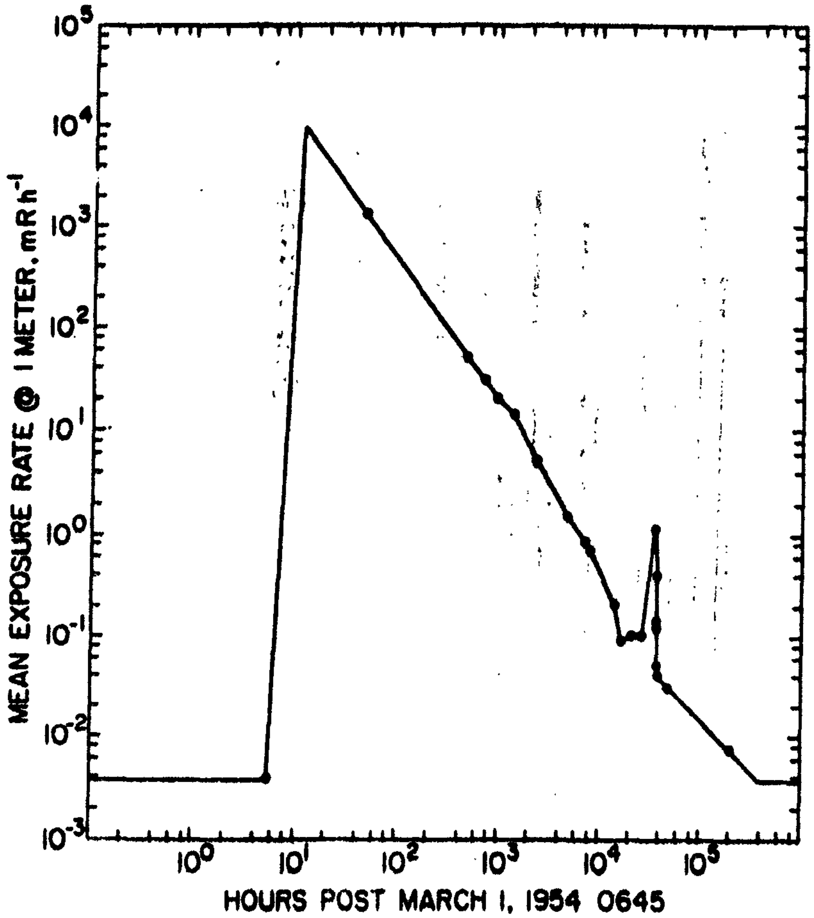

Fig. 24 Rongelap External Exposure Rate History Post Bravo

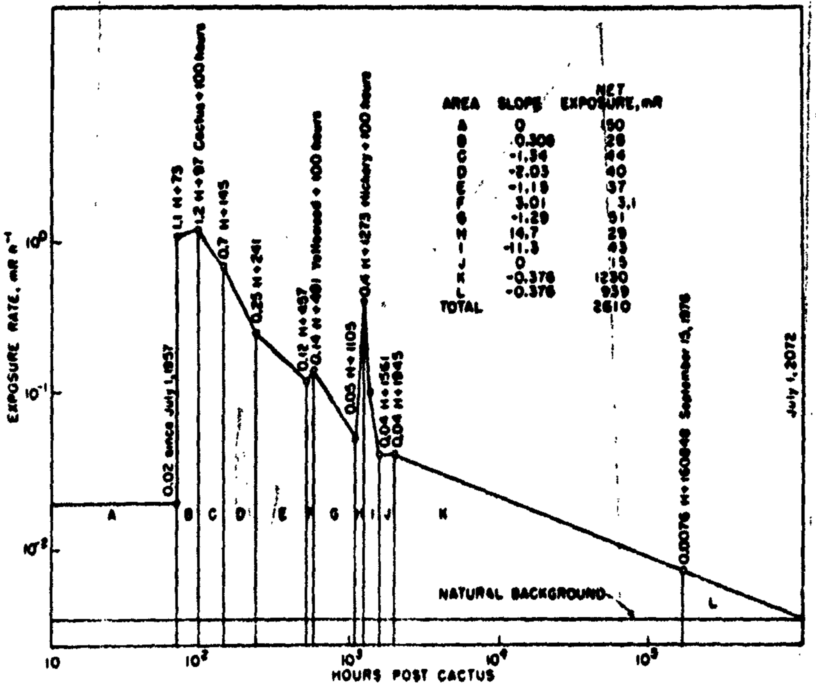

Fig 25 Rongelap External Exposure Rate History
Post Cactus

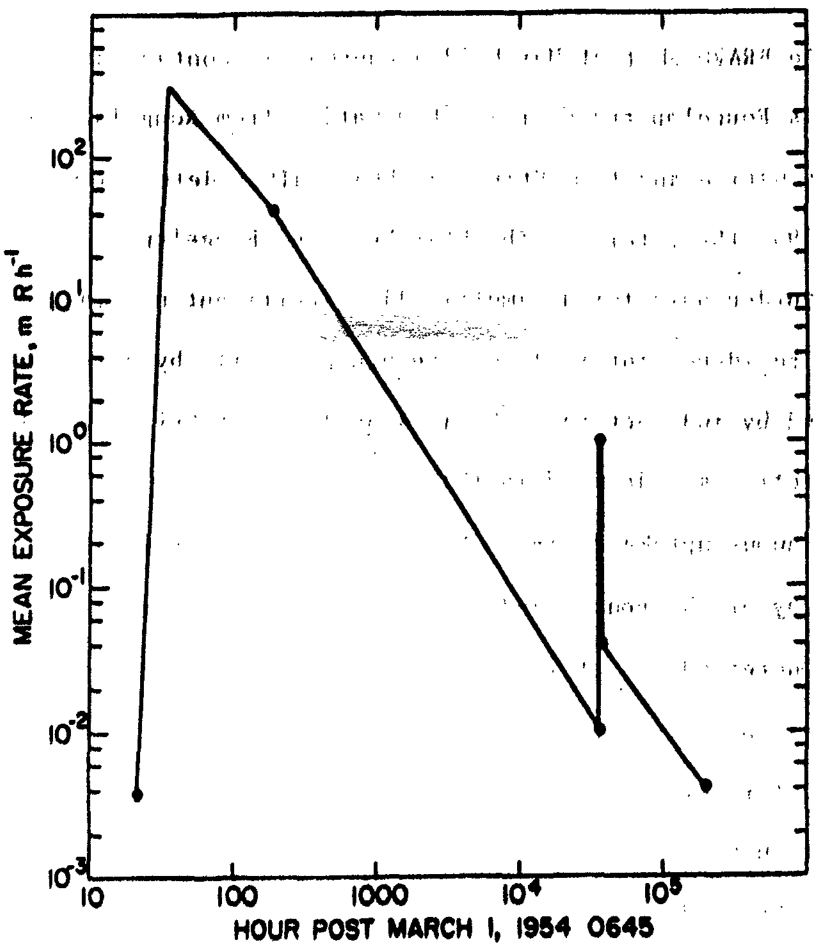

Fig. 26 Utirik External Exposure Rate History
Post Bravo

Figure 25 demonstrates the external exposure following the 1958 testing series. Since return to Rongelap followed 3 years after the BRAVO contamination, this series contributed in large part to the external exposure post return.

SUMMARY

The Castle BRAVO shot of March 1954 caused the contamination of the inhabited atolls Rongelap and Utirik. Evacuation from Rongelap commenced 50 hours after detonation and from Utirik 55 hours after detonation. During June 1954 and June 1957 the return of the Utirikese and Rongelapese occurred respectively. Body burden data for dosimetrically significant nuclides were obtained throughout the residence interval post return primarily by direct in vivo gamma spectroscopy and by indirect radiochemical analysis of urine and blood.

The dosimetric models used in this analysis were representative of a declining continuous uptake regime. Dietary decline of radioactivity included radioactive decay of the source and a conglomerate of other factors which might have included increased use of imported foods and weathering of the source. etary loss rate constants were estimated from sequential body burden data and were comparable for both atolls.

Variation in body burden history data for a particular nuclide on a particular atoll was observed in whole body counting data and urine bioassay results. This was attributed principally to the statistical variation encountered when small groups are sampled from a heterogeneous group of body burdens in people and in the case of urine bioassay additional variation was introduced during laboratory analysis of samples.

Daily activity ingestion rates were determined for all measured radionuclides. In general, infants, children, and adults between 20 and 40

years of age ingested more activity each day than did adolescents and persons greater than 40 years of age. Maximum deviation from the average value of the daily activity ingestion rate for members of an age subgroup was no greater than a factor of 3. However, the population distributions illustrated a maximum factor of 5 times the mean activity ingestion rate value.

Dose equivalent rates post return were determined for members from both atolls. For Rongelap Atoll, the residents received approximately 100 to 200 mRem per year during the first 5000 days post return from internal emitters. The principal contributing nuclide was ^{137}Cs. For Utirik Atoll, the residents received up to 15 Rem per year during the first 400 days post return. The major contributing nuclides were ^{65}Zn and ^{60}Co. Dose equivalent rates to the Utirikese from internal emitters fell below 500 mRem per year at approximately 1200 days post return.

The dose equivalent for population subgroups and for individuals was determined. Table 6 summarizes the results for the total body, thyroid, red marrow, testes, ovaries, lower large intestine wall, and liver. The catenary compartment model of Bernard and Hayes (Ber70) was used to determine doses to various segments of the gastrointestinal tract. The Utirikese received significantly more radiation dose from ^{65}Zn, ^{60}Co, and ^{55}Fe than did the Rongelapese because of short mean residence times of these nuclides in the environment. ^{90}Sr doses to the Rongelapese were 2.5 time greater and ^{137}Cs doses 1.5 times greater than doses received by persons at Utirik. This occurred even though Utirik residents returned to their atoll 3 years earlier and somewhat reflects the degree to which Utirik was less contaminated than Rongelap.

Table 6

Chronic Phase

Dose Equivalent Summary, Rem

Nuclide	Utirik Adults	Rongelap Adults	Utirik Adults	Rongelap Adults
	Total Body		**Thyroid**	
^{90}Sr	.012	.027	.00075	.0017
^{55}Fe	.033	.023	.059	.042
^{137}Cs	1.1	1.7	1.6	2.4
^{60}Co	.51	.014	.36	.010
^{65}Zn	13.	.076	11.	.067
Internal	14.	1.9	13.	2.5
External	3.2	2.0	3.2	2.0
Total	17.	3.9	16.	4.5
	Red Marrow		**Testes-Ovaries**	
^{90}Sr	.054	.12	.00075-.00075	.0017-.0017
^{55}Fe	.060	.042	.058-.062	.074-.043
^{137}Cs	1.7	2.6	1.5-1.7	2.3-2.6
^{60}Co	.63	.018	.44-1.8	0.12-.050
^{65}Zn	17.	.10	11.-16.	.069-.099
Internal	20.	2.9	13.-20.	2.5-2.8
External	3.2	2.0	3.2	2.0
Total	23.	4.9	17.-23.	4.5-4.8
	Lower Large Intestine Wall		**Liver**	
^{90}Sr	.23	.57	.00067	.0015
^{55}Fe	.067	.047	.12	.080
^{137}Cs	.59	.90	1.8	2.7
^{60}Co	4.7	.13	.79	.022
^{65}Zn	15.	.091	17.	.14
Internal	21.	1.7	19.	3.0
External	3.2	2.0	3.2	2.0
Total	24.	3.8	22.	5.0

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