BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.
Upton, Long Island, New York 11973
(516) 282 4250
FTS 666
Safety & Environmental Protection Division

402944

September 13, 1983

J. W. Thiessen, M.D.
U.S. Department of Energy
Office of Health & Environmental
Research
ER-71
Washington, DC 20545

Dear Dr. Thiessen:

Enclosed please find a copy of "Protracted Exposure to Fallout: The Rongelap and Utirik Experience" and a draft of "Thyroid Absorbed Dose For Rongelap and Utirik Residents". The protracted exposure document was accepted by Health Physics. I have recently returned the proofs to the Health Physics Journal and I anticipate it to be published within a few months. The draft document on thyroid absorbed dose has not been peer reviewed, and only two sections of the four section report are included. I am sending it to you because it is a tabulation of information pertinent to the activities of the Litigation Support Working Group. Please excuse any omissions, errors or unit inconsistencies in this draft.

In response to your question about future activities in the Marshall Islands, I am enclosing a detailed five-year plan (1985 through 1989). This plan was prepared several weeks ago for Roger Ray in response to a list of questions set forth by the DOE Marshall Islands Planning Group.

I feel these documents will be useful to the members of the working group and any comments will be appreciated.

Best regards.

Sincerely,

Edward T. Lessard

Edward T. Lessard

ETL/cc

Enclosures

cc: T. McCraw

DRAFT

THYROID ABSORBED DOSE FOR RONGELAP AND UTIRIK RESIDENTS

Safety and Environmental Protection Division

Brookhaven National Laboratory
Associated Universities, Inc.

Under Contract No. DE-AC02-76CH00016 with the
United States Department of Energy.

ABSTRACT

Since March 1954, persons who were present at Rongelap Island, Rongelap Atoll, Sifo Island, Ailinginae Atoll and Utirik Island, Utirik Atoll in the Marshall Islands have been examined by medical specialists to determine if any observable effects occurred as a result of exposure to radioactive fallout from the Pacific weapon test known as Operation Castle BRAVO. Studies indicated short-term effects exhibited over a period of many months and possible long-term effects exhibited over many years. In order to estimate the risk of possible radiation induced thyroid effects, a study was undertaken to refine thyroid absorbed dose estimates for people at Rongelap, Sifo and Utirik Islands using four approaches: (1) relating radiochemical analysis data on March 1954 pooled urine to current intake, retention and excretion models in order to determine I-131 inhaled or ingested, (2) estimating airborne concentrations and areal activities of the iodine isotopes from neutron irradiation studies on archival soil samples, (3) airborne concentrations and areal activities of the iodine isotopes derived from source term, weather data and current computer models which predicted atmospheric diffusion and fallout deposition and (4) determining fallout components based on Bikini Ash, the radioactive fallout which fell on a Japanese fishing vessel in the vicinity of Rongelap Island. Bikini Ash was also used to derive air, water and surface activities of fallout nuclides. This re-examination resulted in a greater mean thyroid absorbed dose estimate (by a factor of 4) over that estimated by James (Ja64). A wide range of possible thyroid absorbed dose due to a wide range of activity intake was also a result. Direct inhalation and ingestion of contaminated water were pathways which contributed in a minor way to fallout activity intake. The pathway contributing to most of the intake was fallout debris falling directly on food prepared and

consumed outdoors during passage of the fallout cloud. The adult mean thyroid absorbed doses at Rongelap and Utirik were 13 and 1.7 grays respectively. The child mean thyroid absorbed doses were 40 grays at Rongelap and 4.9 grays at Utirik. The overall mean cancer risk in the exposed population of 251 people was 1.1 thyroid cancers per 10,000 people per gray per year. The mean time at risk for cancer was 18 years. The overall mean nodule risk was 8.4 nodules per 10,000 people per gray per year and the mean time at risk for nodules was also 18 years.

CONTENTS

Page

Abstract.....

Acknowledgments.....

Introduction.....

Methods and Results.....

I. I-131 Thyroid Burden at Rongelap Island Based on Urine Bioassay.....

II. Radioiodine Air Concentrations Based on Meteorological Data and Source Term Data.....

III. Radioiodine Surface Activity Based on Archival Soil Analysis for I-129.....

IV. Thyroid Absorbed Dose Estimate Based on Bikini Ash Results and Results from I, II, and III.....

A. Surface Radioactivity And Exposure Rate Estimates.....

B. Radioactivity In Food, Water Supplies and Air.....

C. Absorbed Dose for Individuals.....

Discussion.....

Conclusion.....

ACKNOWLEDGMENTS

The authors fully appreciate the fine efforts of Nathanial A. Greenhouse of Lawrence Berkeley Laboratory, Lee V. Kaplan, a student from Yale University, Dr. Fred Brauer of Battelle Pacific Northwest Laboratory, Kendall Peterson of Lawrence Livermore National Laboratory, Dr. Charles Sondhaus of the University of California, Dr. John Baum, Dr. Victor Bond, M.D., Donald Borg, M.D., Robert Conard, M.D., Eugene Cronkite, M.D., Andrew Hull, and Charles Meinhold all from Brookhaven National Laboratory and Dr. Bruce Wachholz from Department of Energy Headquarters in helping to prepare a scientific document. We gratefully acknowledge their contributions of ideas and procedures.

We are also grateful to a number of colleagues who have read the manuscript for this report and offered valuable comments: William Adams, M.D. of Brookhaven National Laboratory, Dr. William Bair and Dr. Richard Gilbert of Battelle Pacific Northwest Laboratory, Dr. Roger McClellan of Lovelace Inhalation Toxicology Research Institute, and Dr. Jack Healy of Los Alamos National Laboratory.

I. I-131 THYROID BURDEN AT RONGELAP ISLAND BASED ON URINE BIOASSAY

Urine samples for 24-hour elimination were pooled and collected on the 17th day post detonation from persons evacuated from Rongelap Island (Co72). The urine was sent to Los Alamos Scientific Laboratory and an estimate of thyroid absorbed dose from internal emitters was reported by Cohn (Cr56). The 64-person composite urine sample was 75% adult urine (18 ℓ, >16 years of age), 20% adolescent urine (4.8 ℓ, 5-16 years of age) and 4.8% child urine (1.2 ℓ, <5 years of age) (Ja64). The adult mean peak thyroid content of I-131 was estimated by Harris to be 11.2 μCi (Ha54). This estimate was based on the assumption that 0.1% of stable iodine intake on the first day would be eliminated via the urine between the 15th and 17th days (Co72). Harris indicated a mean activity of 1.31 x 10^{-2} μCi of I-131 in the Rongelap adult 24-hour urine taken on the 17th day post detonation.

Table 1 is a tabulation of the fraction of an initial I-131 activity intake by ingestion that would be eliminated by an adult on a given day post the intake. These daily fractions were calculated by two methods, one was a model by Johnson (Jo81, see Fig. 1) and the other was a model used by ICRP (ICRP 30, see Fig. 2). Both models incorporated feedback. Both were solved using catenary compartment kinetics and both led to similar values for elimination by a reference man (see Table 1). A comparison to an excretion curve in a normal adult male was made and values tabulated for the case of stable iodine (see Table 1). Values for female individuals may be slightly higher or equivalent as indicated by the comparison between reference male and female values.

On the basis of 1.31 x 10^{-2} μCi in adult urine on the 17th day post intake, a 93 μCi intake was estimated for I-131. Ingestion was assumed to occur

at 0.5 days post detonation at Rongelap Island and elimination was assumed to occur between the begining and the end of the 17th day post detonation.

Table I-1

Fraction of Initial I-131 Activity Ingested That is Excreted On Given Day Post Intake[1]

Days Post Intake	Reference Female[1]	Reference Male[1]	Reference Male[2]
1	6.6×10^{-1}	6.6×10^{-1}	5.9×10^{-1}
5	1.4×10^{-4}	1.4×10^{-4}	1.4×10^{-4}
10	1.9×10^{-4}	1.8×10^{-4}	1.9×10^{-4}
17	1.4×10^{-4}	1.4×10^{-4}	1.4×10^{-4}
25	9.2×10^{-5}	8.0×10^{-5}	9.0×10^{-5}

Fraction of Stable Iodine Ingested That Is Excreted on a Given Day Post Intake for a Normal Adult Male

Days Post Intake	Reference Male[1]	Reference Male[2]	A Normal Male[3]
1	6.6×10^{-1}	5.9×10^{-1}	4×10^{-1}
5	2.3×10^{-4}	2.3×10^{-4}	9×10^{-4}
10	4.3×10^{-4}	4.6×10^{-4}	7×10^{-4}
17	6.4×10^{-4}	6.4×10^{-4}	7×10^{-4}
25	6.9×10^{-4}	7.5×10^{-4}	7×10^{-4}

(1) Johnson Model (Jo81)
(2) ICRP 30 Model (ICRP79)
(3) Berman (Be67), read from graph.

IV. THYROID ABSORBED DOSE ESTIMATE BASED ON BIKINI ASH AND RESULTS FROM I, II AND III.

A. Surface Activity And Exposure Rate Estimates

1. The Nuclide Composition

Radiochemical analysis results for the BRAVO fallout were summarized in Table 1. Bikini Ash, the name of BRAVO fallout given by Yamatera and Tsuzuki (Ya56, Ts56), fell on the Japanese fishing vessel, the 5th Lucky Dragon, on the day of the test. Gross beta activity of Bikini Ash was measured and standardized to day 26 and individual nuclide beta-activity identified and quantified by Japanese scientists. The per cent fission product beta activity expected on day 26 after formation was tabulated in Table 1. The expected beta activity was based on a fallout composition which was unaltered due to chemical or physical mechanisms affecting certain fission product nuclides. This unaltered composition was referred to as unfractionated. This unfractionated composition was calculated from data given by Crocker (Cr65). The comparison between the measured values of Bikini Ash beta activity and per cent unfractionated fission product beta activity required conversion of the Yamatera and Tsuzuki data sets into per cent fission product beta activity, that is, exclusion of the beta activity of the activation products S-35, Ca-45 and the transuranic nuclide U-237. It was assumed that U-237 which represented 20% of the beta activity on day 26 in the Tsuzuki data also represented 20% of the beta activity in the Yamatera data. The data in Table 1 headed "U-238TN Unfractionated % Fission Product Beta Activity" represented the day 26 theoretical per cent of selected unfractionated fission products following thermonuclear neutron fission of U-238. This neutron energy spectrum and uranium target were chosen to represent the BRAVO device (OC68). The difference between Japanese

measurements and the expected beta activity data given in Table 1 represented differences between fractionated and unfractionated fallout.

As previously implied, the term fractionation indicated alterations of nuclide composition in fallout debris. The ratio of two nuclides in fallout was often used to describe fractionation quantitatively (Fr61). The denominator of the ratio was taken to be the activity of ZrNb-95 (Fr61). To quantify fractionation between two nuclides the beta activity ratios were compared. The term "degree of fractionation" represented the range of variability of the nuclide ratio. The term "extent of fractionation" represented the portion of the total nuclide produced which departed from the unfractionated ratio.

A review of the data in Table 1 indicated the nuclides' Te-132, I-132, I-131, Ce-141, RuRh-106, CePr-144 measured activity ratios (ratioed to measured ZrNb-95 beta activity) did not differ by a factor greater than about 1.5 from the unfractionated ratios. The nuclides BaLa-140, Nd-147, Y-91, SrY-90, Ru-103 and Pr-143 fractionated by about a factor of 2 relative to the unfractionated ratios and the nuclides Sr-89 and Te-129m-Te-129 fractionated by about a factor of 3 relative to the unfractionated ratios. The nuclides Y-91, RuRh-106, Te-129m-Te-129, Te-132, I-132, CePr-144, Pr-143 and Nd-147 were in greater abundance relative to unfractionated debris. The other nuclides were in less abundance.

Freiling (Fr61) indicated that the degree of fractionation from a surface burst could be significant. The extent of the fractionation throughout the debris was another variable he observed to be significant. Freiling emphasized the high degree of fractionation between nuclides classified as volatile and refractory for coral atoll surface bursts. Generalizations to be used with much caution were made. Freiling, indicated that fractionation in general

would decrease as device yield decreased. He also indicated fractionation would increase with depth, that is, air bursts would be less fractionated than surface bursts which would be less fractionated than sub-surface bursts. From Freiling's studies it could be cautiously expected that the high yield surface burst creating the BRAVO fallout caused a moderate to high degree of fractionation which occurred moderately to extensively throughout the debris.

For the coral surface burst, Freiling observed that the ratio of Zr-95 to Sr-89 activity could be chosen as a representative measure of the overall degree of fractionation between refractory and volatile elements. This ratio was observed twice and had a value of 5 for a deep water surface burst of megaton range and a value of 100 for a coral surface burst (Fr61). The unfractionated value for this ratio on day 26 post detonation for thermonuclear neutron fission of U-238 was calculated to be 1.6 from data given by Crocker (Cr65). From the average of Yamatera and Tsuzuki data, the calculated ratio of Zr-95 activity to Sr-89 activity measured on day 26 was 4.8. This measured value for the degree of fractionation was characteristic of a deep water surface burst of the megaton range, moderately but not highly fractionated. This moderate fractionation probably occurred to extensively throughout the fallout because of the large yield and surface location of the device (Fr61).

The effect of fractionation on decay rate is very complex and simple observation of overall radioactive decay does not yield significant information. Even so, the decay rate from widely distributed samples obtained out to 300 miles away from the BRAVO detonation site were similar as were the decay rates from activity on different size fallout granules collected at the same site (Oc68). These facts alone may not be used to indicate the same fractionation was common to all granule sizes. In fact, small granules traveled

with the cloud for longer periods of time and possibly absorbed more longer-lived nuclides than did the very large granules. In the forthcoming analysis, the fractionation observed for Bikini Ash granules was assumed to be similar for granules at Rongelap, Sifo and Utirik Islands. With the possible exception of Utirik Island, this was considered a value assumption due to the proximity of Rongelap and Sifo Islands to the 5th Lucky Dragon.

2. The Decay of Fallout

The gamma and beta decay of the BRAVO radioactivity after the first 10 days post detonation was measured by many researchers (e.g. Miller, Servis, Tomkins, Wilsey and Stetson, see OC68). Decay data measured prior to 10 days was not found in the literature. Fallout samples, taken weeks after the BRAVO event, were from Bikini Atoll, Rongelap Atoll and from the surface of US Navy ships in the area. The measured decay exponent after two weeks was used by many researchers to extrapolate exposure rate back to times prior to sample collection and in one case was used to estimate activity decline every hour post detonation (Miller (OC68)). These calculations by Miller for the decay of fallout activity from several hours out to a few weeks post BRAVO apparently excluded the decay characteristics of non-fission nuclides. This would impact on surface activity estimates at the islands of interest since these estimates relied on extrapolated exposure rates. The thyroid dose from internal sources would be affected also by decay characteristics because it relied in part on surface activity estimates.

In order to derive ground activity estimates at times close to BRAVO detonation and to derive external and internal thyroid dose, the gamma or beta decay rate decline over short periods of time was assumed to have followed the relationship

$$x_2 = x_1 \left(\frac{t_2}{t_1}\right)^m \qquad (1)$$

where x_1 = gamma or beta decay rate at time t_1, and
x_2 = gamma or beta decay rate at time t_2.
m = decay exponent

During early times post BRAVO and for short time intervals of a few hours it seemed Miller's decay exponents may have departed significantly from the standard value used for planning fallout activity decline ($m = -1.2$) and thus his tabulations described the early decay of BRAVO fallout adequately. These values for m at different times post detonation of BRAVO were listed in Table 2. The overall decay exponent calculated from Miller's data for the period one hour to sixty days post detonation was -1.2 and agreed with the standard value used for decay of unfractionated fission products. Thus, the impact on exposure rate due to non-fission nuclides was not folded into Miller's tabulations and further study was needed to establish BRAVO decay (OC68).

Surveys performed by the crew members of the USS PHILIP, the ship dispatched to evacuate Rongelap Island, have recorded an exposure rate level for Rongelap village of 1,473 mR h^{-1} average and 1,900 mR h^{-1} maximum at 2.2 days post detonation (COMTASK GROUP 7.3 Disp 020848Z of March 1954, OC68). A similar but less precise statement of the exposure rate at the time of evacuation was given by Sharp (Sh57). In order to reconstruct the BRAVO exposure rate decline prior to evacuation and not use standard decay exponent ($m = -1.2$) additional information about the arrival time and nuclide composition of the BRAVO fallout activity was derived from Bikini Ash measurements.

3. The Build-Up of BRAVO Fallout on the Ground

The studies by Suito, Takiyama and Uyeda (Su56) indicated Bikini Ash consisted of irregularly shaped white granules. Bikini Ash, taken from the deck of the 5th Lucky Dragon, deposited while the ship was located about 150 Km from the detonation site (Ts55). From the size and shape distributions it was determined the mean volume diameter of Bikini Ash granules was 320μ ± 70μ (Su56). The mean volume diameter was the diameter corresponding to the mean volume. The mass of one granule was 0.039 mg (Su56). The specific gravity was 2.4, slightly less than the specific gravity of $CaCO_3$ (Su56). The granules were aggregates of smaller unit particles with shapes that varied from spindles to cubes (Su56). The diameters of these unit particles making up the granules varied from 0.1 to 3.0 μ (Su56). It was suggested by Suito that Bikini Ash was formed by evaporation of the coral reef to its constituent atoms and then by recrystallization of Ca with H_2O and CO_2 in the air.

The granule size distribution of Bikini Ash influenced the estimate of time over which the bulk of the fallout activity fell on the fishing vessel. Larger volume granules carried a major portion of the activity which fell at early times post detonation (La65). The activity versus granule diameter distribution in % of total activity as a function of granule diameter was plotted in Figure 1 for Bikini Ash. In order to construct this histogram, the activity of a granule was assumed proportional to the 3.5 power of the radius of the granule as indicated by Lavrenchik (La65). The number of granules in each granule size class was taken from Suito (Su56). Other granule size distributions (Figs. 3 and 5) were based on the relative positions of the 5th Lucky Dragon, Rongelap Island, Sifo Island and Utirik Island to the BRAVO explosion site.

These distributions were in turn used to determine the rate at which exposure rate and activity increased at these island locations.

Information regarding granule fall time as a function of granule diameter was derived from deposition models reviewed by Norment (No66). Four models of fallout settling were presented as a function of granule diameter and initial height (No66). Expressions for granule fall time from various heights were derived by using the model results of Davies, Hedman, Hastings or Ksanda as presented by Norment (No66). The resulting granule fall time versus granule diameter equation was in each case best described by a power function. Tsuzuki (Ts55), in his article, indicated the observed fallout arrival time, cessation time and granule size for Bikini Ash. This data was used to model a power function relationship which related granule diameter to granule fall time specifically for BRAVO fallout as follows:

$$T = 79.5 \quad D^{-0.524} \tag{2}$$

where

T = granule fall time in hours post BRAVO,
D = granule diameter in micrometers.

It was assumed that the largest granules in the Bikini Ash fell upon arrival and the smallest granules fell upon cessation of fallout. Equation 2 was used with the activity versus granule diameter distribution to describe the rate at which activity increased at Rongelap, Utirik and Sifo Islands and on the 5th Lucky Dragon.

Equation 2 was a simple model to describe fallout arrival time versus granule diameter. The bulk of the activity of BRAVO was at the base of the cloud at 17 to 29 km above ground ten minutes after the burst (OC68). Granules

of a given size were spread throughout the stem, the base of the cloud and up to the cloud top at 40 km. In fact an entire distribution of granule sizes would reach the surface at any point in time not just one size. The simple model (Eq. 2) was adequate for the purpose of estimating the rate of rise of exposure rate and the rate of accummulation of activity at the surface. The approximation was sufficient to estimate external exposure during the period of rising exposure rates. The measurement of rate of rise of exposure rate for weapons tests during the Hardtack Series in 1957 were in agreement with the rate of rise of the exposure rate for BRAVO calculated from using Eq. 2 (USPHS59).

These estimates of granule fall time, granule diameter and activity versus granule diameter were combined in a straight forward manner to determine the cumulative per cent of activity deposited on the surface of the 5th Lucky Dragon as a function of time after the BRAVO explosion. This estimate was plotted in Fig. 2. The rate of activity build up was taken as the slope of the curve on Fig. 2. The result indicated the bulk of the activity had fallen on the fishing vessel by three and a half hours post BRAVO detonation due to the greater amount of activity carried by the more abundant large diameter granules which fall first. Granules could no longer be seen falling be the crew of the fishing vessel by about 8 hours post BRAVO (Ts55).

Interviews with Rongelap people indicated the granules were noticed first at 5 hours post detonation (Sh57). At the time of the BRAVO detonation people were located at Rongelap Island, Rongelap Atoll, about 210 km from Namu Island, Bikini Atoll, the original location of BRAVO fallout. The duration of the fallout was observed for about 7 hours (Sh57). Equation 2 yielded granule diameter information for Rongelap Island based on the observed fallout arrival and cessation times. The Rongelap granule diameter distribution was

assumed to have the same shape as that of Bikini Ash as given by Suito (Su56). Using the assumption that the activity of a granule was proportional to the 3.5 power of the radius of the granule (La65), an activity versus granule diameter distribution was estimated for Rongelap Island (see Fig. 3). The activity median diameter for fallout at Rongelap Island was about 150 microns. The activity median diameter was the granule diameter corresponding to the median activity. The cumulative per cent of total activity deposited on the surface of Rongelap Island versus time post detonation (see Fig. 4) was estimated from the times of arrival and cessation of fallout, Eq. 2 and Fig. 3.

The first analysis of arrival time of BRAVO fallout at Utirik Island, Utirik Atoll was done by Sondhaus, Sharp, Bond and Cronkite (Cr56). It was estimated by them to be 22 hours post detonation. The estimate was based on an assumed mean wind speed and the distance between Namu and Utirik Islands. Visible fallout was not observed on Utirik Island, therefore arrival and cessation times were not observed first hand. Fallout cessation was estimated by Sondhaus to be 34 hours post detonation (Cr56).

New values of fallout arrival and cessation at Utirik Island were estimated based on observations on the fishing vessel, Rongelap Island and Rongerik Atoll, a military outpost. Fallout was first seen at 150 km at 3 hours post detonation by the Japanese fishermen and lasted for 5 hours (Ts55). It was then seen at Rongelap Island at 210 km at 5 hours post detonation and was reported to last for 7 hours (Sh57). Fallout was first observed at Eniwetak Island, Rongerik Atoll at about 7 hours post detonation (Sh57). This last value came from military personnel stationed at Eniwetak Island, 270 km from ground zero. Fallout duration at Eniwetak was reported to last into the night and perhaps into the next day (Sh57). A linear regression curve fit of the values for

distance versus time of arrival or distance versus time of duration yielded an estimated fallout arrival of 17 hours post detonation at Utirik Island and a fallout cessation time of 36 hours post detonation. These new values for arrival and cessation times were estimated based on the fact that people at Utirik Island were 570 km from the BRAVO detonation site. The derived values for fallout arrival and cessation times at Utirik Island departed somewhat from the original estimates of Sondhaus.

Based on Eq. 2 and the new fallout arrival and cessation time estimates, granule diameter data for Utirik Island were determined. Using the assumption that the activity of a granule was proportional to the 3.5 power of the radius (La65), an activity versus granule diameter distribution was estimated for Utirik Island (see Fig. 5). The number of granules in each granule size class was based on Bikini Ash (Su56). The activity median diameter for fallout at Utirik Island was about 14.5 microns. This agreed with the fact that fallout was not visible to the eye at Utirik. The cumulative per cent of total activity deposited on the surface of Utirik Island (see Fig. 6) was estimated from Fig. 5 and Eq. 2. An adjustment for decay of each granule size class from the onset of fallout to the time of surface deposition was not made in order to generate Figs. 2, 4 and 6. The activity referred to in these figures was the activity which would have existed at the onset of fallout at each location. Correction for decay leads to a slightly steeper rise (1-5%) in the cumulative per cent activity versus hours post BRAVO detonation at each location.

Eighteen Rongelap people went to Sifo Island, Ailiginae Atoll to fish and make copra (Sh57). They left Rongelap Island prior to or about the time of the BRAVO detonation (Sh57). These people who went to Sifo Island, a few hours transit time away from Rongelap, were located about 150 km from the

detonation site, thus these persons would have received fallout with similar granule diameters as that given in Fig. 1 for Bikini Ash. Their location was further south than the location reported for the 5th Lucky Dragon (Ts57) thus less debris fell on Sifo Island. The fallout encountered by these people was estimated to be off the centerline of the BRAVO cloud by about 30 km.

4. A Simple Model for Exposure Rate History at Rongelap, Sifo and Utirik Islands

The exposure rate survey by the crew members of the USS PHILIP (OC68), the early fallout decay exponents indicated by Miller (OC68) and the time of arrival of fallout on the surface of Rongelap were combined to estimate the exposure rate history at Rongelap Island prior to evacuation (see Table 3) (Cr56). This exposure rate history would not include the contribution from non-fission fragment nuclides since it was based on fission product decay exponent given by Miller (OC68). The total integrated exposure at Rongelap Island from the onset of fallout until evacuation was 180 R for one meter above the surface. The maximum exposure rate of about 12 R h^{-1} was estimated to occur about 5 hours post detonation, however, it was assumed that all the fallout was on the ground at this time, that is, an instantaneous rise in exposure rate. The crew of the U.S.S. PHILIP also surveyed Sifo Island and the crew of the USS RENSHAW surveyed Utirik Island during their evacuation efforts (OC68). The exposure rate histories for Utirik Island and Sifo Island were given in Table 3. In summary, the exposure rates in Table 3 were based on Miller's decay estimates and do not account for build-up of exposure rate but are in agreement with initial estimates. A more refined estimate of external exposure rate history was based on Bikini Ash as follows.

5. Activity and Exposure Rate History Based On Bikini Ash

a. Areal Activity of Nuclides Observed in Bikini Ash

The Yamatera and Tsuzuki data were used to estimate BRAVO fallout activity on the ground and exposure rate prior to the evacuation. This estimate accounts for the fractionation of fission products, the presence of transuranic products observed in Bikini Ash and the build-up of exposure rate. In order to make this estimate, the data in Table 1 were first used to generate the per cent of fallout beta activity represented by each nuclide's beta activity in Bikini Ash (recorded in Table 4 column 2). This column of data was calculated based on the mean value of the Yamatera and Tsuzuki data if two values for the measurement of beta activity in Bikini Ash were available for each nuclide. The day 26 exposure rate, at one meter above the surface of a planar source of a unit area of Bikini Ash activity (Table 4 column 3), was calculated for each nuclide based on the data of Kocher (Ko80), Beck (Be80) and Table 4 column 2. By summing the exposure rate relative to fallout beta activity per unit area from each nuclide in Bikini Ash and using Table 4 column 2, the beta activity of each nuclide per unit area relative to a unit fallout exposure rate from Bikini Ash was determined for day 26 post detonation and was listed in Table 4 column 4. The summed fallout exposure rate per unit Bikini Ash activity per unit area was 5.8×10^{-3} μR per hour per mCi per km^2 at 26 days post detonation.

Held indicated a mean exposure rate at Rongelap Island of about 40 mR h^{-1} at 26 days post detonation (He65). Held reported after the initial contamination there was a storm with heavy rain about two weeks post detonation (He65). This was followed by a reduction in exposure rate greater than what would have been expected from decay alone. Glasstone reports a 40% reduc-

tion in the exposure rate and attributed it to weathering during the first 25 days post BRAVO in certain areas of the Marshall Islands (G162).

To estimate the reduction in exposure rate due to weathering at Rongelap Island it was assumed the measurement taken at 2.2 days by the USS PHILIP survey team was for unweathered fallout and that the fallout was decaying with the exponent $m = -1.4$ from day 2.2 out to day 26. This value for m, the decay exponent, was the mean value calculated for the nuclide mixture reported by Yamatera and Tsuzuki for the period 2.2 to 26 days post detonation. This calculated value of the decay exponent was based on the decay of 142 nuclides given in Table 5. The estimate accounted for the contribution to exposure rate from 1) the transuranic nuclides U-237 and Np-239, 2) the neutron induced nuclides S-35 and Ca-45, 3) the day 26 fission products which had fractionated according to the mean of the Japanese data (Ya56, Ts56) and 4) the fission product and transuranic product precursors which were present on day 2.2. This decay exponent and the measurement data of the USS PHILLIP crew resulted in an adjustment for weathering losses which increased the exposure rate reported by Held from 40 to 47 mR h^{-1} on day 26 at Rongelap Island, an 18 per cent increase. This was the estimated mean unweathered exposure rate which should have existed on day 26 had the rain storm not occurred.

b. Areal Activity at Fallout Cessation

Using the estimate of 47 mR h^{-1} as the value for the unweathered average exposure rate on day 26, the unweathered average activity per unit area on Rongelap Island was calculated for the nuclide mixture present on day 26. This estimate was made by multiplying 47 mR h^{-1} by 1000 and by the value for nuclide activity per unit area per unit Bikini Ash exposure rate as given in Table 4 column 4. Although the magnitudes of the uncertainties in the

mean unweathered activity per unit area were not well defined, it is thought the calculated mean activities per unit area at Rongelap Island had a standard deviation partly based on the original Bikini Ash measurements (e.g., Zr-95, S.D. = ±20%, (Is56)) and partly based on the point to point variation reported in soil samples taken from the surface of Rongelap, Sifo and Utirik Islands. The mean day 26 unweathered activities per unit area for the 25 nuclides in Table 4 were tabulated in Table 5 column 5. The standard deviation of the mean unweathered activity per unit area would be greatly affected by random fallout deposition and physical mechanisms which move deposited fallout around. This standard deviation was estimated to be plus or minus 140% of the mean value. This was based on the variation in surface activity measurements reported by O'Conner (OC68) for surface samples taken from the Northern Marshall Islands following BRAVO.

The estimates of mean unweathered activity per unit area due to BRAVO fallout on Rongelap Island were extrapolated back to 0.5 days post detonation and results listed in Table 5. The 0.5 day post detonation time was chosen to represent a point in time at which the fallout at Rongelap Island had probably all been on the ground (Sh57). First order linear kinetics for serially related nuclide species (Bal0) and decay schemes from Table of the Isotopes (Le78) were used to calculate the 0.5 day activity from the day 26 activity. The mean unweathered activity per unit area for short-lived precursor nuclides not present on day 26 but on the ground at the end of fallout at 0.5 days were calculated and also listed in Table 5.

c. Areal Activity of Nuclides Without Descendents in Bikini Ash

Many short-lived nuclides had no daughter radionuclides present on day 26. The activity of these short-lived nuclides was based on the activity of a reference nuclide. An equation was used to relate the unknown activ-

ity of the short-lived nuclide with no daughters present on day 26 to the known activity of a nuclide which had been observed on day 26 and had fractionated in the same fashion as the unknown. Fractionation was based on the behavior of isotopes of the unknown which were present on day 26. If no isotope was present on day 26 then an isotope of an isobaric precursor of the unknown was chosen to represent the fractionation behavior of the unknown. The equation used to relate a short-lived nuclide to a reference nuclide was

$$A = \frac{B\ \lambda_a\ B_n}{\lambda_b\ A_n}\ , \tag{3}$$

where

A = activity per unit area of nuclide A at time t post detonation,
B = activity per unit area of nuclide B at time t post detonation,
λ_a = decay constant of nuclide A,
λ_b = decay constant of nuclide B,
A_n = number of A atoms per unit fission at time t,
B_n = number of B atoms per unit fission at time t.

The quantity A_n or B_n was calculated using 1) first order linear kinetics equations, 2) fission yields for 14 MeV fission obtained from the evaluated nuclear data files of the National Nuclear Data Center (EN82), and 3) branching fractions and decay schemes from the seventh edition of the Table of Isotopes (Le78). Since each nuclide accounted for was the nth member of an isobaric chain, the number of atoms at time t would increase or decrease relative to the number at time of detonation due to decay and ingrowth phenomenon of precursor isobars. The exceptions were the few products arising from short-lived neutron emitting precursors. This decay and ingrowth phenomenon was accounted for by Eq. 4 which was originally described by Bateman (Ba10) and later recast in a more general form by Skrable (Sk75).

$$A_n = \sum_{i=1}^{i=n} \prod_{j=i}^{j=n-1} \lambda_j \, f_{j,j+1} \sum_{j=i}^{j=n} \frac{A_i^o \, e^{-\lambda_j t}}{\prod_{\substack{p=i \\ p \neq j}}^{p=n} (\lambda_p - \lambda_j)} , \qquad (4)$$

where

A_n = the number of atoms of the nth member of an isobaric chain at time t post detonation per unit fission,
A_i^o = the independent yield at t = 0 of the ith isobar in the A_n isobaric chain per unit fission,
λ_j = decay constant of the jth isobar,
$f_{j,j+1}$ = branching fraction of the jth isobar leading to the creation of the jth + 1 isobar,
t = time post BRAVO detonation.

The use of Eqs. 3 and 4 led to the inclusion in Table 5 of all fission products with the exclusion of only a few of the dosimetrically insignificant ones. A few important transuranics and activation products were included in Table 5 based on the Tsuzuki measurements on day 26 fallout (Ts55) and use of parent-daughter transformation equations given by Bateman (Ba10).

d. Non-Fission Fragment Nuclides Not Accounted For

The nuclides which may have been present at some level but remain unaccounted for are Be-7, Na-24, Mn-56, Fe-55, Fe-59, Co-57, Co-58, Co-60, Cu-64, Cu-67, U-240, Np240m, Np-240, Am-241 and Cm-242. Two short lived activation products, Na-24 and Mn-56, might have accounted for some of the exposure rate measured at day 2.2 at Rongelap Island. Borg (Du56) tabulated the photon energy spectrum from a BRAVO fallout sample collected at Rongelap Island. The fallout sample was reported to be analyzed at 4 days post detonation. The spectrum showed a significant peak energy at 850 keV. Mn-56 has a characteristic photon at 847 keV but so do about 30 other nuclides that were present in fallout at that time (RSIC73). Mather (Du56) indicated that short-lived neutron activa-

tion products may account for as much as 20-50% of the photon intensity during the first day post detonation, however, most Na-24 and Mn-56 activity remained close to the point of creation. In the case of BRAVO this was near Namu Island, Bikini Atoll. It is doubtful that Na-24 and Mn-56 contributed to exposure rate at Rongelap Island because they were created hundreds of kilometers away.

An assessment of the exposure rate contribution from the accounted for nuclides at distances far from the detonation site was approximated based on studies of fallout composition at the Nevada Test Site (Hi81). An approximation of the exposure rate due to all unaccounted for nuclides listed above would be less than 1% of the total exposure rate on day 0.5 post detonation. This may not be a fair comparative assessment since a device like BRAVO was not reported as being studied at the Nevada Test Site.

e. Input Data to Kinetics Equations

A check on the activity per unit fission data at any time was made. The theoretical activity of unfractionated iodine isotopes following 10,000 thermonuclear fissions of U-238 as given by Crocker (Cr65) were compared to the activity at any time following fission of U-238 with 14 MeV neutrons as calculated here. The comparison calculation was made using decay schemes from Table of the Isotopes (Le78), independent yield data for fission products from the National Nuclear Data Center (EN82) or from Crocker (Cr65) and Eq. 4. The Crocker yields were based on a slightly different neutron energy spectrum than that used in the calculation made here. The kinetics equations, verified yield data and decay scheme approach resulted in remarkably similar results when compared to Crocker. The maximum difference, approximately 50% was for I-134 at two hours post detonation. All iodine isotope activities were within 20% of

the Crocker estimate at about 10 hours post detonation and virtually identical activities were estimated after 100 hours post detonation.

f. Exposure Rate from Surface Activity

The mean exposure rate estimate from all the nuclides given in Table 5 and present on day 0.5 post detonation of the BRAVO device was 1.1×10^1 R h^{-1}. This estimate included the contribution from noble gas nuclides which would not have remained on the surface with fallout particles. Exclusion of the noble gas activity yields 9.7 R h^{-1} for the exposure rate at day 0.5.

Due to surface roughness effects the unweathered exposure rate estimate of 47 mR h^{-1} could have been an underestimate which would have resulted in an underestimate of surface activity on day 26 post detonation. Surface roughness effects were approximated by comparing Beck's values for mR h^{-1} μCi^{-1} m^2 for a smooth flat plane, to a plane where activity was distributed depthwise with a relaxation length of 0.16 gm cm^{-2}. This translates into an underestimate of the activity present by 15%.

Based on Bikini Ash composition and neglecting the impact of surface roughness effects and unaccounted for nuclides, the estimate of average exposure rate at Rongelap Island on day 0.5 at one meter above the surface was taken to be 9.7 R h^{-1}. This was significantly different from the extrapoled value of 5.8 R h^{-1} on day 0.5 derived from Miller's decay estimates (see Table 3). The decay exponent derived from Bikini Ash data was -1.42 for the period 2.2 days to 26 days post detonation. The value for the decay exponent for the period 12 hours to 2.2 days was -1.23, from 9 hours to 12 hours it was -1.31, and from 5 hours to 9 hours it was -1.41. These early values for the decay exponent were significantly different from those derived from Miller's decay estimates (see Table 3) and indicated much more rapid decline in the exposure rate.

Most of the difference is from the decay of Np-239 and other transuranics and from activation products.

g. Integrated Exposure and Whole Body Absorbed Dose

The total integrated exposure calculated from Bikini Ash data was 280 R while people were at Rongelap Island. This estimate accounts for the build-up of fallout described previously. A plot of exposure rate versus time at Rongelap Island was included in Fig. 7. Based on the decay exponents derived from Bikini Ash components and the exposure rate survey data obtained by the crews of the USS RENSHAW and the USS PHILIP, exposure rate versus time post detonation plots were determined for Sifo and Utirik Islands as well (see Fig. 7). The total integrated exposure at one meter above the surface of Sifo Island was 170 R and at Utirik Island 16 R.

Although these exposure estimates differ from those of Cronkite (Cr56), they are in agreement with respect to Cronkite et al whole body and external thyroid absorbed dose calculations. The Marshallese reported no significant deviation from routine living patterns as reported by Sharp (Sh57). In a previous document by Greenhouse and Miltenberger (Gr77), it was shown that external exposure inhomogeneities due to various living patterns (such as fishing in the lagoon, standing on the beach, etc.) could be accounted for by multiplying the island exposure rate by 0.73 to obtain whole body absorbed dose rate. Thus the conservative one to one relationship between exposure and absorbed dose assumed by Cronkite et al yields external absorbed dose estimates which are about 12% less than those estimated here.

B. Radioactivity In Food, Water Supplies and Air

1. Activity in Cistern Water

The main water supplies at Rongelap, eight cisterns, each contained 0.23 m high of water during the later part of March and early April 1954 (Sh57). Held reported a storm with heavy rain on or about March 15, 1954 (He65). This storm followed many weeks of drought (Sh57). Water was drawn from six of these cisterns at Rongelap for gross beta analysis on March 2, 1954 (Report of the USS PHILIP, OC68), and one other cistern was reported as out. Each cistern opening was about 0.65 m^2 (see Fig. 8) and was fed by galvanized metal sheeting used for catching rainwater (Sh57). A little rain was reported on the afternoon of March 1, 1954 (Sh57). The additional area for catchment of water with subsequent runoff into cistern water was not assumed to contribute to the estimate of water or activity in the cistern. The concentration of activity was taken to be dependent on cistern water height which was taken to be at the level reported by Sharp (Sh57). Fallout in runoff feeding the cisterns and a different cistern water height, both of which were possible on March 1, 1954 would impact on the estimate of water activity concentration.

Results of the analysis for gross beta activity concentration in cistern water ranged from 11,000 to 120,000 dm^{-1} ml^{-1} with a mean of 60,000 dm^{-1} ml^{-1} at 50 hours post detonation (OC68). The fallout from Castle series coral surface bursts including BRAVO was barely soluble in water (Ka66). Rain and water would have disolved part of the fallout particle and released only a fraction of the iodine near the surface of the particle (Ka66). In BRAVO fallout which was collected with mixtures of rain and sea spray, 20-50% of the iodine activity was found in the liquid phase (Ka66). The servicemen at Rongerik Atoll examined the terrestrial fallout under a microscope and reported that the

sand like granules were not soluble in water on the microscope slide (Sh57). Most BRAVO activity probably remained with the fallout particles at the bottom of the cistern. The radioactivity in solution was probably in large part due to radioiodines because of their solubility. Extrapolating the 50 hour post detonation beta activity concentration back to 0.5 days post detonation, based on the decay characteristics of Bikini Ash components, results in a range of water gross beta activity concentrations of 0.003 to 0.05 $\mu Ci\ ml^{-1}$ with a mean of 0.03 $\mu Ci\ ml^{-1}$. At 0.5 days, a total of 1 $Ci\ m^{-2}$ of Bikini Ash gross beta activity was estimated from Table 5. Given the area of a cistern opening, this implied the average cistern contained 37 m^3 of water if all the Bikini Ash activity was in the liquid phase. This was about 250 times greater than the observed water volume of the cisterns as previously indicated by Sharp (Sh57). If one assumes only 35% of the radioiodine activity in the liquid phase of cistern water, then an average cistern water content estimate of 0.3 m^3 of water results, about twice the water volume of cisterns as observed in late March, 1954. Assuming only 20% of the iodine activity in the liquid phase, the lowest estimate given by Kawahara (Ka66), and the appropriate activity of each iodine isotope in Bikini Ash at 50 hours post detonation leads to about the same estimate of cistern water content as that which was reported by Sharp and others (Sh57).

Based on 1) Bikini Ash activity per unit area estimates given in Table 5, 2) a 20% release of iodine activity from fallout granules to cistern water and, 3) an average cistern water volume of 0.15 m^3, the radioiodine activity concentrations were estimated for cisterns located at Rongelap Island. A range of cistern water activity at Rongelap Island was estimated to be between 0.2 and 2 times the average values given in Table 6. The range was estimated on the basis of the range reported for the gross beta activity measured in Rongelap

Island cistern water at 50 hours post detonation. The activity concentration in Sifo Island cistern water was assumed to be 12% the values given at Rongelap Island. This was based on a ratio of mean exposure rate at both islands at one point in time and the ratio of the fractions of total granule activity on the surface of the mean granule size in each cistern.

The cisterns and wells at Utirik Island were observed to be covered as reported by the evacuation team aboard the USS RENSHAW (OC68). Interestingly, the range of cistern water activity at Utirik Island was 7,200 to 33,000 dm^{-1} as computed for 0930 on March 3, 1954 based on 2 different cistern water samples taken on March 9 (OC68). The roof over each cistern apparently was not effective in preventing some contamination. The mean Utirik cistern water activity was about 1/3 the mean cistern water activity reported for Rongelap Island at this same time. On the basis that activity in the liquid phase in two cisterns would be directly proportional to the ratio of exposure rates near each cistern and, directly proportional to the ratio of the fraction of total activity on the surface of the mean granule size in each cistern, one would expect roughly equal activity in the liquid phase in cisterns at Rongelap and Utirik Islands at the same point in time. Thus, covered cisterns at Utirik provided some degree of activity reduction in drinking water. On the basis of the observed average gross beta activity ratio of Utirik to Rongelap cistern water on March 3, 1954, the estimates of radioiodine activity in Utirik Island cistern water were made (see Table 6). The instantaneous activity concentrations given in Table 6 were modified by the activity deposition rate indicated by the slope of Figs. 2, 4 or 6.

3

2. Activity Ingested with Drinking Water

In the weeks preceding the BRAVO contamination, water from cisterns was rationed to one pint cup per person each day (Sh57). Assuming this wording implies US liquid measure, then 470 cm^3 of water per person per day was distributed. This water was used to make tea and coffee and was directly injested (Sh57). Naidu observed an average intake of about 1000 cm^3 of coconut water per day for adults, 800 cm^3 for adolescents and 500 cm^3 for 1 to 3 year old children (Na80). Marshallese also consumed coconut tree sap, about 700 cm^3 per day for adults, 600 cm^3 for adolescents and 400 cm^3 for 1-3 year old children (Na80). Not counting the water intake from ingesting food and by oxidation of food, a 70 Kg adult would ingest about 2000 cm^3 per day of fluids and a 10 year old child 1400 cm^3 per day in order to balance normal water losses (ICRP74). Therefore it was likely each person drank his or her daily cistern water ration of 470 cm^3 especially since ambient temperatures were greater than 25°C (ICRP74) which would increase body water losses. People reported drinking this water regardless of the concern expressed about the taste and color (Sh57).

On the basis of one pint cup intake of cistern water per day, 150 cm^3 of water was assumed to be taken with each meal. At Rongelap Island, this was assumed to occur at 5.5 (lunch), 12 (dinner), 24 (breakfast), 30 (lunch), 38 (dinner) and 50 (breakfast) hours post detonation. No literature was found to indicate rationing was necessary at Sifo or Utirik Islands. Based on fluid balance studies (Na80, ICRP74) it was assumed one pint cup per person per day was the cistern water intake at these islands as well. The 150 cm^3 intake of water with meals was assumed at Sifo Island, also at the same meal times assumed for Rongelap Island and at 57 (lunch) hours post detonation as well. The 150 cm^3 mealtime water intake was assumed at Utirik Island to occur at at 24, 31, 38,

50, 57, 64 and 76 hours post detonation. Evacuation at Utirik was completed at 78 hours post detonation (OC68). These assumed water intakes led to estimates of ingested activity which were tabulated in Table 7. This was a conservative estimate of radioiodine activity intake from this pathway because all the activity in the liquid phase in the cistern was assumed to be due only to the iodine isotopes.

3. Activity in Food

Preparation and consumption of food in the open was a common practice among the Marshallese people (Na83). Fallout was ingested directly with food (see Figures 9-15). Food was reported to taste strange by persons interviewed at Rongelap during the 1954 evacuation (Sh57). Fallout was reported at Rongelap to appear like table salt and flour, or like taro powder or chalk dust, and taste like cement and blackened the sky as if night were approaching (Sh57). One family group reported that the only food not dusted by fallout was coconut meat and milk (Sh57). Most families reported eating in the usual open air style and prepared foods such as cooked pumpkin, starch tubes, rice and bread products over open campfires. In addition, fish was normally dried on open air racks prior to intake.

4. Activity Ingested with Food

The majority of activity fell during the afternoon at Rongelap Island during preparation of the mid-day and evening meals. Fallout was even visible on peoples skin; it caused itching, sneezing and coughing (Sh57). The open air living pattern of the Marshallese led to direct ingestion of BRAVO fallout in amounts which can only be estimated roughly. The living patterns at Utirik and Sifo were similar to those at Rongelap and, at Utirik the fallout was not visible during or following deposition (OC68). No attempt at removing visible

fallout from food was reported by persons evacuated from Rongelap or Sifo Islands (Sh57).

Fallout was distributed on the surface of Rongelap Island at 12 hours post detonation at a level of about 1 Ci m^{-2} (see Table 5). This was in good agreement with soil sample data obtained on March 8, 1954 (OC68). Based on a conversion factor given by the persons doing the soil analysis (OC68) the measured soil specific activity was converted to activity per unit area at 12 hours post detonation for comparison purposes. Their value for Rongelap Island was 0.53 ± 0.72 Ci m^{-2} and was based on four samples. Considering the variables involved with the Bikini Ash estimate of activity per unit area and the variability in soil sampling (see Section III), these two estimates were in very good agreement. Random soil sampling was done at Utirik Island, Sifo Island, Eniwetak Island and other islands of Rongelap, Ailinginae, Utirik and Rongerik Atolls as well (OC68). At the end of fallout deposition at Utirik Island, estimated to be 36 hours post detonation, the surface activity based on one sample was 0.058 Ci m^{-2}. This one data point was about 5 times too high based on exposure rate data, however, soil analysis data exhibited wide variations in soil taken from nearly the same spot (OC68). At Sifo Island, the fallout cloud passed by at 8 hours post detonation. The activity per unit area at Sifo was measured also with one soil sample and was 0.032 Ci m^{-2}. At Eniwetak Island the BRAVO cloud was estimated to pass by at 16 hours post detonation and the measured surface activity at that time was 0.32 ± 0.21 Ci m^{-2}, based on 2 samples.

The outside area used to prepare food for the mid-day or evening meals at Rongelap may have been about 1-2 m^2 for a family (see Figs. 9-15). Cooking was done over an open fire fueled by coconut shells (Na80). Boiling and

frying was done this way (Na80). Roasting of green breadfruit, fish and nuts was done over a coconut shell or husk fueled fire, when it had turned to coals (Na80). Ground ovens, used for baking breadfruit, were normally covered with banana leaves to prevent large amounts of dirt and dust from entering (Na80). These outdoor preparation and cooking modes allowed significant amounts of BRAVO debris to be mixed with food.

Table 8 was the summary of activity per unit area and time post detonation for Rongelap Island for nuclides contributing significantly to thyroid dose. The tabulation was based on Bikini Ash and was done in the same way as previously indicated from the 12 hour post detonation values given in Table 5. Instantaneous surface activities during fallout deposition were modified by the actvity deposition rate indicated by the slope of Fig. 4. The activity per unit area of selected nuclides at Utirik Island was estimated by ratio of the exposure rates at Rongelap and Utirik and during fallout deposition by adjusting for activity deposition rate as indicated by the slope of Fig. 6. This same method was used to estimate the surface activity at Sifo Island. The exposure rate ratio between Rongelap and Sifo Islands was 3.0 to 1.0 and between Rongelap and Utirik Islands, 9.5 to 1.0.

Although BRAVO debris was not highly soluble in water, calcium carbonate and hydrated calcium oxide (the matrix in which BRAVO fallout was entrained) were both highly soluble in acid (Co72). Therefore ingestion of BRAVO debris would result in release of radioiodines and other nuclides trapped in the granules due to the acid environment of the stomach. The mass and volume of BRAVO fallout granules was insignificant relative to the normal amount of food eaten per meal, about 400 g for adults (Ev66). The mass of BRAVO fallout per m^2 at Rongelap Island was 4.4 g and the volume was 1.9 cm^3, about four

tenths the volume of a teaspoon. The mass per m^2 and corresponding volume at Utirik Island was 0.46 g and 0.20 cm^3. For Sifo Island it was 1.5 g m^{-2} and 0.48 cm^3 m^{-2}. These mass and volume estimtes were for the point in time at which all the fallout was on the ground, the cessation of fallout. The values for Utirik and Sifo Islands were estimated by ratio of the exposure rate at Rongelap Island at the end of fallout, at the same point in time.

The amount of fallout dust ingested per meal would be dependent upon the amount that fell into utensils and plates during preparation and during consumption. Resuspension and subsequent deposition on food and preparation of food on dusty surfaces would be secondary pathways. During the mid-day meal at Rongelap Island, BRAVO dust probably fell directly onto plates and on the surfaces of fish which were drying in the open. The area of one plate exposed to BRAVO fallout plus the area of a small fish are approximately 0.04 m^2. If a 30 minute lunch interval beginning at 5 hours post detonation was assumed to be the plate and fish exposure interval to dust, then about 40 mg (about 4/1000ths of a teaspoon) would fall on this eating area at Rongelap Island. During the preparation of the evening meal about 0.1 m^2 of surface area was assumed as the family food preparation area exposed to dust during fallout deposition. On the average, about 4.5 people were estimated in each family (Sh57). Therefore an additional 100 mg of BRAVO debris per family member was estimated to be consumed with the evening meal at 12 hours post detonation. This corresponds to a total per person ingestion of about 90 μCi of I-131; 30 μCi at 5.5 hours post detonation and 60 μCi at 12 hours post detonation. As indicated by the reassessment of urine bioassay in a previous section, a 93 μCi intake of I-131 gives agreement between current biotransport models and the measured I-131 in urine on day 17. Therefore ingestion of fallout dust with meals provides a rational pathway

for the intake. Table 9 presents the activity intake of selected nuclides at Rongelap Island. An adult male was assumed to take in 93 μCi of I-131 in order to correspond to urine data. Activity intake with meals was modified by body weight for the other members of the population. This modification was based on an exponential relationship between total element intake and body weight derived from data tabulated in Reference Man. (ICRP74).

Ingestion of activity directly with meals at Utirik Island would have resulted during breakfast, lunch and dinner on March 2, 1954 due to fallout dusting plates and food preparation areas and food itself throughout the early morning hours and all day. As mentioned previously, fallout particles were not visible to the eye at Utirik Island (OC68). Also, fallout activity was measured in cisterns even though cisterns were covered, indicating BRAVO dust may have entered food not just by direct deposition alone. Essentially all of the BRAVO activity fell during the eating of breakfast and during breakfast food preparation (see Fig. 6). Assuming the same food eating and preparation areas as at Rongelap, and the same family size, then about 30 mg of BRAVO dust was ingested with the breakfast meal at 24 hours post detonation. Dust ingested with lunch and evening meals was not considered in the estimate. Resuspension followed by redeposition was considered secondary to direct deposition prior to and during breakfast.

At Sifo Island, the majority of fallout fell for one hour, a mid-morning hour between the breakfast and lunch times. Assuming the same food preparation area as at Rongelap Island, but no deposition on plates during the eating of lunch, values for intake were estimated and recorded in Table 9. Approximatey 60 mg of BRAVO dust were assumed to be ingested at 5.5 hours post

detonation. This dust would be large sized, 320μ average diameter, and be visible on food preparation surfaces.

5. Activity Intake by Breathing Contaminated Air

Mean air concentration estimates of the activity of selected nuclides were based on the deposition rates of fallout. The percent of activity deposited per minute at a point in time at Rongelap Island was estimated from the slopes of tangents to the curve in Fig. 4. The diameter of particles at a point in time was estimated from Eq. 2. The velocity corresponding to particle diameter was taken from Fig. 8 of Holland (Ho63).

The air activity concentration at a point in time was assumed, 1) directly proportional to the percent of total activity deposited per minute at that point in time, 2) directly proportional to the activity on the ground at the end of fallout corrected for decay back to that point in time, and 3) inversly proportional to velocity of fall of granules at that time. This same method was applied to surface activity data for Sifo and Utirik Islands as well. Values for air concentration at all three islands and times post BRAVO detonation were tabulated and given in Table 10. The air activity concentrations for Rongelap Island derived from Bikini Ash data were in agreement with air activity concentration data derived by Peterson (Pe81). Peterson used the MATHEW-ADPIC code suite and all the observed wind data (see Section II).

The air activity concentrations for Utirik Island relative to those at Rongelap Island might be expected to be less because of the exposure rate differences that were observed. The velocity of fall of a granule corresponding to the activity median diameter was greater by a factor of 95 at Rongelap Island when compared to Utirik Island, while the exposure rate after deposition differed by only a factor of 9.5. If the deposition intervals at

both islands were the same length and the air activity concentrations were equal then 95 times less exposure rate at Utirik Island would be anticipated not 9.5. Therefore, the fallout cloud duration at Utirik must have been longer, in fact it was longer by a factor of 2 to 3 when compared to Rongelap. It was not long enough to satisfy the known values of exposure rate and the estimated values of granule fall time and fallout duration. Therefore the air concentration at Utirik Island was calculated to be greater than at Rongelap for certain long lived nuclides (see I-131, Table 10). Peterson (see Section II) in an attempt to satisfy the exposure rate data and weather data indicated the cloud may have been blown back to Utirik which would in effect increase the overall fallout duration time rather than air concentration. The total fallout activity on the surface of Rongelap Island was still ten times greater than at Utirik Island regardless of air concentration during fallout deposition largely due to the rate at which granules fell to the surface.

Airborne activity intakes were dependent upon breathing rate of individuals during fallout cloud passage. Breathing rate was assumed proportional to body mass as derived from reference data for persons less than 58 kg (ICRP74). Adult reference values for breathing rate (ICRP74) were assumed for Marshallese adults regardless of adult body mass. At Rongelap Island, BRAVO debris passed during the afternoon, a period of light physical activity for the population. At Utirik Island, the debris passed during the night, a period of rest- ing. At Sifo Island a period of light physical activity was assumed in order to estimate breathing rate. Values for airborne activity intake were compiled from data in Table 10 and breathing rate estimates and were given in Table 11. Body mass and corresponding age and breathing rate were also listed in Table 11. On the basis of urine data it was determined that inhalation could

not account for the estimated activity intake for I-131. In fact lethal external exposure rates would have to accompany significant radioiodine intakes if inhalation is assumed to be the dominant intake pathway.

C. Absorbed Dose For Individuals

1. Total Activity Intake

Table 12 was compiled using data from Tables 7, 9 and 11. Total activity intake and corresponding age were tabulated. Newborn babies were assumed to inhale activity at Rongelap and Utirik Islands, no newborns were reported at Sifo Island (Co74). Newborns from Rongelap Island were assumed to ingest 850 ml of breast milk per day (ICRP74) for 3 days past detonation. A fraction of 10^{-5} per ml of adult female breast milk was assumed to be the fraction of mother's intake of iodine transferred to the newborn (Ma81). This breast milk intake was assumed at Utirik as well. Decay of the iodines between the time of intake for the mother and the time of intake for the newborn was neglected. Intake of breast milk contaminated with radioiodine from the long-term clearance compartments of the mother's body was considered insignificant relative to the intake from breast milk contaminated with short-term-clearance-radioiodine from the mother's body (Ma81).

2. Absorbed Dose per Unit Activity Intake

Table 13 was compiled from data generated by Johnson (Jo82). An exponential interpolation of non-adult values given by Johnson was performed in order to generate the values given here. Thyroid absorbed dose commitment was generated because the nuclides of interest all had halflives much shorter than 50 years, the integration interval used by Johnson to generate 50 year dose equivalents (Jo82). Absorbed dose was generated on the assumption of a quality factor of one. The absorbed dose per unit activity intake values for adults

were those given by Johnson directly (Jo82) and the values for the tellurium isotopes were generated from reference man data in "Limits for Intakes of Radionuclides by Workers" (ICRP79). Tellurium isotope values in Table 13 for the ages less than adult were generated by ratio of the Johnson values for the appropriate iodine daughters. The thyroid absorbed dose for any age person per unit tellurium isotope activity intake was assumed proportional to the product of the adult value and the ratio of the iodine value. For example Te-132 rad per μCi for a six year old (see Table 13) would be the product of 0.22 (taken from the Te-132 column of Table 13) and the ratio of 0.048 to 0.013 (taken from the I-132 column of Table 13).

3. Thyroid Absorbed Dose

The product of age specific intake (see Table 12) and age specific thyroid absorbed dose per unit intake (see Table 13) was compiled for different ages in Table 14. The thyroid absorbed dose from all iodine and tellurium nuclides was 8.0 times the dose due to I-131 at Rongelap Island. It was 10 times the dose due to I-131 at Sifo Island and 4.9 times the dose due to I-131 at Utirik Island. The dose evaluation by James (Ja64) for a 3.5 year old Rongelap girl was given as 1,445 rads (most probable value for ingestion). James assumed the total thyroid absorbed dose from ingestion of all iodine isotopes in fallout was 2.6 times the thyroid dose due to I-131. Since James based the total thyroid dose on I-131 measurements in urine and this factor of 2.6, a significant difference between the Bikini Ash method and the James method occurs. Adjusting the James ingestion dose estimate by multiplying by the ratio of 8.0 to 2.6 increases the total thyroid absorbed dose estimate by James to 4,450 rads (most probable value for ingestion). The value for a 3.5 year old from Bikini Ash data was 3,580 rads, smaller than the adjusted James value. The contribution

from each radioiodine to thyroid absorbed dose was dependent upon the time post detonation and upon the fractionation of the isobaric chains giving rise to the radiodines. Both factors influenced the Bikini Ash thyroid absorbed dose estimate made here. James assumed theoretical fission yields and assumed one-third of the ingestion intake occurred at ten hours and two-thirds at 30 hours post detonation. Also James only considered I-131, I-133 and I-135 in the thyroid dose estimate. Additionally James adjusted the thyroid dose downward to 1,050 rads for a 3.5 year old to account for part of the I-131 intake being due to inhalation. Inhalation intake based on Bikini Ash data was not significant relative to ingestion intake.

Several methods were used to estimate a range of fallout material ingested. One was to ingest with meals known quantities of drug grade $CaCO_3$ and subjectively arrive at similar descriptions of taste as given by the Rongelap people at the time of evacuation in March, 1954. A group of five adult white males at BNL reported that 200 mg when mixed with food, could not be sensed by taste at all. Another method was to assume the range associated with the weight of the contents of the stomach in cases of sudden death (Ev66). This range 0 to 380 grams, mean 82 grams, implies a maximum of about 5 times the mean value. Another method was to examine the range of Cs-137 daily activity intake from 1957 to 1983 for Rongelap and Utirik people. The range of Cs-137 intake was about 5 times the mean value (Le83). Another method was to examine the range of Cs-137 body burdens exhibited by the population inhabiting Bikini Island from 1974 to 1978 (Mi83). The range was about 3.2 times the mean value. Based on the above range values, a value of 4 times the intake and thus 4 times the mean thyroid absorbed dose was assumed for estimates of range made here (see Table 15).

External thyroid absorbed dose estimates were based on integrated photon exposure given previously and based on an adjustment for living pattern in a variable exposure rate environment. Further detail about the adjustment can be found in (Na80) and (Le83).

Some questions about the external beta dose to the thyroid were expressed by Cronkite (Cr81). The thickness of tissue overlying the thyroid ranges from 0.4 to 2.0 cm, average 0.82 cm, and does not correlate with age or body weight very well (ICRP74). The minimum beta energy for penetration of 0.82 cm of tissue was estimated to be 1.8 MeV. At Rongelap Island about 70% of the population has skin lesions on some part of the neck appearing initially about 21 days post exposure (Cr56). This would imply a skin surface dose of several thousand rads. Only a small per cent of the beta flux was above 1.8 MeV in kinetic energy. Of this higher energy flux, only a small fraction would penetrate 0.82 cm of tissue and deposit energy in the thyroid. Thus thyroid dose from this pathway was considered insignificant.

REFERENCES

Ba10 Bateman, H., 1910, The Solution of a System of Differential Equations Occurring in the Theory of Radioactive Transformations, Proceedings of the Cambridge Philosophical Society, 15, 423.

Be67 Berman, M., 1967, "The Iodine Pool," In Compartments Pools and Spaces in Medical Physiology, U.S. Atomic Energy Commission Report, Symposium Series II.

Be80 Beck, H. L., 1980, "Exposure Rate Conversion Factors for Radionuclides Deposited on the Ground," Environmental Measurements Laboratory Report, EML-378.

Co72 Cole, R., 1972, "Inhalation of Radioiodine from Fallout: Hazards and Countermeasures", Environmental Science Associates Report, ESA-TR-72-01.

Co74 Conard, R.A. et. al., 1974, "A Twenty Year Review of Medical Findings In a Marshallese Population Accidentally Exposed to Radioactive Fallout", Brookhaven National Laboratory Report, BNL 50424.

Cr56 Cronkite, E. P., Bond, V. P., and Dunham, C. L., Editors, "Some Effects of Ionizing Radiation on Human Beings," United States Atomic Energy Commission Report.

Cr65 Crocker, G. R. and Turner, T., 1965, "Calculated Activities, Exposure Rates, and Gamma Spectra for Unfractionated Fission Products," United States Naval Radiological Defense Laboratory Report, USNRDL-TR-1009.

Cr81 Cronkite, E., 1981, Letter to Charles Sondhaus, University of California.

Du56 Dunning, G. and Hilcken, J., Editors, 1956, "The Shorter-Term Biological Hazards of a Fallout Field," United States Atomic Energy Commission and United States Department of Defense.

EN82 National Nuclear Data Center, 1982, "Evaluated Nuclear Data Files," Brookhaven National Laboratory Report, ENDF BIV.

Ev66 Eve, I. S., 1966, "A Review of the Physiology of the Castrointestinal Tract in Relation to Radiation Doses from Radioactive Materials," Health Physics, 12, 131-161.

Fr61 Freiling, E. C., 1961, "Radionuclide Fractionation in Bomb Debris," Science, 133, 1991-1998.

Gl62 Glasstone, S., 1962, "The Effects of Nuclear Weapons," United States Atomic Energy Commision and United States Department of Defense, Revised Edition.

Ha54 Harris, P.S., 1954, "A Summary of the Results of Urine Analyses on Rongelap Natives, Americans and Japanese Fisherman to Date," Los Alamos Scientific Laboratory, Internal Memorandum.

He65 Held, E., "Gamma Dose Rates at Rongelap Atoll, 1954-1963," 1965, Laboratory of Radiation Biology, University of Washington Report, UWFL-91.

Ho63 Holland, J. Z., 1963, "Distribution and Physical-Chemical Nature of Fallout," Federation Proceedings, 22, 1390-1397.

ICRP-74 International Commission on Radiological Protection, 1974, "Reference Manual," ICRP Publication 23, Pergamon Press, Oxford.

ICRP-79 International Commission on Radiological Protection, 1979, "Limits for Intakes of Radionuclides by Workers," ICRP Publication 30, Pergamon Press, Oxford.

Is56 Ishibasi, M., Shigematsu, T., Ishida, T., Okada, S., Nishi, T., Takahashi, H., Matsumoto, C., Shimizu, S., Hyodo, T., Hirayama, F. and Okamoto, S., 1956, "Radiochemical Analysis of the Bikini Ashes," Research in the Effects and Influences of the Nuclear Bomb Test Explosions, Japan Society for the Promotion of Science.

Ja64 James, R.A., 1964, "Estimate of Radiation Dose to Thyroids of Rongelap Children Following the BRAVO Event," Lawrence Radiation Laboratory Report, UCRL-12273.

Jo81 Johnson, J.R., 1981, "Radioiodine Dosimetry," Journal of Radioanalytical Chemistry, V. 65, p. 223-238.

Jo82 Johnson, J.R., 1982, "Fetal Thyroid Dose From Intakes of Radioiodine by the Mother," Health Physics, 43, 573-582.

Ka66 Kawahara, F. K., O'Conner, J. D., Lee, H. and Connors, M. A., 1966, "Local Fallout From Nuclear Test Detonations", Vol. III, Defense Atomic Support Agency, DASA 1251.

Ki56 Kimura, K., 1956, "Radiochemical Studies on the Radioactive Dust Due to the Nuclear Detonation at the Bikini Atoll on 1st March, 1954," Research in the Effects and Influences of the Nuclear Bomb Test Explosions, Japan Society for the Promotion of Science.

La65 Lavrenchik, V. N., 1965, "Global Fallout Products of Nuclear Explosions," Atomic Energy Commission Report, AEC-tr-6666.

Le78 Lederer, C. M., and Shirley, V. S., Editors, 1978, Table of The Isotopes, Seventh Edition, Wiley Interscience.

Le83 Lessard, E. T., Miltenberger, R. P., Cohn, S. H., Musolino, S. V. and Conard, R. A., 1983, "Protracted Exposure to Fallout these Rongelap and Utirik Experience," Submitted to Health Physics.

Ma81 Mattson, Sorën, et al., 1981, "Excretion of Radionuclides In Human Breast Milk Following Administration of I-125 Fibrinogen, Tc-99-MAA and Cr-51 EDTA "Third Internation Radiopharmaceutical Dosimetry Symposium, Proceedings of a Conference Held at Oak Ridge, Tennessee, HHS Publication FDA 81-8166.

Mi83 Miltenberger, R. P. and Lessard, E. T., Editors, 1983, "Body Burdens and Dose Assessment for Bikini Island Residents".

Na80 Naidu, J. Greenhouse, N., Knight, G. and Graghead, E., 1980, "Marshall Islands" A Study of Diet and Living Patterns," Brookhaven National Laboratory Report, BNL 51313.

Na83 Naidu, J., 1983, Personal Communication.

No66 Norment, H. G., Schwenke, T. W. and Kohlberg, I., 1966, "Development of an Improved Land-Surface Fallout Model," Technical Operations Research Report, TO-B 65-99.

OC68 O'Conner, J. D. and Crocker, G. R., 1968, "Local Fallout From Nuclear Test Detonations," Vol. IV, Defense Atomic Support Agency, DASA1251.

Pe81 Peterson, K., 1981, "Castle-Bravo Air Concentration and Deposition Patterns from a 3-D Particle-in-Cell Code," Lawrence Livermore National Laboratory Report, UASG 81-20.

RSIC73 Radiation Shielding Information Committee, Analytical Chemistry Division and Neutron Physics Division, 1973, Data Library Collection, Radionuclide Gamma-Ray Energy and Intensity Compilation," Oak Ridge National Laboratory Report, ORNL-TM-4095.

Sh57 Sharp, R., and Chapman, W., 1957, "Exposure of Marshall Islanders and American Military Personnel to Fallout," Naval Medical Research Institute Report, WT-938.

Sk75 Skrable, K., French, C., Chabot, G., Major, A. and Ward, K., 1974, Kinetics Equation for Linear First-Order Nuclear Phenomena, Nuclear Safety, 16, 337-344.

Su56 Suito, E., Tokiyama, K. and Uyeda, N., 1956, "Colloid Morphological and Crystalline Studies of "Bikini Dust"," Research in the Effects and Influences of the Nuclear Bomb Test Explosions, Japan Society for the Promotion of Science.

Ts55 Tsuzuki, M., 1955, "Erfahrungen uber Radioaktive Schudigung der japanische Fisher durch Bikini-asche," Muench. Med. Wochsch., 31, 988-994.

USPHS59 United States Public Health Service, 1959, Report of the Public Health Service Off-Site Radiological Monitoring Data, Operation Hardtack Phase I 1958, publisher unknown, manuscript attached to letter from Lt. Colonel Belmont Evans, USA to Robert Conard, M.D., Brookhaven National Laboratory, Upton, NY.

Ya56 Yamatera, 1956, "Radiochemical Analysis of Dust Due To the Thermonuclear Test on March 1, 1954," Research in the Effects and Influences of the Nuclear Bomb Test Explosions, Japan Society for the Promotion of Science.

TABLE IV-1

MEASURED BRAVO FALLOUT COMPOSITION AND UNFRACTIONATED COMPOSITION ON DAY 26

Nuclide(s)	Yamatera Data, % of Beta Activity	Yamatera % Fission Product Beta Activity	Tsuzuki Data, % of Beta Activity	Tsuzuki % Fission Product Beta Activity	U238TN Unfractionated % of Fission Product Beta Activity
Sr-89	1.6	2.0	1.0	1.3	4.2
SrY-90	0.02	0.025	0.040	0.050	0.062
Y-91	-	-	8.0	10.	4.1
ZrNb-95	9.8	12.	8.0	10.	9.6
Ru-103	5.0	6.3	-	-	8.5
RuRh-106	1.4	1.8	-	-	0.94
Te-129m-Te-129	1.3	1.6	-	-	0.42
Te-132	1.0	1.3	15.	19.	0.83
I-131	4.5	5.6	-	-	6.1
I-132	1.0	1.3	-	-	0.83
BaLa-140	11.	14.	11.	14.	23.
Ce-141	9.7	12.	7.0	8.8	10.
CePr-144	2.8	3.5	4.0	5.0	2.9
Pr-143	-	-	16.	20.	12.
Nd-147	-	-	9.0	11.	5.3
Ca-45	-	-	0.20	-	-
U-237	51.	-	20.	-	-
Pu-239 (α)	-	-	0.00040	-	-
S-35	-	-	0.050	-	-

TABLE IV-2

BRAVO Gamma or Beta Exponent
Indicated by Miller's Data (OC68).

Time Post Detonation, t_1 to t_2	Decay Exponent, m
1h to 2h	-1.4
2h to 3h	-1.2
3h to 6h	-.92
6h to 9h	-.81
9h to 12h	-.78
12h to 24h	-.82
24h to 48h	-1.0
52h to 96h	-1.2

30

TABLE IV-3

BRAVO FALLOUT EXPOSURE RATE DECLINE BASED ON MILLER'S DECAY ESTIMATES

Rongelap Island, Rongelap Atoll

Time Post Detonation, hours	Exposure Rate,(1) R h^{-1}	Integral Exposure,(2) R
5	12	-
7	9.0	21
9	7.3	37
17	4.4	84
20	3.8	96
25	3.2	110
30	2.7	130
35	2.3	140
40	2.0	150
45	1.8	160
54	1.5(3)	180

Utirik Island, Utirik Atoll

Time Post Detonation, hours	Exposure Rate,(1) R h^{-1}	Integral Exposure,(2) R
17	0.46	-
19	0.42	0.88
21	0.39	1.7
24	0.35	2.8
27	0.31	3.8
30	0.28	4.7
35	0.24	6.0
40	0.21	7.1
45	0.19	8.1
55	0.15	9.8
75	0.10(4)	12
78	0.095	12

Sifo Island, Ailinginal Atoll

Time Post Detonation, hours	Exposure Rate,(1) R h^{-1}	Integral Exposure,(2) R
3	6.4	-
5	4.0	10
7	3.0	17
9	2.4	23
15	1.6	35
20	1.3	42
25	1.1	48
30	0.88	53
35	0.76	57
40	0.66	61
45	0.59	64
50	0.53	67
57	0.45	70
62	0.41(5)	72

(1) In air at about one meter above surface.

(2) Numerical integration.

(3) Village average: maximum was 1.9 R h^{-1}; U.S.S. PHILIP report (OC68).

(4) Village average; maximum was 0.13 R h^{-1}; U.S.S. RENSHAW report (OC68).

(5) Village average; maximum was 0.48 R h^{-1}; U.S.S. PHILIP report (OC68).

TABLE IV-4

BRAVO FALLOUT BETA ACTIVITY RELATED TO BRAVO FALLOUT EXPOSURE RATE

	Day 26 Post Detonation		
Nuclide	% of Bikini Ash Beta Activity	$\frac{(\mu R\ h^{-1})\ \text{nuclide}}{(mCi\ Km^{-2})\ \text{Bikini Ash}}$	$\frac{(mCi\ Km^{-2})\ \text{nuclide}}{(\mu R\ h^{-1})\ \text{Bikini Ash}}$
Sr-89	1.3	3.3×10^{-8}	2.2×10^{0}
Sr-90	.013	0.0×10^{0}	2.2×10^{-2}
Y-90	.013	3.5×10^{-11}	2.2×10^{-2}
Y-91	8.0	5.0×10^{-6}	1.4×10^{1}
Zr-95	6.2	8.6×10^{-4}	1.1×10^{1}
Nb-95	2.7	3.9×10^{-4}	4.7×10^{0}
Ru-103	5.0	4.5×10^{-4}	8.6×10^{0}
Ru-106	0.70	0.0×10^{0}	1.2×10^{0}
Rh-106	0.70	2.7×10^{-5}	1.2×10^{0}
Te-129	0.35	3.6×10^{-6}	6.0×10^{-1}
Te-129m	0.95	5.3×10^{-6}	1.6×10^{0}
Te-132	1.0	3.8×10^{-5}	1.7×10^{0}
I-131	4.5	3.3×10^{-4}	7.8×10^{0}
I-132	1.0	4.2×10^{-4}	1.7×10^{0}
Ba-140	5.0	1.4×10^{-4}	8.6×10^{0}
La-140	6.0	2.3×10^{-3}	1.0×10^{1}
Ce-141	8.4	1.0×10^{-4}	1.4×10^{1}
Ce-144	1.7	4.7×10^{-6}	2.9×10^{0}
Pr-144	1.7	9.0×10^{-6}	2.9×10^{0}
Pr-143	16.	2.7×10^{-11}	2.8×10^{1}
Nd-147	9.0	2.3×10^{-4}	1.6×10^{1}
Ca-45	0.20	1.8×10^{-12}	3.5×10^{-1}
U-237	20.	4.6×10^{-4}	3.5×10^{1}
Pu-239 (α)	0.0004	5.4×10^{-10}	6.9×10^{-4}
S-35	0.050	0.0×10^{0}	8.6×10^{-2}

TABLE IV-5

ESTIMATED UNWEATHERED ACTIVITY ON SURFACE AND EXPOSURE RATE

AT ONE METER, RONGELAP ISLAND

Nuclide	Reference Nuclide	H+0.5 Day Activity Per Unit Area, Ci Km^{-2}	H+0.5 Day Exposure Rate, R h^{-1}	H+26 Day Activity Per Unit Area, Ci Km^{-2}	H+26 Day Exposure Rate, R h^{-1}
S-35	S-35	$5.0x10^{0}$	-	$4.0x10^{0}$	-
Ca-45	Ca-45	$1.8x10^{0}$	$2.5x10^{-12}$	$1.7x10^{1}$	$2.3x10^{-12}$
Ge-75	Zr-95	$4.9x10^{0}$	$2.3x10^{-6}$	-	-
Ge-77	Zr-95	$9.0x10^{0}$	$1.9x10^{-4}$	-	-
As-77	Zr-95	$1.5x10^{1}$	$1.9x10^{-6}$	-	-
As-78	Zr-95	$5.7x10^{1}$	$1.2x10^{-3}$	-	-
Se-77m	Zr-95	$4.7x10^{-2}$	$6.7x10^{-8}$	-	-
Se-81	Zr-95	$1.9x10^{-1}$	$2.6x10^{-6}$	-	-
Se-81m	Zr-95	$1.3x10^{-1}$	$2.6x10^{-8}$	-	-
Br-82	Zr-95	$2.8x10^{-2}$	$1.3x10^{-6}$	-	-
Br-83	Zr-95	$1.8x10^{3}$	$2.5x10^{-4}$	-	-
Br-84	Zr-95	$4.6x10^{-2}$	$1.3x10^{-6}$	-	-
Kr-83m	Zr-95	$5.0x10^{4}$	$3.0x10^{-2}$	-	-
Kr-85m	Zr-95	$7.9x10^{3}$	$2.7x10^{-2}$	-	-
Kr-87	Zr-95	$4.1x10^{2}$	$5.3x10^{-3}$	-	-
Kr-88	Zr-95	$8.9x10^{3}$	$2.7x10^{-1}$	-	-
Rb-86	Zr-95	$5.7x10^{-3}$	$9.2x10^{-9}$	-	-
Rb-88	Y-91	$1.7x10^{4}$	$1.8x10^{-1}$	-	-
Rb-89	Sr-89	$3.9x10^{-9}$	$1.4x10^{-13}$	-	-
Sr-89	Sr-89	$1.5x10^{2}$	$3.8x10^{-7}$	$1.0x10^{2}$	$2.4x10^{-7}$
Sr-90	Sr-90	$1.0x10^{0}$	-	$1.0x10^{0}$	-
Sr-91	Y-91	$5.7x10^{4}$	$7.1x10^{-1}$	-	-
Sr-92	Y-91	$2.0x10^{4}$	$4.6x10^{-1}$	-	-
Y-89m	Sr-89	$1.4x10^{-3}$	$2.4x10^{-8}$	-	-
Y-90	Y-90	$1.4x10^{-1}$	$3.7x10^{-11}$	$1.0x10^{0}$	$2.5x10^{-10}$
Y-91	Y-91	$6.6x10^{2}$	$3.7x10^{-5}$	$6.6x10^{2}$	$3.7x10^{-5}$
Y-91m	Y-91	$3.4x10^{4}$	$3.4x10^{-1}$	-	-
Y-92	Y-91	$8.4x10^{4}$	3.8x10	-	-
Y-93	Y-91	$7.0x10^{4}$	$1.1x10^{-1}$	-	-
Zr-95	Zr-95	$6.8x10^{2}$	$9.6x10^{-3}$	$5.2x10^{2}$	$7.2x10^{-3}$

TABLE IV-5 (cont'd)

ESTIMATED UNWEATHERED ACTIVITY ON SURFACE AND EXPOSURE RATE

AT ONE METER, RONGELAP ISLAND

Nuclide	Reference Nuclide	H+0.5 Day Activity Per Unit Area, Ci Km^{-2}	H+0.5 Day Exposure Rate, R h^{-1}	H+26 Day Activity Per Unit Area, Ci Km^{-2}	H+26 Day Exposure Rate, R h
Zr-97	Zr-95	$4.0x10^{4}$	$1.3x10^{-1}$	-	-
Nb-95	Nb-95	$3.1x10^{-1}$	$4.0x10^{-6}$	$2.1x10^{2}$	$2.7x10^{-3}$
Nb-95m	Zr-95	$6.4x10^{1}$	$1.4x10^{-4}$	-	-
Nb-97	Zr-95	$4.4x10^{4}$	$5.4x10^{-1}$	-	-
Nb-97m	Zr-95	$3.9x10^{4}$	$5.3x10^{-1}$	-	-
Mo-99	Zr-95	$1.5x10^{4}$	$4.5x10^{-2}$	-	-
Tc-99m	Zr-95	$1.0x10^{4}$	$2.2x10^{-2}$	-	-
Ru-103	Ru-103	$6.4x10^{2}$	$5.9x10^{-3}$	$4.0x10^{2}$	$3.8x10^{-3}$
Ru-105	Zr-95	$2.8x10^{4}$	$4.1x10^{-1}$	-	-
Ru-106	Ru-106	$5.9x10^{1}$	-	$5.7x10^{1}$	-
Rh-103m	Ru-103	$6.3x10^{2}$	$1.2x10^{-4}$	-	-
Rh-105	Zr-95	$1.7x10^{4}$	$2.5x10^{-2}$	-	-
Rh-105	Zr-95	$7.9x10^{3}$	$3.5x10^{-3}$	-	-
Rh-106	Rh-106	$5.9x10^{1}$	$2.2x10^{-4}$	$5.7x10^{1}$	$2.1x10^{-4}$
Pd-109	Zr-95	$1.3x10^{4}$	$1.7x10^{-4}$	-	-
Pd-111	Zr-95	$2.7x10^{3}$	$1.2x10^{-3}$	-	-
Pd-111m	Zr-95	$3.5x10^{3}$	$2.2x10^{-2}$	-	-
Pd-112	Zr-95	$2.0x10^{4}$	$3.1x10^{-4}$	-	-
Ag-109m	Zr-95	$1.3x10^{4}$	$9.3x10^{-3}$	-	-
Ag-111	Zr-95	$3.7x10^{2}$	$1.7x10^{-4}$	-	-
Ag-111m	Zr-95	$2.8x10^{3}$	$1.9x10^{-}$	-	-
Ag-112	Zr-95	$2.1x10^{3}$	$2.5x10^{-2}$	-	-
Ag-113	Zr-95	$1.1x10^{3}$	$5.6x10^{-3}$	-	-
Ag-115	Zr-95	$2.0x10^{-6}$	$2.0x10^{-11}$	-	-
Cd-115	Zr-95	$8.3x10^{2}$	$3.7x10^{-3}$	-	-
Cd-115m	Zr-95	$2.4x10^{1}$	$9.3x10^{-6}$	-	-
Cd-117	Zr-95	$3.3x10^{2}$	$6.1x10^{-}$	-	-
Cd-117m	Zr-95	$6.3x10^{2}$	$2.1x10^{-2}$	-	-
Cd-118	Zr-95	$3.0x10^{0}$	-	-	-
In-115m	Zr-95	$4.6x10^{2}$	$2.7x10^{-3}$	-	-

TABLE IV-5 (cont'd)

ESTIMATED UNWEATHERED ACTIVITY ON SURFACE AND EXPOSURE RATE

AT ONE METER, RONGELAP ISLAND

Nuclide	Reference Nuclide	H+0.5 Day Activity Per Unit Area, Ci Km^{-2}	H+0.5 Day Exposure Rate, R h^{-1}	H+26 Day Activity Per Unit Area, Ci Km^{-2}	H+26 Day Exposure Rate, R h^{-1}
In-117	Zr-95	$1.4x10^{3}$	$1.8x10^{-2}$	-	-
In-117m	Zr-95	$2.1x10^{3}$	$3.0x10^{-3}$	-	-
In-118	Zr-95	$3.0x10^{0}$	$1.3x10^{-5}$	-	-
Sn-119m	Zr-95	$7.9x10^{-2}$	$6.4x10^{-9}$	-	-
Sn-121	Zr-95	$4.4x10^{3}$	-	-	-
Sn-121m	Zr-95	$2.2x10^{-2}$	$1.4x10^{-9}$	-	-
Sn-123	Zr-95	$4.3x10^{-1}$	$5.2x10^{-8}$	-	-
Sn-123m	Zr-95	$3.1x10^{-1}$	$7.3x10^{-7}$	-	-
Sn-125	Zr-95	$5.6x10^{-1}$	$3.1x10^{-6}$	-	-
Sn-127	I-132	$3.8x10^{2}$	$1.3x10^{-2}$	-	-
Sn-128	I-132	$1.5x10^{2}$	$1.9x10^{-3}$	-	-
Sb-125	Zr-95	$3.5x10^{0}$	$2.8x10^{-5}$	-	-
Sb-126	Zr-95	$5.3x10^{2}$	$2.5x10^{-2}$	-	-
Sb-127	I-132	$5.1x10^{3}$	$6.6x10^{-2}$	-	-
Sb-128	I-132	$1.9x10^{3}$	$1.1x10^{-1}$	-	-
Sb-128m	I-132	$1.9x10^{2}$	$6.8x10^{-3}$	-	-
Sb-129	I-132	$3.2x10^{4}$	$7.9x10^{-1}$	-	-
Sb-130	I-132	$3.1x10^{0}$	$1.7x10^{-4}$	-	-
Sb-131	I-132	$5.2x10^{-4}$	$1.8x10^{-8}$	-	-
Te-125m	Zr-95	$1.4x10^{-3}$	$2.0x10^{-9}$	-	-
Te-127	I-132	$2.4x10^{3}$	$2.4x10^{-4}$	-	-
Te-127m	I-132	$3.7x10^{0}$	$1.7x10^{-6}$	-	-
Te-129	Te-129	$1.4x10^{4}$	$1.5x10^{-2}$	$2.8x10^{1}$	$3.5x10^{-5}$
Te-129m	Te-129m	$1.1x10^{2}$	$6.1x10^{-5}$	$7.6x10^{1}$	$6.7x10^{-5}$
Te-131	I-132	$6.8x10^{2}$	$5.2x10^{-3}$	-	-
Te-131m	I-132	$3.1x10^{3}$	$7.9x10^{-2}$	-	-
Te-132	Te-132	$1.8x10^{4}$	$6.8x10^{-2}$	$7.9x10^{1}$	$3.1x10^{-4}$
Te-133	I-132	$2.7x10^{1}$	$4.6x10^{-4}$	-	-
Te-133m	I-132	$1.3x10^{2}$	$5.4x10^{-3}$	-	-
Te-134	I-132	$1.4x10^{1}$	$2.2x10^{-4}$	-	-

TABLE IV-5 (cont'd)

ESTIMATED UNWEATHERED ACTIVITY ON SURFACE AND EXPOSURE RATE

AT ONE METER, RONGELAP ISLAND

Nuclide	Reference Nuclide	H+0.5 Day Activity Per Unit Area, Ci Km^{-2}	H+0.5 Day Exposure Rate, R h^{-1}	H+26 Day Activity Per Unit Area, Ci Km^{-2}	H+26 Day Exposure Rate, R h^{-1}
I-129	I-132	$4.5x10^{-6}$	$5.6x10^{-12}$	-	-
I-130	I-132	$2.6x10^{0}$	$1.1x10^{-4}$	-	-
I-131	I-131	$3.1x10^{3}$	$2.2x10^{-2}$	$3.5x10^{2}$	$2.6x10^{-3}$
I-132	I-132	$1.9x10^{4}$	$7.9x10^{-1}$	$8.0x10^{1}$	$3.4x10^{-3}$
I-133	I-132	$6.5x10^{4}$	$7.4x10^{-1}$	-	-
I-133m	I-131	$1.1x10^{1}$	$3.1x10^{-4}$	-	-
I-134	I-132	$6.5x10^{2}$	$3.1x10^{-2}$	-	-
I-135	I-132	$7.8x10^{4}$	$2.1x10^{0}$	-	-
Xe-131m	I-132	$1.8x10^{0}$	$1.7x10^{-6}$	-	-
Xe-133	I-132	$2.1x10^{3}$	$3.2x10^{-3}$	-	-
Xe-133m	I-132	$3.2x10^{2}$	$4.5x10^{-4}$	-	-
Xe-135	I-132	$8.9x10^{4}$	$4.6x10^{-1}$	-	-
Xe-135m	I-132	$1.2x10^{4}$	$1.0x10^{-1}$	-	-
Cs-135	I-132	$1.4x10^{-3}$	-	-	-
Cs-136	I-132	$1.5x10^{1}$	$6.0x10^{-4}$	-	-
Cs-137	I-132	$7.0x10^{0}$	-	-	-
Cs-138	I-132	$8.7x10^{-1}$	$3.4x10^{-5}$	-	-
Ba-137m	I-132	$6.5x10^{0}$	$7.4x10^{-5}$	-	-
Ba-139	I-132	$3.3x10^{3}$	$2.1x10^{-3}$	-	-
Ba-140	Ba-140	$1.7x10^{3}$	$4.5x10^{-3}$	$4.0x10^{2}$	$1.1x10^{-3}$
La-140	La-140	$3.1x10^{2}$	$1.2x10^{-2}$	$4.7x10^{2}$	$1.9x10^{-2}$
La-141	Ce-141	$3.0x10^{4}$	$2.1x10^{-2}$	-	-
La-142	Ce-141	$2.6x10^{3}$	$1.1x10^{-1}$	-	-
Ce-141	Ce-141	$9.9x10^{2}$	$1.2x10^{-3}$	$6.6x10^{2}$	$7.9x10^{-4}$
Ce-143	Ce-141	$1.9x10^{4}$	$9.2x10^{-2}$	-	-
Ce-144	Ce-144	$1.4x10^{2}$	$4.0x10^{-5}$	$1.4x10^{2}$	$4.0x10^{-5}$
Pr-143	Pr-143	$9.2x10^{2}$	$1.5x10^{-10}$	$1.3x10^{3}$	$2.2x10^{-10}$
Pr-144	Pr-144	$1.4x10^{2}$	$7.4x10^{-5}$	$1.4x10^{2}$	$7.4x10^{-5}$
Pr-144m	Ce-141	$1.7x10^{0}$	$7.8x10^{-7}$	-	-
Pr-145	Ce-141	$2.6x10^{4}$	$6.1x10^{-3}$	-	-

TABLE IV-5 (cont'd)

ESTIMATED UNWEATHERED ACTIVITY ON SURFACE AND EXPOSURE RATE

AT ONE METER, RONGELAP ISLAND

Nuclide	Reference Nuclide	H+0.5 Day Activity Per Unit Area, Ci Km^{-2}	H+0.5 Day Exposure Rate, R h^{-1}	H+26 Day Activity Per Unit Area, Ci Km^{-2}	H+26 Day Exposure Rate, R h^{-1}
Pr-146	Ce-141	$2.6x10^{-3}$	$5.2x10^{-8}$	-	-
Nd-144	Ce-141	$4.7x10^{-17}$	-	-	-
Nd-147	Nd-147	$3.5x10^{3}$	$8.9x10^{-3}$	$7.1x10^{2}$	$1.8x10^{-3}$
Nd-149	Ce-141	$1.4x10^{3}$	$9.8x10^{-3}$	-	-
Pm-147	Ce-141	$5.7x10^{-1}$	$4.1x10^{-11}$	-	-
Pm-149	Ce-141	$4.7x10^{3}$	$1.0x10^{-3}$	-	-
Pm-150	Ce-141	$3.8x10^{3}$	$1.1x10^{-1}$	-	-
Pm-151	Ce-141	$4.3x10^{3}$	$2.5x10^{-2}$	-	-
Sm-151	Ce-141	$5.1x10^{-2}$	$9.4x10^{-11}$	-	-
Sm-153	Ce-141	$1.3x10^{3}$	$1.2x10^{-3}$	-	-
Sm-156	Ce-141	$9.6x10^{2}$	$1.9x10^{-3}$	-	-
Eu-155	Ce-141	$7.3x10^{-1}$	$6.8x10^{-7}$	-	-
Eu-156	Ce-141	$3.5x10^{1}$	$8.0x10^{-4}$	-	-
Eu-157	Ce-141	$6.5x10^{2}$	$3.0x10^{-3}$	-	-
Eu-158	Ce-141	$2.1x10^{-2}$	$5.2x10^{-7}$	-	-
Gd-159	Ce-141	$1.9x10^{3}$	$1.4x10^{-3}$	-	-
Tb-161	Ce-141	$9.8x10^{0}$	$1.3x10^{-6}$	-	-
U-237	U-237	$2.4x10^{4}$	$5.4x10^{-2}$	$1.7x10^{3}$	$3.8x10^{-3}$
U-239	Pu-239	$1.0x10^{-2}$	$8.1x10^{-9}$	-	-
Np-237	U-237	$1.1x10^{-5}$	$4.0x10^{-12}$	-	-
Np-239	Pu-239	$1.0x10^{5}$	$3.0x10^{-1}$	-	-
Pu-239	Pu-239	$4.3x10^{-3}$	$5.7x10^{-10}$	$3.2x10^{-2}$	$4.3x10^{-9}$

TABLE IV-6

AVERAGE ESTIMATE OF RADIOIODINE ACTIVITY IN CISTERN WATER $\mu Ci\ cm^{-3}$,

AND TIME AFTER THE BRAVO DETONATION

Time Post BRAVO	I-135	I-134	I-133	I-133m	I-132	I-131	I-130	I-129
Rongelap Island								
5.5	4.0×10^{-2}	2.5×10^{-2}	1.8×10^{-2}	2.6×10^{-4}	3.8×10^{-3}	6.8×10^{-4}	9.6×10^{-7}	3.8×10^{-13}
7.0	1.3×10^{-1}	2.4×10^{-2}	6.7×10^{-2}	4.1×10^{-4}	1.6×10^{-2}	2.7×10^{-3}	3.6×10^{-6}	2.7×10^{-12}
9.0	1.0×10^{-1}	5.5×10^{-3}	6.4×10^{-2}	1.2×10^{-4}	1.6×10^{-2}	2.7×10^{-3}	3.3×10^{-6}	3.2×10^{-12}
12	6.8×10^{-2}	5.7×10^{-4}	5.7×10^{-2}	9.6×10^{-6}	1.7×10^{-2}	2.7×10^{-3}	2.3×10^{-6}	3.9×10^{-12}
17.5	3.8×10^{-2}	7.0×10^{-6}	4.8×10^{-2}	1.5×10^{-7}	1.6×10^{-2}	2.7×10^{-3}	1.9×10^{-6}	4.2×10^{-12}
20	2.9×10^{-2}	9.5×10^{-7}	4.5×10^{-2}	2.2×10^{-8}	1.5×10^{-2}	2.7×10^{-3}	1.7×10^{-6}	4.4×10^{-12}
25	1.6×10^{-2}	1.7×10^{-8}	3.8×10^{-2}	5.4×10^{-10}	1.4×10^{-2}	2.7×10^{-3}	1.2×10^{-6}	4.7×10^{-12}
30	1.0×10^{-2}	7.8×10^{-10}	3.1×10^{-2}	1.2×10^{-11}	1.4×10^{-2}	2.7×10^{-3}	8.1×10^{-7}	4.7×10^{-12}
35	6.0×10^{-3}	-	2.6×10^{-2}	-	1.3×10^{-2}	2.6×10^{-3}	6.9×10^{-7}	4.7×10^{-12}
40	3.5×10^{-3}	6.5×10^{-13}	2.2×10^{-2}	5.9×10^{-15}	1.2×10^{-2}	2.6×10^{-3}	5.7×10^{-7}	4.7×10^{-12}
45	1.9×10^{-3}	-	1.9×10^{-2}	-	1.2×10^{-2}	2.6×10^{-3}	3.8×10^{-7}	4.7×10^{-12}
50	1.1×10^{-3}	4.9×10^{-16}	1.6×10^{-2}	6.6×10^{-18}	1.1×10^{-2}	2.6×10^{-3}	2.2×10^{-7}	4.7×10^{-12}
54	7.4×10^{-4}	-	1.5×10^{-2}	-	1.1×10^{-2}	2.6×10^{-3}	2.0×10^{-7}	4.7×10^{-12}
Sifo Island								
3.5	1.2×10^{-2}	1.5×10^{-2}	4.1×10^{-3}	3.5×10^{-4}	8.6×10^{-4}	1.5×10^{-7}	2.4×10^{-7}	8.3×10^{-14}
5.5	1.9×10^{-2}	1.2×10^{-2}	8.6×10^{-3}	1.2×10^{-4}	1.8×10^{-3}	3.3×10^{-4}	4.6×10^{-7}	1.8×10^{-13}
7.0	1.6×10^{-2}	3.0×10^{-3}	8.3×10^{-3}	5.1×10^{-5}	2.0×10^{-3}	3.4×10^{-4}	4.5×10^{-7}	3.4×10^{-13}
9.0	1.2×10^{-2}	6.8×10^{-4}	8.0×10^{-3}	1.5×10^{-5}	2.0×10^{-3}	3.4×10^{-4}	4.1×10^{-7}	4.0×10^{-13}
12	8.4×10^{-3}	7.1×10^{-5}	7.1×10^{-3}	1.2×10^{-3}	2.1×10^{-3}	3.4×10^{-4}	2.9×10^{-7}	4.9×10^{-13}
17.5	4.5×10^{-3}	8.4×10^{-7}	5.8×10^{-3}	1.8×10^{-8}	1.9×10^{-3}	3.4×10^{-4}	2.3×10^{-7}	5.0×10^{-13}
20	3.6×10^{-3}	1.2×10^{-7}	5.6×10^{-3}	2.7×10^{-9}	1.9×10^{-3}	3.4×10^{-4}	2.1×10^{-7}	5.4×10^{-13}
25	2.0×10^{-3}	2.1×10^{-9}	4.7×10^{-3}	6.5×10^{-11}	1.7×10^{-3}	3.4×10^{-4}	1.5×10^{-7}	5.8×10^{-13}
30	1.2×10^{-3}	9.7×10^{-11}	3.9×10^{-3}	1.5×10^{-12}	1.7×10^{-3}	3.4×10^{-4}	1.0×10^{-7}	5.8×10^{-13}
35	7.5×10^{-4}	-	3.2×10^{-3}	-	1.6×10^{-3}	3.2×10^{-4}	8.6×10^{-7}	5.8×10^{-13}
40	4.3×10^{-4}	8.1×10^{-14}	2.7×10^{-3}	7.3×10^{-16}	1.5×10^{-3}	3.2×10^{-4}	7.1×10^{-8}	5.8×10^{-13}
45	2.4×10^{-4}	-	2.4×10^{-3}	-	1.5×10^{-3}	3.2×10^{-4}	4.7×10^{-8}	5.8×10^{-13}
50	1.4×10^{-4}	6.1×10^{-17}	2.0×10^{-3}	8.2×10^{-19}	1.4×10^{-3}	3.2×10^{-4}	2.7×10^{-8}	5.8×10^{-13}
54	9.2×10^{-5}	-	1.9×10^{-3}	-	1.4×10^{-3}	3.2×10^{-4}	2.5×10^{-8}	5.8×10^{-13}
62	3.8×10^{-5}	2.9×10^{-21}	1.4×10^{-3}	-	1.3×10^{-3}	3.2×10^{-4}	2.0×10^{-8}	5.8×10^{-13}

TABLE IV-6 (Cont'd)

AVERAGE ESTIMATE OF RADIOIODINE ACTIVITY IN CISTERN WATER $\mu Ci\ cm^{-3}$,

AND TIME AFTER THE BRAVO DETONATION

Utirik Island

Time Post BRAVO	I-135	I-134	I-133	I-133m	I-132	I-131	I-130	I-129
17.5	$1.3x10^{-3}$	$2.3x10^{-7}$	$1.6x10^{-3}$	$5.0x10^{-4}$	$5.3x10^{-4}$	$9.0x10^{-5}$	$6.3x10^{-8}$	$1.4x10^{-13}$
20	$5.8x10^{-3}$	$1.9x10^{-7}$	$9.0x10^{-3}$	$4.4x10^{-9}$	$2.8x10^{-3}$	$5.4x10^{-4}$	$3.4x10^{-7}$	$9.4x10^{-13}$
25	$5.3x10^{-3}$	$5.7x10^{-9}$	$1.3x10^{-2}$	$4.7x10^{-9}$	$5.0x10^{-3}$	$9.0x10^{-4}$	$4.0x10^{-7}$	$1.6x10^{-12}$
30	$3.3x10^{-3}$	$2.6x10^{-10}$	$1.0x10^{-2}$	$4.0x10^{-12}$	$5.0x10^{-3}$	$9.0x10^{-4}$	$2.7x10^{-7}$	$1.6x10^{-12}$
35	$2.0x10^{-3}$	-	$8.7x10^{-3}$	-	$4.3x10^{-3}$	$8.7x10^{-4}$	$2.3x10^{-7}$	$1.6x10^{-12}$
40	1.2x10-3	$2.2x10^{-13}$	$7.3x10^{-3}$	$2.0x10^{-15}$	$4.0x10^{-3}$	$8.7x10^{-4}$	$1.9x10^{-7}$	$1.6x10^{-12}$
45	$6.3x10^{-4}$	-	$6.3x10^{-3}$	-	$4.0x10^{-3}$	$8.7x10^{-4}$	$1.3x10^{-7}$	$1.6x10^{-12}$
50	$3.7x10^{-4}$	$1.6x10^{-16}$	$5.3x10^{-3}$	$2.2x10^{-18}$	$3.7x10^{-3}$	$8.7x10^{-4}$	$7.3x10^{-8}$	$1.6x10^{-12}$
54	$2.5x10^{-4}$	-	$5.0x10^{-3}$	-	$3.7x10^{-3}$	$8.7x10^{-4}$	$6.7x10^{-8}$	$1.6x10^{-12}$
75	$2.3x10^{-5}$	-	$2.4x10^{-3}$	-	2.5x10-3	$8.7x10^{-4}$	$1.8x10^{-8}$	$1.6x10^{-12}$

TABLE IV-7

ESTIMATED ACTIVITY INTAKE FROM CISTERN WATER

	Rongelap Island μCi	Sifo Island μCi	Utirik Island μCi
I-135	21	4.7	1.8
I-134	3.8	1.8	-
I-133	28	4.2	7.0
I-133m	0.040	0.018	-
I-132	11	1.6	3.9
I-131	2.1	0.29	0.93

TABLE VI-8

ACTIVITY PER UNIT AREA AT TIMES POST BRAVO, $\mu Ci\ m^{-2}$

Nuclide	Hours Post Detonation 3.5	5.5	7.0	9.0	12	17.5	20	25	30	35	40	45	50	54	75
Rongelap Island															
I-135	-	4.5×10^{4}	1.5×10^{5}	1.1×10^{5}	7.8×10^{4}	4.4×10^{4}	3.3×10^{4}	1.8×10^{4}	1.1×10^{4}	6.9×10^{3}	4.0×10^{3}	2.2×10^{3}	1.3×10^{3}	3.6×10^{2}	7.9×10^{1}
I-134	-	2.9×10^{4}	2.8×10^{4}	6.3×10^{3}	6.5×10^{2}	8.0×10^{0}	1.1×10^{0}	2.0×10^{-2}	8.9×10^{-4}	-	-	-	-	-	-
I-133	-	2.1×10^{4}	7.7×10^{4}	7.3×10^{4}	6.5×10^{4}	5.5×10^{4}	5.2×10^{4}	4.4×10^{4}	3.6×10^{4}	3.0×10^{4}	2.5×10^{4}	2.2×10^{4}	1.8×10^{4}	1.7×10^{4}	8.3×10^{3}
I-132	-	4.4×10^{3}	1.8×10^{4}	1.8×10^{4}	1.9×10^{4}	1.8×10^{4}	1.7×10^{4}	1.6×10^{4}	1.5×10^{4}	1.5×10^{4}	1.4×10^{4}	1.4×10^{4}	1.3×10^{4}	1.2×10^{4}	1.0×10^{4}
I-131	-	7.8×10^{2}	3.1×10^{3}	3.1×10^{3}	3.1×10^{3}	3.1×10^{3}	3.1×10^{3}	3.1×10^{3}	3.1×10^{3}	3.0×10^{3}	3.0×10^{3}	3.0×10^{3}	3.0×10^{3}	3.0×10^{3}	3.0×10^{3}
Te-132	-	4.8×10^{3}	1.9×10^{4}	1.8×10^{4}	1.8×10^{4}	1.7×10^{4}	1.7×10^{4}	1.6×10^{4}	1.5×10^{4}	1.5×10^{4}	1.4×10^{4}	1.4×10^{4}	1.3×10^{4}	1.2×10^{4}	1.0×10^{4}
Te-131m	-	9.1×10^{2}	3.5×10^{3}	3.3×10^{3}	3.1×10^{3}	2.7×10^{3}	2.6×10^{3}	2.3×10^{3}	2.0×10^{3}	1.8×10^{3}	1.6×10^{3}	1.4×10^{3}	1.3×10^{3}	1.2×10^{3}	7.2×10^{2}
Sifo Island															
I-135	3.8×10^{4}	6.0×10^{4}	5.0×10^{4}	3.6×10^{4}	2.6×10^{4}	1.5×10^{4}	1.1×10^{4}	6.0×10^{3}	3.6×10^{3}	2.3×10^{3}	1.3×10^{3}	7.3×10^{2}	4.3×10^{2}	1.2×10^{2}	2.6×10^{1}
I-134	4.9×10^{4}	3.9×10^{4}	9.3×10^{3}	2.1×10^{3}	2.2×10^{2}	2.6×10^{0}	3.6×10^{-1}	6.6×10^{-3}	2.9×10^{-4}	-	-	-	-	-	-
I-133	1.3×10^{4}	2.8×10^{4}	2.5×10^{4}	2.4×10^{4}	2.2×10^{4}	1.8×10^{4}	1.7×10^{4}	1.5×10^{4}	1.2×10^{4}	9.9×10^{3}	8.3×10^{3}	7.3×10^{3}	6.0×10^{3}	5.6×10^{3}	2.7×10^{3}
I-132	2.8×10^{3}	5.9×10^{3}	6.0×10^{3}	6.0×10^{3}	6.3×10^{3}	6.0×10^{3}	5.6×10^{3}	5.3×10^{3}	5.0×10^{3}	5.0×10^{3}	4.6×10^{3}	4.6×10^{3}	4.3×10^{3}	4.0×10^{3}	3.3×10^{3}
I-131	4.5×10^{2}	1.0×10^{3}	1.0×10^{3}	1.0×10^{3}	1.0×10^{3}	1.0×10^{3}	1.0×10^{3}	1.0×10^{3}	1.0×10^{3}	9.9×10^{2}	9.9×10^{2}	9.9×10^{2}	9.9×10^{2}	9.9×10^{2}	9.9×10^{2}
Te-132	2.9×10^{3}	6.4×10^{3}	6.3×10^{3}	6.0×10^{3}	6.0×10^{3}	5.6×10^{3}	5.6×10^{3}	5.3×10^{3}	5.0×10^{3}	5.0×10^{3}	4.6×10^{3}	4.6×10^{3}	4.3×10^{3}	4.0×10^{3}	3.3×10^{3}
Te-131m	5.7×10^{2}	1.2×10^{3}	1.2×10^{3}	1.1×10^{3}	1.0×10^{3}	8.9×10^{2}	8.6×10^{2}	7.6×10^{2}	6.6×10^{2}	6.0×10^{2}	5.3×10^{2}	4.6×10^{2}	4.3×10^{2}	4.0×10^{2}	2.4×10^{2}
Utirik Island															
I-135	-	-	-	-	-	4.7×10^{2}	2.1×10^{3}	1.9×10^{3}	1.2×10^{3}	7.3×10^{2}	4.2×10^{2}	2.3×10^{2}	1.4×10^{2}	3.8×10^{1}	8.3×10^{0}
I-134	-	-	-	-	-	8.5×10^{-2}	7.0×10^{-2}	2.1×10^{-3}	9.4×10^{-5}	-	-	-	-	-	-
I-133	-	-	-	-	-	5.7×10^{2}	3.2×10^{3}	4.6×10^{3}	3.8×10^{3}	3.2×10^{3}	2.6×10^{3}	2.3×10^{3}	1.9×10^{3}	1.8×10^{3}	8.7×10^{2}
I-132	-	-	-	-	-	1.9×10^{2}	1.1×10^{3}	1.7×10^{3}	1.6×10^{3}	1.6×10^{3}	1.5×10^{3}	1.5×10^{3}	1.4×10^{3}	1.3×10^{3}	1.1×10^{3}
I-131	-	-	-	-	-	3.3×10^{1}	2.0×10^{2}	3.3×10^{2}	3.3×10^{2}	3.2×10^{2}	3.2×10^{2}	3.2×10^{2}	3.2×10^{2}	3.2×10^{2}	3.2×10^{2}
Te-132	-	-	-	-	-	1.8×10^{2}	1.1×10^{3}	1.7×10^{3}	1.6×10^{3}	1.6×10^{3}	1.5×10^{3}	1.5×10^{3}	1.4×10^{3}	1.3×10^{3}	1.1×10^{3}
Te-131m	-	-	-	-	-	2.8×10^{1}	1.6×10^{2}	2.4×10^{2}	2.1×10^{2}	1.9×10^{2}	1.7×10^{2}	1.5×10^{2}	1.4×10^{2}	1.3×10^{2}	7.6×10^{1}

TABLE IV-9

ESTIMATED ACTIVITY INTAKE WITH MEALS, μCi

Age	Body Weight, Kg	I-135	I-134	I-133	I-132	I-131	TR-132	Te-131m
Rongelap Island								
Adult Male	70	3400	1200	2100	550	93	550	80
Adult Female	58	3000	1000	1800	480	81	480	70
Fourteen Year Old	50	2800	980	1700	450	76	450	66
Twelve Year Old	40	2500	890	1600	410	69	410	59
Nine Year Old	30	2300	800	1400	370	62	370	54
Six Year Old	20	2100	720	1300	330	56	330	48
One Year Old	10	1900	660	1200	300	51	300	44
Utirik Island								
Adult Male	70	140	0.00028	280	100	20	100	15
Adult Female	58	120	0.00024	240	87	17	87	13
Fourteen Year Old	50	115	0.00023	230	82	16	82	12
Twelve Year Old	40	100	0.00021	210	74	15	74	11
Nine Year Old	30	94	0.00019	190	67	13	67	10
Six Year Old	20	84	0.00017	170	60	12	60	9
One Year Old	10	77	0.00015	150	55	11	55	8
Sifo Island								
Adult Male	70	1200	780	560	120	20	130	24
Adult Female	58	1000	670	490	100	17	115	21
Fourteen Year Old	50	980	640	460	98	16	110	20
Twelve Year Old	40	890	580	410	89	15	97	18
Nine Year Old	30	800	520	380	80	13	87	16
Six Year Old	20	720	470	340	72	12	78	14
One Year Old	10	660	430	310	66	11	72	13

TABLE IV-10

AIR ACTIVITY CONCENTRATION OF SELECTED NUCLIDES, $\mu Ci\ cm^{-3}$

Hours Post BRAVO	I-135	I-134	I-133	I-132	I-131	TR-132	Te-131m
Rongelap Island							
5.06	5.4×10^{-6}	3.8×10^{-6}	2.5×10^{-6}	5.4×10^{-7}	1.0×10^{-7}	6.0×10^{-7}	1.2×10^{-7}
5.27	9.0×10^{-6}	5.8×10^{-6}	4.3×10^{-6}	8.9×10^{-7}	1.7×10^{-7}	1.1×10^{-6}	2.0×10^{-7}
5.51	1.3×10^{-5}	7.0×10^{-6}	6.0×10^{-6}	1.4×10^{-6}	2.5×10^{-7}	1.5×10^{-6}	2.9×10^{-7}
5.78	2.1×10^{-5}	9.6×10^{-6}	9.6×10^{-6}	2.2×10^{-6}	4.0×10^{-7}	2.4×10^{-6}	4.7×10^{-7}
6.10	9.8×10^{-6}	3.4×10^{-6}	5.0×10^{-6}	1.1×10^{-6}	2.1×10^{-7}	1.2×10^{-6}	2.3×10^{-7}
6.48	7.5×10^{-6}	2.4×10^{-6}	3.9×10^{-6}	9.2×10^{-7}	1.6×10^{-7}	9.7×10^{-7}	1.9×10^{-7}
6.94	1.5×10^{-6}	2.7×10^{-7}	7.1×10^{-7}	1.7×10^{-7}	3.0×10^{-8}	1.8×10^{-7}	3.4×10^{-8}
7.51	3.1×10^{-7}	5.3×10^{-8}	1.7×10^{-7}	4.2×10^{-8}	7.4×10^{-9}	4.4×10^{-8}	8.2×10^{-9}
8.23	1.3×10^{-7}	1.2×10^{-8}	7.5×10^{-8}	2.0×10^{-8}	3.4×10^{-9}	2.0×10^{-8}	3.8×10^{-9}
9.21	3.4×10^{-8}	1.8×10^{-9}	2.3×10^{-8}	6.1×10^{-9}	1.1×10^{-9}	6.1×10^{-9}	1.7×10^{-9}
10.6	6.6×10^{-9}	1.4×10^{-10}	4.7×10^{-9}	1.3×10^{-9}	2.3×10^{-10}	1.3×10^{-9}	2.4×10^{-10}
Sifo Island							
3.07	6.4×10^{-7}	1.2×10^{-6}	2.3×10^{-7}	4.2×10^{-8}	8.3×10^{-9}	5.5×10^{-8}	1.1×10^{-8}
3.20	9.5×10^{-7}	1.7×10^{-6}	3.5×10^{-7}	6.5×10^{-8}	1.3×10^{-8}	8.5×10^{-8}	1.7×10^{-8}
3.36	1.4×10^{-6}	2.4×10^{-6}	5.4×10^{-7}	1.0×10^{-7}	2.0×10^{-8}	1.3×10^{-7}	2.6×10^{-8}
3.54	1.1×10^{-6}	3.1×10^{-6}	8.3×10^{-6}	1.5×10^{-7}	2.9×10^{-8}	1.9×10^{-7}	3.8×10^{-8}
3.75	1.0×10^{-6}	1.4×10^{-6}	4.0×10^{-7}	7.8×10^{-8}	1.5×10^{-8}	9.9×10^{-8}	1.9×10^{-8}
4.01	7.5×10^{-7}	8.5×10^{-7}	3.0×10^{-7}	5.9×10^{-8}	1.1×10^{-8}	7.1×10^{-8}	1.4×10^{-8}
4.33	1.3×10^{-7}	1.3×10^{-7}	5.4×10^{-8}	1.1×10^{-8}	2.0×10^{-9}	1.3×10^{-8}	2.5×10^{-9}
4.73	3.0×10^{-8}	2.4×10^{-8}	1.3×10^{-8}	2.7×10^{-9}	4.8×10^{-10}	3.1×10^{-9}	6.0×10^{-10}
5.26	1.9×10^{-8}	1.1×10^{-8}	8.2×10^{-9}	1.8×10^{-9}	3.1×10^{-10}	2.0×10^{-9}	3.8×10^{-10}
6.02	2.8×10^{-9}	1.0×10^{-9}	1.3×10^{-9}	3.0×10^{-10}	5.1×10^{-11}	3.2×10^{-10}	6.3×10^{-11}
7.44	2.4×10^{-10}	3.5×10^{-11}	1.2×10^{-10}	3.0×10^{-10}	5.0×10^{-12}	3.1×10^{-11}	5.9×10^{-12}
Utirik Island							
17.3	5.4×10^{-6}	1.7×10^{-10}	7.0×10^{-6}	2.1×10^{-6}	4.1×10^{-7}	2.2×10^{-6}	3.4×10^{-7}
18.0	6.6×10^{-6}	1.2×10^{-10}	9.0×10^{-6}	2.8×10^{-6}	5.4×10^{-7}	2.9×10^{-6}	4.4×10^{-7}
18.8	1.1×10^{-5}	9.9×10^{-11}	1.6×10^{-5}	5.1×10^{-6}	9.8×10^{-7}	5.1×10^{-6}	7.7×10^{-7}
19.7	1.6×10^{-5}	8.7×10^{-11}	2.3×10^{-5}	7.5×10^{-6}	1.4×10^{-6}	7.5×10^{-6}	1.1×10^{-6}
20.7	6.8×10^{-6}	2.4×10^{-11}	1.1×10^{-5}	3.8×10^{-6}	7.4×10^{-7}	3.8×10^{-6}	5.6×10^{-7}
21.9	2.2×10^{-6}	-	9.5×10^{-6}	3.3×10^{-6}	6.4×10^{-7}	3.3×10^{-6}	4.8×10^{-7}
23.3	9.7×10^{-7}	-	1.8×10^{-6}	6.5×10^{-7}	1.3×10^{-7}	6.5×10^{-7}	9.3×10^{-8}
24.9	1.9×10^{-7}	-	4.3×10^{-7}	1.6×10^{-7}	3.2×10^{-8}	1.6×10^{-7}	2.2×10^{-8}
27.3	6.0×10^{-8}	-	1.6×10^{-7}	6.4×10^{-8}	1.3×10^{-8}	6.4×10^{-8}	8.8×10^{-9}
30.0	1.9×10^{-8}	8.0×10^{-17}	6.1×10^{-8}	2.6×10^{-8}	5.3×10^{-9}	2.6×10^{-8}	3.4×10^{-9}
33.8	2.8×10^{-9}	-	1.2×10^{-8}	5.6×10^{-9}	1.2×10^{-9}	5.6×10^{-9}	7.0×10^{-10}

TABLE IV-11

AVERAGE INHALATION INTAKE OF SELECTED NUCLIDES, μCi

Age	Body Weight, Kg	Breathing Rate $cm^3\ min^{-13}$	I-135	I-134	I-133	I-132	I-131	Te-132	Te-131m
Rongelap Island									
Adult Male	70	20,000	24	10	11	2.6	0.48	2.9	0.55
Adult Female	58	19,000	22	9.9	11	2.5	0.45	2.7	0.52
Fourteen Year Old	50	19,000	22	9.9	11	2.5	0.45	2.7	0.52
Twelve Year Old	40	15,280	18	8.0	8.7	2.0	0.36	2.2	0.42
Nine Year Old	30	11,530	14	6.0	6.6	1.5	0.27	1.7	0.32
Six Year Old	20	7,790	9.2	4.1	4.5	1.0	0.19	1.1	0.21
One Year Old	10	4,050	4.8	2.1	2.3	0.53	0.096	0.58	0.11
Newborn	3.5	1,620	1.9	0.85	0.93	0.21	0.039	0.23	0.045
Sifo Island									
Adult Male	70	20,000	2.2	2.3	2.3	0.12	0.023	0.15	0.029
Adult Female	58	19,000	2.1	2.2	2.2	0.11	0.022	0.14	0.028
Fourteen Year Old	50	19,000	2.1	2.2	2.2	0.11	0.022	0.14	0.028
Twelve Year Old	40	15,280	1.7	1.8	1.7	0.090	0.017	0.11	0.023
Nine Year Old	30	11,530	1.3	1.3	1.3	0.068	0.013	0.085	0.017
Six Year Old	20	7,790	0.85	0.90	0.89	0.046	0.0089	0.058	0.012
One Year Old	10	4,050	0.44	0.47	0.46	0.024	0.0046	0.030	0.0060
Utirik Island									
Adult Male	70	7,500	1.9	0.00020	33	11	2.1	11	1.7
Adult Female	58	6,500	1.7	0.00017	29	9.6	1.8	9.6	1.4
Fourteen Year Old	50	6,500	1.7	0.00017	29	9.6	1.8	9.6	1.4
Twelve year Old	40	5,650	1.5	0.00014	25	8.4	1.6	8.3	1.2
Nine Year Old	30	4,250	1.1	0.00011	19	6.3	1.2	6.3	0.94
Six Year Old	20	2,850	0.74	0.000074	13	4.2	0.80	4.2	0.63
One Year Old	10	1,450	0.37	0.000038	6.4	2.2	0.41	2.1	0.32
Newborn	3.5	540	0.14	0.000014	2.4	0.80	0.15	0.79	0.12

TABLE IV-12

TOTAL RADIOIODINE AND RADIOTELLURIUM ACTIVITY INTAKE (μCi)

AND CORRESPONDING AGE

Age	I-135	I-134	I-133	I-132	I-131	Te-132	Te-131m
Rongelap Island							
Adult Male	$3.5x10^3$	$1.2x10^3$	$2.1x10^3$	$5.6x10^2$	$9.6x10^1$	$5.5x10^2$	$8.1x10^1$
Adult Female	$3.0x10^3$	$1.0x10^3$	$1.8x10^3$	$4.9x10^2$	$8.4x10^1$	$4.8x10^2$	$7.1x10^1$
Fourteen Year Old	$2.8x10^3$	$9.9x10^2$	$1.7x10^3$	$4.6x10^2$	$7.9x10^1$	$4.5x10^2$	$6.7x10^1$
Twelve Year Old	$2.5x10^3$	$9.0x10^2$	$1.6x10^3$	$4.2x10^2$	$7.1x10^1$	$4.1x10^2$	$5.9x10^1$
Nine Year Old	$2.3x10^3$	$8.1x10^2$	$1.4x10^3$	$3.8x10^2$	$6.4x10^1$	$3.7x10^2$	$5.4x10^1$
Six Year Old	$2.1x10^3$	$7.3x10^2$	$1.3x10^3$	$3.4x10^2$	$5.8x10^1$	$3.3x10^2$	$4.8x10^1$
One Year Old	$1.9x10^3$	$6.7x10^2$	$1.2x10^3$	$3.1x10^2$	$5.3x10^1$	$3.0x10^2$	$4.4x10^1$
Newborn	$7.9x10^1$	$2.6x10^1$	$4.8x10^1$	$1.3x10^1$	$5.2x10^0$	$1.2x10^1$	$1.8x10^0$
Sifo Island							
Adult Male	$1.2x10^3$	$7.8x10^2$	$5.7x10^2$	$1.2x10^2$	$2.0x10^1$	$1.3x10^2$	$2.4x10^1$
Adult Female	$1.0x10^3$	$6.7x10^2$	$5.0x10^2$	$1.0x10^2$	$1.7x10^1$	$1.2x10^2$	$2.1x10^1$
Fourteen Year Old	$9.9x10^2$	$6.4x10^2$	$4.7x10^2$	$9.9x10^2$	$1.6x10^1$	$1.1x10^2$	$2.0x10^1$
Twelve Year Old	$9.0x10^2$	$5.8x10^2$	$4.2x10^2$	$9.0x10^1$	$1.5x10^1$	$9.7x10^1$	$1.8x10^1$
Nine Year Old	$8.1x10^2$	$5.2x10^2$	$3.9x10^2$	$8.1x10^1$	$1.3x10^1$	$8.7x10^1$	$1.6x10^1$
Six Year Old	$7.3x10^2$	$4.7x10^2$	$3.5x10^2$	$7.3x10^1$	$1.2x10^1$	$7.8x10^1$	$1.4x10^1$
One Year Old	$6.7x10^2$	$4.3x10^2$	$3.1x10^2$	$6.7x10^1$	$1.1x10^1$	$7.2x10^1$	$1.3x10^1$
Utirik Island							
Adult Male	$1.4x10^2$	-	$3.2x10^2$	$1.1x10^2$	$2.3x10^1$	$1.1x10^2$	$1.7x10^1$
Adult Female	$1.2x10^2$	-	$2.8x10^2$	$1.0x10^2$	$2.0x10^1$	$9.7x10^1$	$1.4x10^1$
Fourteen Year Old	$1.2x10^2$	-	$2.7x10^2$	$9.5x10^1$	$1.9x10^1$	$9.2x10^1$	$1.3x10^1$
Twelve Year Old	$1.0x10^2$	-	$2.4x10^2$	$8.6x10^1$	$1.8x10^1$	$8.2x10^1$	$1.2x10^1$
Nine Year Old	$9.7x10^1$	-	$2.2x10^2$	$7.7x10^1$	$1.5x10^1$	$7.3x10^1$	$1.1x10^1$
Six Year Old	$8.7x10^1$	-	$1.9x10^2$	$6.7x10^1$	$1.4x10^1$	$6.4x10^1$	$1.0x10^1$
One Year Old	$7.9x10^1$	-	$1.6x10^2$	$6.0x10^1$	$1.3x10^1$	$5.7x10^1$	$8.3x10^0$
Newborn	$3.1x10^0$	-	$9.4x10^0$	$3.1x10^0$	$6.5x10^1$	$3.2x10^0$	$1.2x10^{-}$

TABLE IV-13

RADIOIODINE AND RADIOTELLURIUM THYROID ABSORBED DOSE COMMITMENT PER UNIT ACTIVITY INTAKE (rad μCi^{-1}) AND CORRESPONDING AGE

Rongelap Island

Age	I-135	I-134	I-133	I-132	I-131	Te-132	Te-131m
Adult Male	0.056	0.0025	0.26	0.013	1.4	0.22	0.16
Adult Female	0.067	0.0035	0.31	0.015	1.7	0.25	0.19
Fourteen Year Old	0.10	0.0041	0.46	0.022	2.5	0.38	0.29
Twelve Year Old	0.12	0.0053	0.56	0.027	2.9	0.46	0.33
Nine Year Old	0.16	0.0077	0.75	0.036	3.8	0.61	0.43
Six Year Old	0.21	0.011	1.0	0.048	4.8	0.81	0.55
One Year Old	0.49	0.026	2.3	0.11	11	1.9	1.3
Newborn	0.62	0.032	3.0	0.14	15.	2.4	1.7
In Utero, 3rd tri.*	0.042	0.0021	0.21	0.0089	1.0	0.15	0.11
In Utero, 2nd tri.*	0.12	0.0050	0.54	0.022	2.5	0.37	0.29
In Utero, 1st tri.*	-	-	-	-	-	-	-

*Per Unit Activity Intake of the Mother

TABLE IV-14

ESTIMATED RADIOIODINE AND RADIOTELLURIUM THYROID ABSORBED DOSE (rad)

AND CORRESPONDING AGE

Age	I-135	I-134	I-133	I-132	I-131	Te-132	Te-131m	Total
Rongelap Island								
Adult Male	1.9×10^{2}	3.0×10^{0}	5.5×10^{2}	7.3×10^{0}	1.3×10^{2}	1.2×10^{2}	1.3×10^{1}	1.0×10^{3}
Adult Female	2.0×10^{2}	3.5×10^{0}	5.7×10^{2}	7.4×10^{2}	1.4×10^{2}	1.2×10^{2}	1.3×10^{1}	1.1×10^{3}
Fourteen Year Old	2.8×10^{2}	4.0×10^{0}	7.5×10^{2}	1.0×10^{1}	2.0×10^{2}	1.7×10^{2}	1.9×10^{1}	1.4×10^{3}
Twelve Year Old	3.0×10^{2}	4.8×10^{0}	9.1×10^{2}	1.1×10^{1}	2.1×10^{2}	1.9×10^{2}	1.9×10^{1}	1.6×10^{3}
Nine Year Old	3.7×10^{2}	6.2×10^{0}	1.1×10^{3}	1.4×10^{1}	2.4×10^{2}	2.3×10^{2}	2.3×10^{1}	2.0×10^{3}
Six Year Old	4.5×10^{2}	8.0×10^{0}	1.3×10^{3}	1.6×10^{1}	2.8×10^{2}	2.7×10^{2}	2.6×10^{1}	2.4×10^{3}
One Year Old	9.5×10^{2}	1.7×10^{1}	2.8×10^{3}	3.4×10^{1}	5.8×10^{2}	5.7×10^{2}	5.7×10^{1}	5.0×10^{3}
Newborn	4.9×10^{1}	8.3×10^{-1}	1.4×10^{2}	1.8×10^{0}	3.3×10^{1}	2.3×10^{1}	3.1×10^{0}	2.5×10^{2}
In Utero, 3rd tri.	1.3×10^{2}	2.1×10^{0}	3.8×10^{2}	4.4×10^{0}	8.4×10^{1}	7.2×10^{1}	7.8×10^{0}	6.8×10^{2}
Sifo Island								
Adult Male	6.7×10^{1}	2.0×10^{0}	1.5×10^{2}	1.6×10^{0}	2.8×10^{1}	2.9×10^{1}	3.8×10^{0}	2.8×10^{2}
Adult Female	6.7×10^{1}	2.3×10^{0}	1.6×10^{2}	1.5×10^{0}	2.9×10^{1}	3.0×10^{1}	4.0×10^{0}	2.9×10^{2}
Fourteen Year Old	9.9×10^{1}	2.6×10^{0}	2.2×10^{2}	2.2×10^{0}	4.0×10^{1}	4.2×10^{1}	5.8×10^{0}	4.1×10^{2}
Twelve Year Old	1.1×10^{2}	3.1×10^{0}	2.4×10^{2}	2.4×10^{0}	4.4×10^{1}	4.5×10^{1}	5.9×10^{0}	4.5×10^{2}
Nine Year Old	1.3×10^{2}	4.0×10^{0}	2.9×10^{0}	2.9×10^{0}	4.9×10^{1}	5.3×10^{1}	6.9×10^{0}	5.4×10^{2}
Six Year Old	1.5×10^{2}	5.2×10^{0}	3.5×10^{2}	3.5×10^{0}	5.8×10^{1}	6.3×10^{1}	7.7×10^{0}	6.4×10^{2}
One Year Old	3.3×10^{2}	1.1×10^{1}	7.1×10^{2}	7.4×10^{0}	1.2×10^{2}	1.4×10^{2}	1.7×10^{1}	1.3×10^{3}
In Utero, 2nd tri.	1.2×10^{2}	3.4×10^{0}	2.7×10^{2}	2.2×10^{0}	4.3×10^{1}	4.4×10^{1}	6.1×10^{0}	4.9×10^{2}
Utirik Island								
Adult Male	7.8×10^{0}	-	8.3×10^{1}	1.4×10^{0}	3.2×10^{1}	2.4×10^{1}	2.7×10^{0}	1.5×10^{2}
Adult Female	8.0×10^{0}	-	8.7×10^{1}	1.5×10^{0}	3.4×10^{1}	2.4×10^{1}	2.7×10^{0}	1.6×10^{2}
Fourteen Year Old	1.2×10^{1}	-	1.2×10^{2}	2.1×10^{0}	4.8×10^{1}	3.5×10^{1}	3.8×10^{0}	2.2×10^{2}
Twelve Year Old	1.2×10^{1}	-	1.3×10^{2}	2.3×10^{0}	5.2×10^{1}	3.8×10^{1}	4.0×10^{0}	2.4×10^{2}
Nine Year Old	1.6×10^{1}	-	1.7×10^{2}	2.8×10^{0}	5.7×10^{1}	4.5×10^{1}	4.7×10^{0}	3.0×10^{2}
Six Year Old	1.8×10^{1}	-	1.9×10^{2}	3.2×10^{0}	6.7×10^{1}	5.2×10^{1}	5.5×10^{0}	3.4×10^{2}
One Year Old	3.9×10^{1}	-	3.7×10^{2}	6.6×10^{2}	1.4×10^{2}	1.1×10^{2}	1.1×10^{1}	6.6×10^{2}
Newborn	1.9×10^{0}	-	2.8×10^{1}	4.3×10^{-1}	9.8×10^{0}	7.7×10^{0}	2.0×10^{-1}	4.8×10^{1}
In Utero, 3rd tri.	5.0×10^{0}	-	5.6×10^{1}	8.9×10^{-1}	2.0×10^{1}	1.5×10^{1}	1.5×10^{0}	9.8×10^{1}
In Utero, 2nd tri.	1.4×10^{1}	-	1.5×10^{2}	2.2×10^{0}	5.0×10^{1}	3.6×10^{1}	4.1×10^{0}	2.6×10^{2}

TABLE IV-15

TOTAL THYROID ABSORBED DOSE ESTIMATE, rads

Age	Rongelap Island			Sifo Island			Utirik Island		
	Internal	External	Total	Internal	External	Total	Internal	External	Total
ESTIMATE									
Adult Male	1000	200	1200	280	120	400	150	12	160
Adult Female	1100	200	1300	290	120	410	160	12	170
Fourteen Year Old	1400	200	1600	410	120	530	220	12	230
Twelve Year Old	1600	200	1800	450	120	570	240	12	250
Nine Year Old	2000	200	2200	540	120	660	300	12	310
Six Year Old	2400	200	2600	640	120	760	340	12	350
One Year Old	5000	200	5200	1300	120	1400	670	12	680
Newborn	250	200	450	-	-	-	48	12	60
In Utero, 3rd tri.	680	200	880	-	-	-	98	12	110
In Utero, 2nd tri.	-	-	-	490	120	610	260	12	270
MAXIMUM ESTIMATE									
Adult Male	4000	200	4200	1120	120	1200	600	12	610
Adult Female	4400	200	4600	1160	120	1300	640	12	650
Fourteen Year Old	5600	200	5800	1600	120	1700	880	12	890
Twelve Year Old	6400	200	6600	1800	120	1900	960	12	970
Nine Year Old	8000	200	8200	2200	120	2300	1200	12	1200
Six Year Old	9600	200	9800	2600	120	2700	1400	12	1400
One Year Old	20000	200	20000	5200	120	5300	2700	12	2700
Newborn	1000	200	1200	-	-	-	190	12	200
In Utero, 3rd tri.	2700	200	2900	-	-	-	390	12	400
In Utero, 2nd tri.	-	-	-	2000	120	2100	1000	12	1000

Table IV-16

(to be done)

TABLE IV-17

SUMMARY OF THYROID DATA

Age at Exposure	Total Number	Nodules(A)	No. with Carcinoma	Expected Nodules(B)	Expected Cancers(C)	Mean Adsorbed Dose, rads	Mean Time at Risk (Cancer), years	Mean Nodule Risk, no. per 10^6 per rad per year	Mean Cancer Risk, no. per 10^6 per rad per year
Rongelap									
In Utero	3	2	0	0.079(C)	0.026(C)	600	23(-)	46	-
<10	19	15	1	0.50	0.17	4000	13(15)	15	0.73
10-18	11	3	1	0.84	0.14	1700	17(22)	6.8	2.1
>18	32	3	2	2.8	0.22	1300	17(13)	0.28	3.3
All Ages	65	23	4	4.2	0.56	2100	15(16)	9.2	1.6
Sifo									
In Utero	1	0	0	0.026(C)	0.0087(C)	610	-(-)	-	-
<10	7	2	0	0.18	0.061	1100	22(-)	11	-
10-18	-	-	-	-	-	-	-(-)	-	-
>18	11	4	0	0.98	0.075	410	18(-)	37	-
All Ages	19	6	0	1.2	0.15	670	19(-)	20	-
Utirik									
In Utero	8	0	0	0.21(C)	0.070(C)	130	-(-)	-	-
<10	54	4	1	1.4	0.47	490	25(21)	3.9	0.95
10-18	19	4	0	1.4	0.24	220	22(-)	28	-
>18	86	9	1	7.7	0.59	170	22(22)	4.0	1.3
All Ages	167	17	2	11	1.4	280	23(21)	5.6	0.61
All Exposed									
In Utero	12	2	0	0.32(C)	0.10(C)	290	23(-)	21	-
<10	80	21	2	2.1	0.70	1400	16(18)	10	0.65
10-18	30	7	1	2.2	0.38	760	20(22)	16	1.2
>18	129	16	3	11	0.89	470	20(16)	4.1	2.2
All Ages	251	46	6	16	2.1	790	18(18)	8.4	1.1

(A) Includes some cases not surgically treated.
(B) Based on prevalence in unexposed Marshallese.
(C) Based on age less than ten prevalence.

FIGURE IV-1

Activity vs. Granual Diameter For Bikini Ash

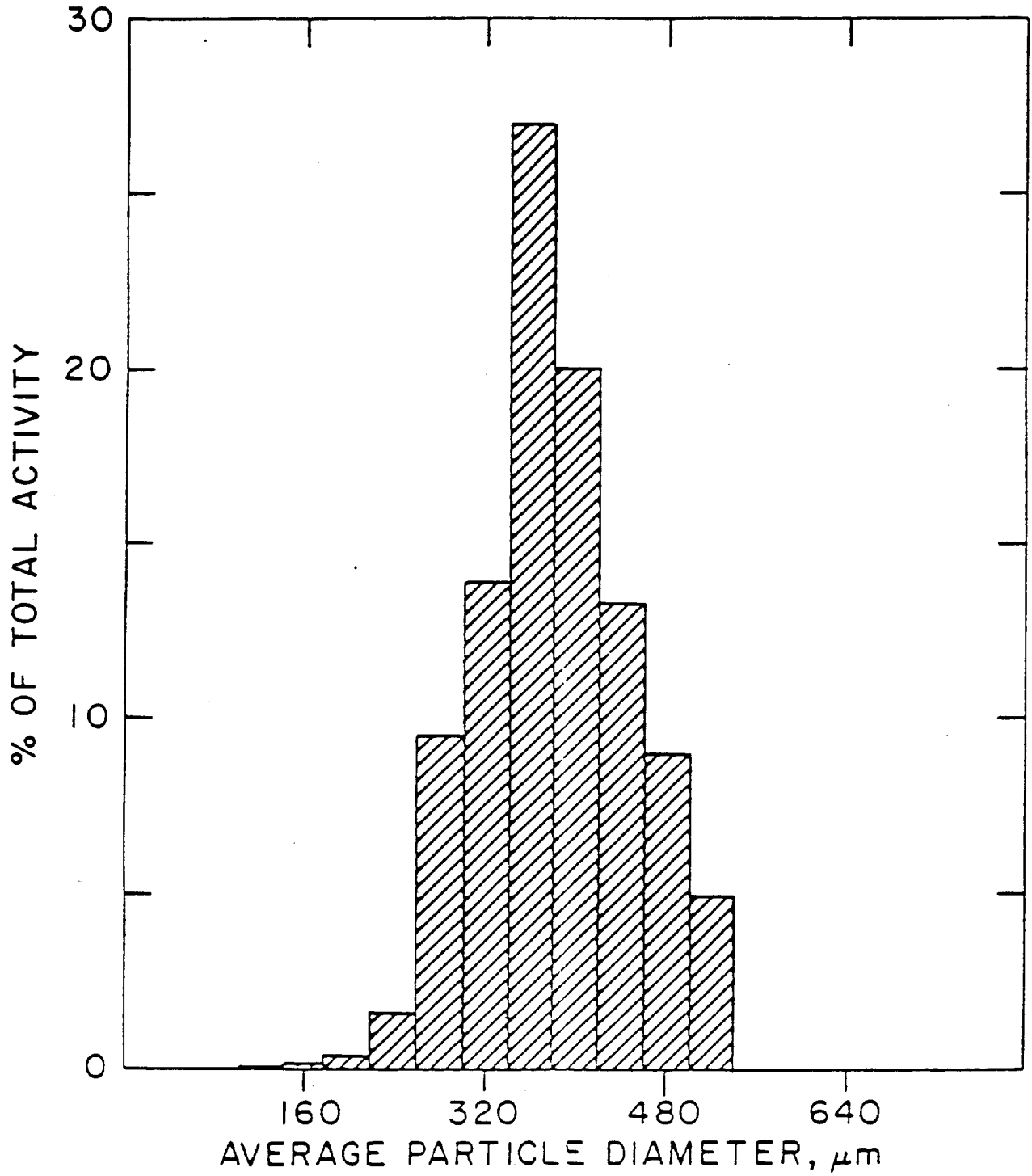


FIGURE IV-2

Cumulative % Of Activity Deposited On The 5th Lucky Dragon vs. Time Post BRAVO Detonation

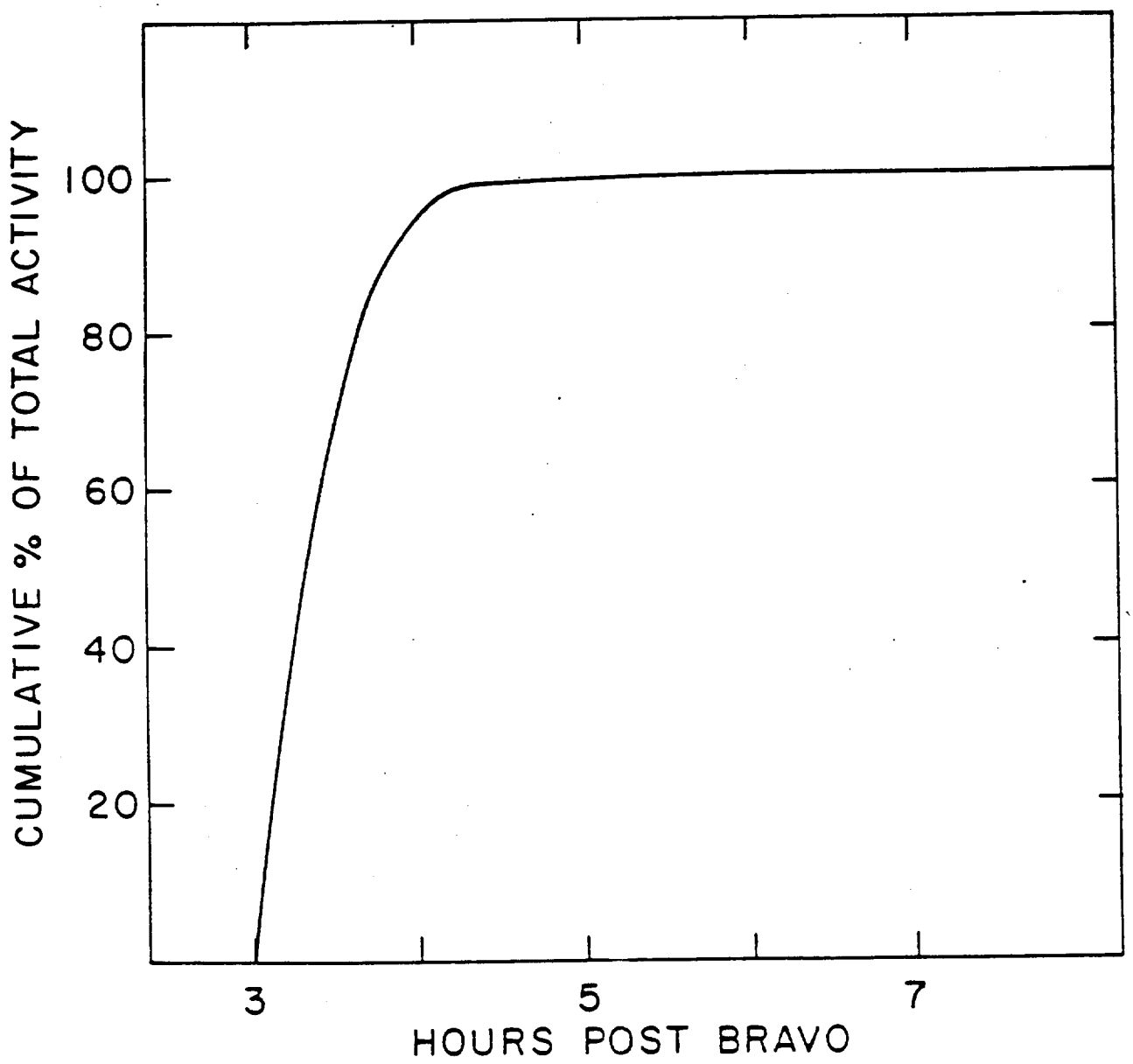


FIGURE IV-3

Activity vs. Granual Diameter For Rongelap Island Fallout

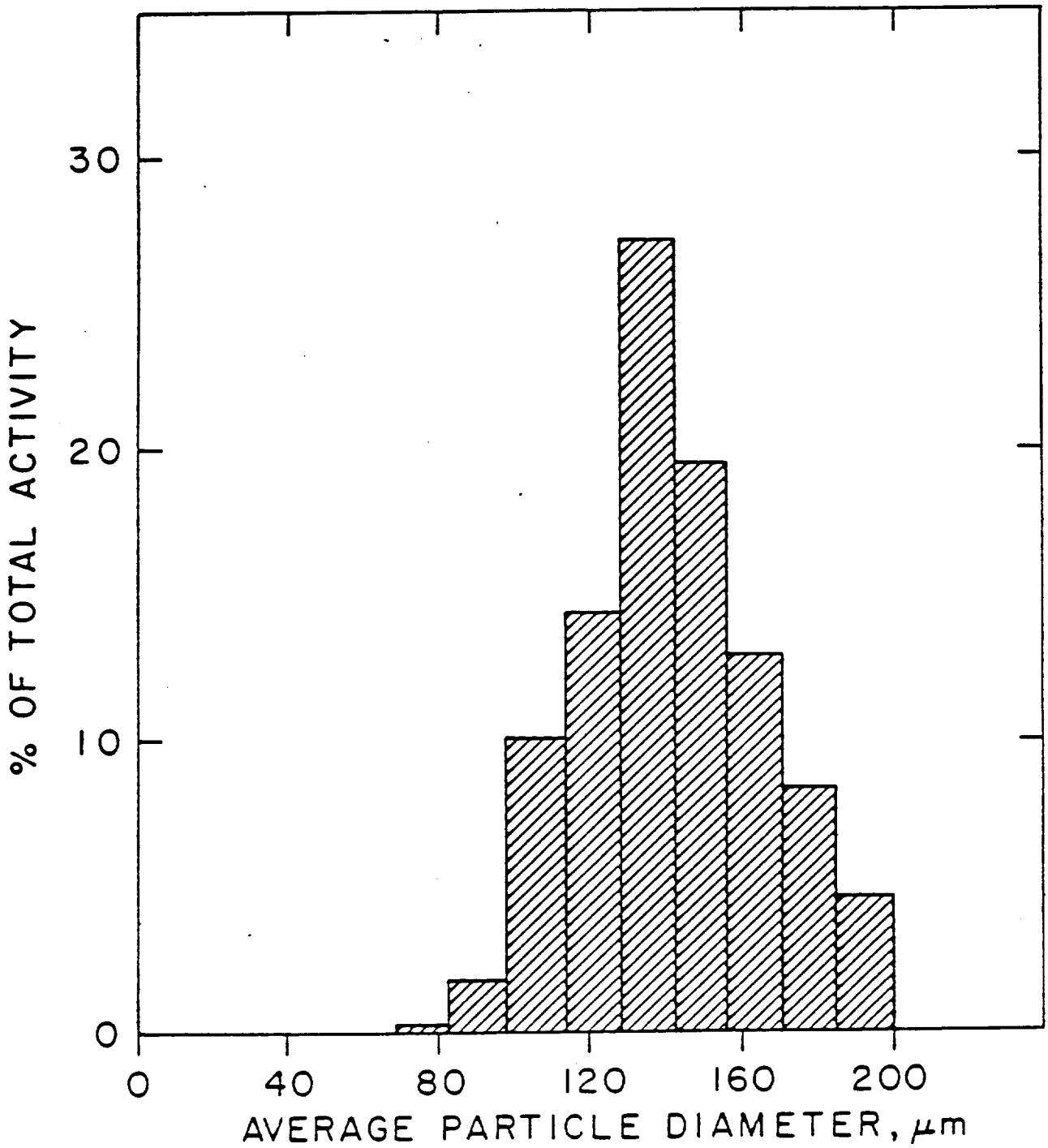


FIGURE IV-4

Cumulative % Of Activity Deposited On Rongelap Island, Rongelap Atoll vs. Time Post BRAVO Detonation

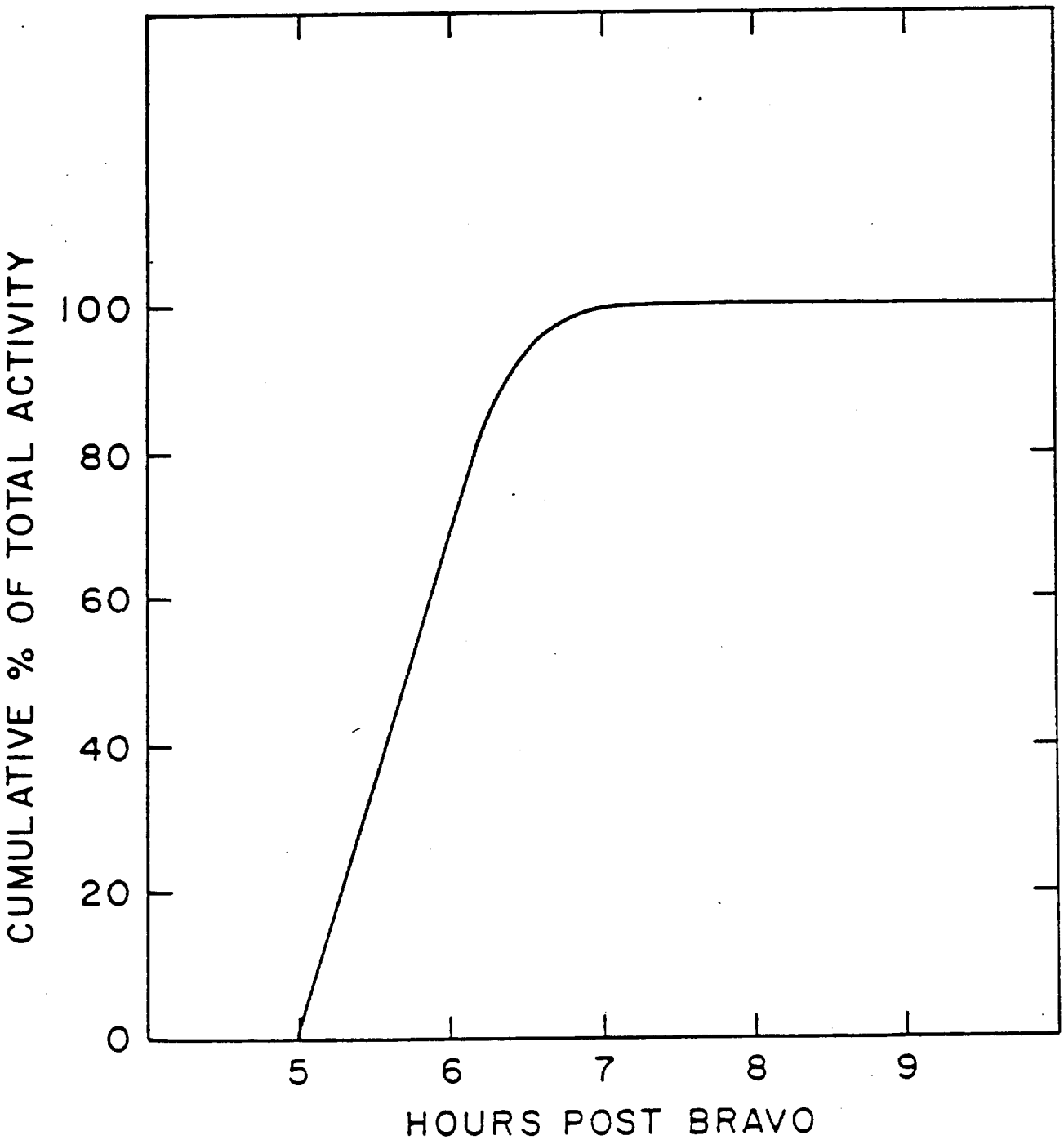


FIGURE IV-5

Activity vs. Granule Diameter For Utirik Island Fallout

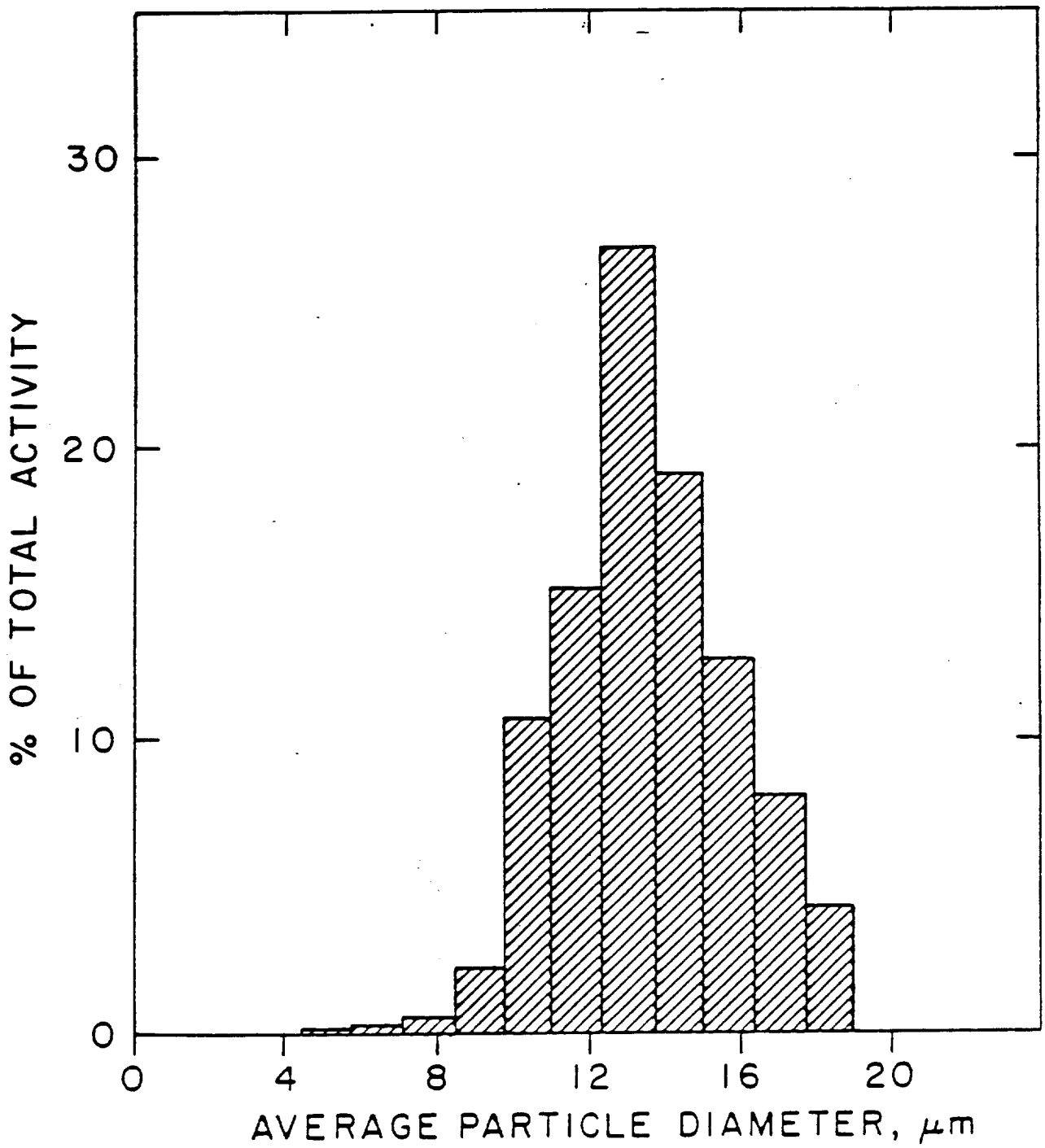


FIGURE IV-6

Cumulative % Of Activity Deposited On Utirik Island,
Utirik Atoll vs. Time Post BRAVO Detonation

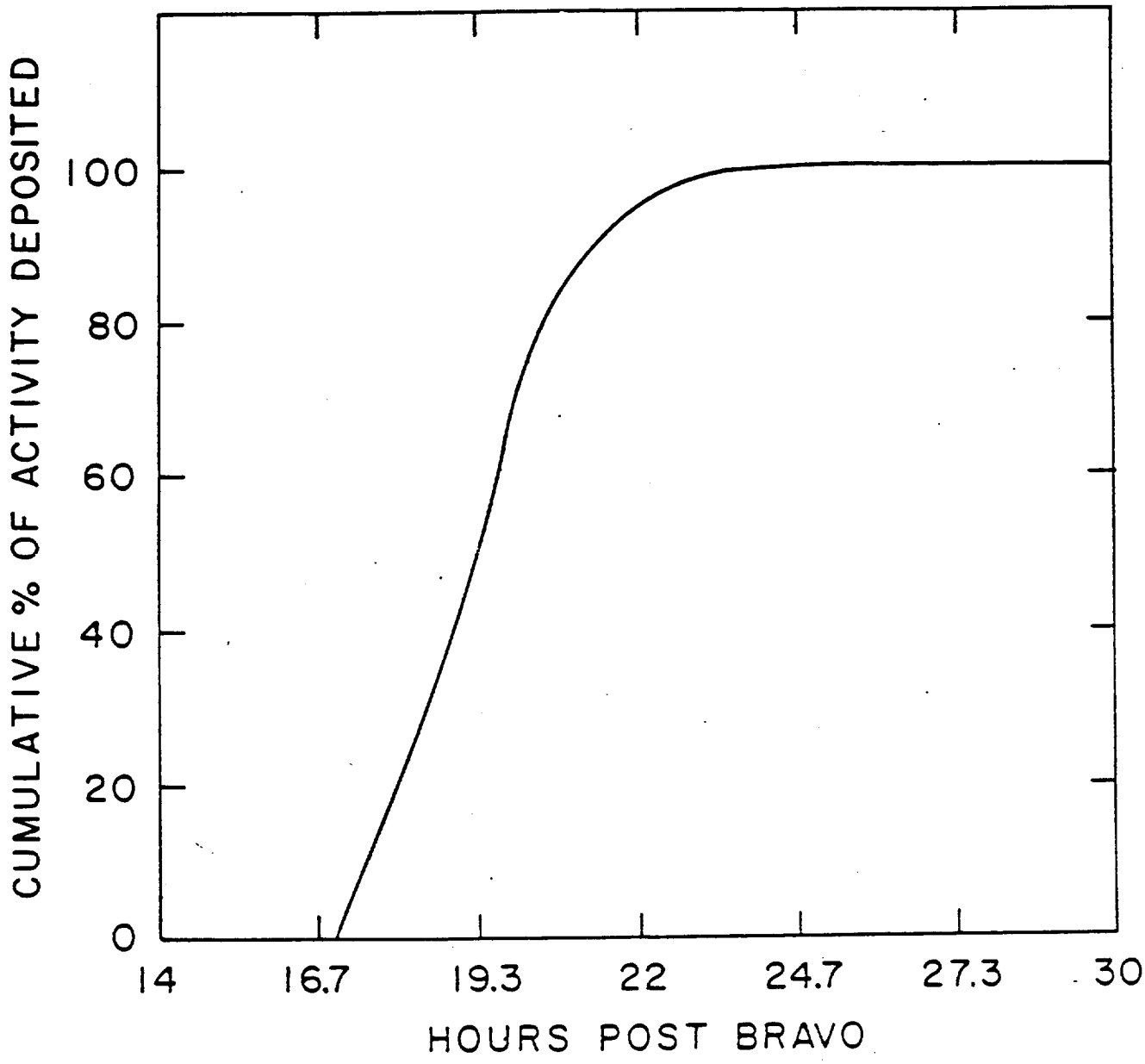


FIGURE IV-7

Exposure Rate Histories For Rongelap, Sifo And Utirik Islands Based On Bikini Ash Characteristics

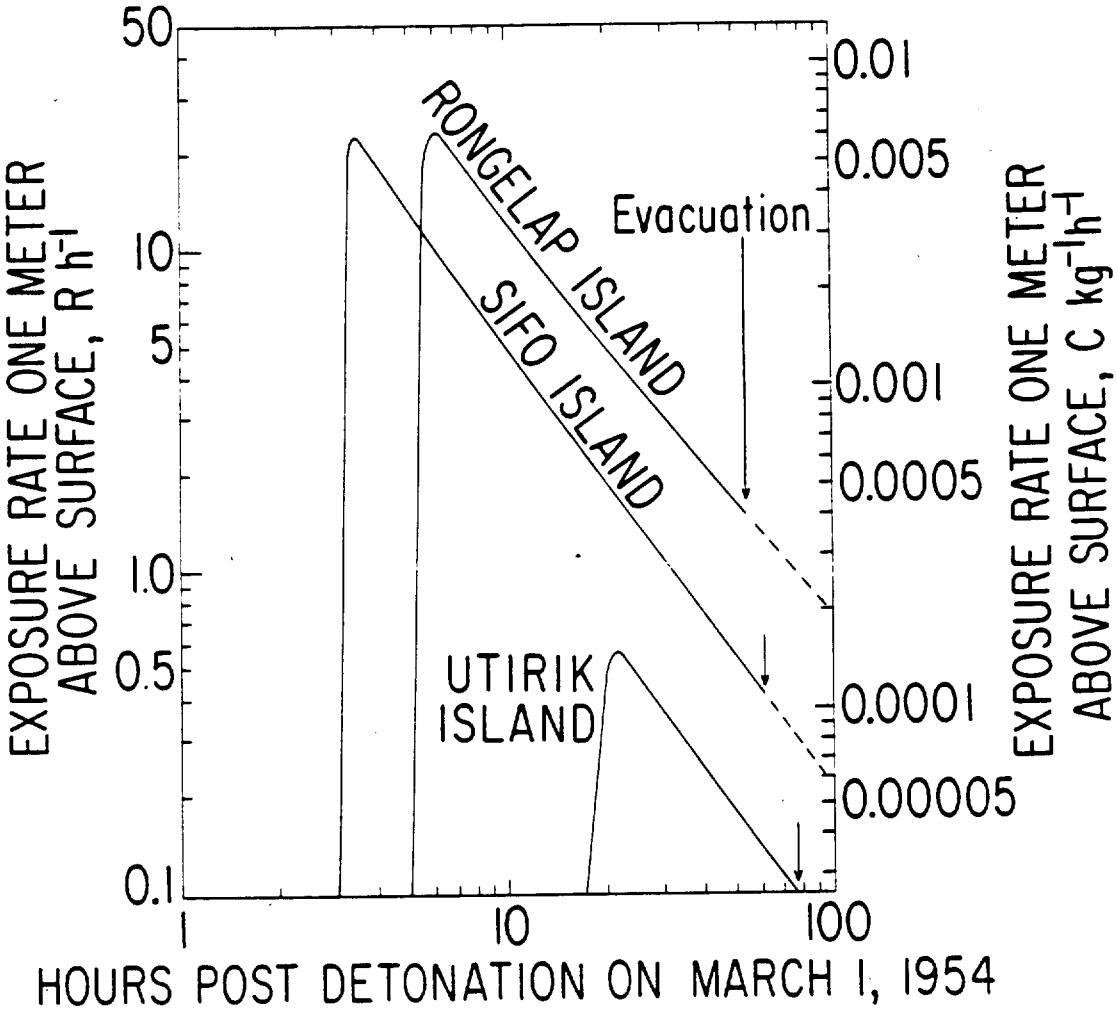


FIGURE IV-8

A Cistern At Rongelap Island

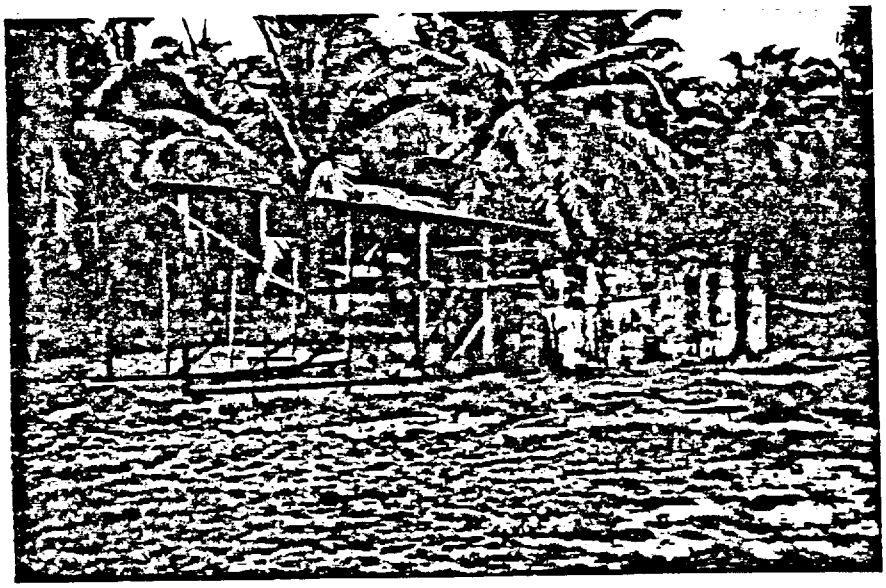


FIGURE IV-9

Food Prepared And Consumed Outdoors

FIGURE IV-10

Food Prepared And Consumed Outdoors

FIGURE IV-11

Food Prepared Outdoors

FIGURE IV-12

Food Prepared Outdoors

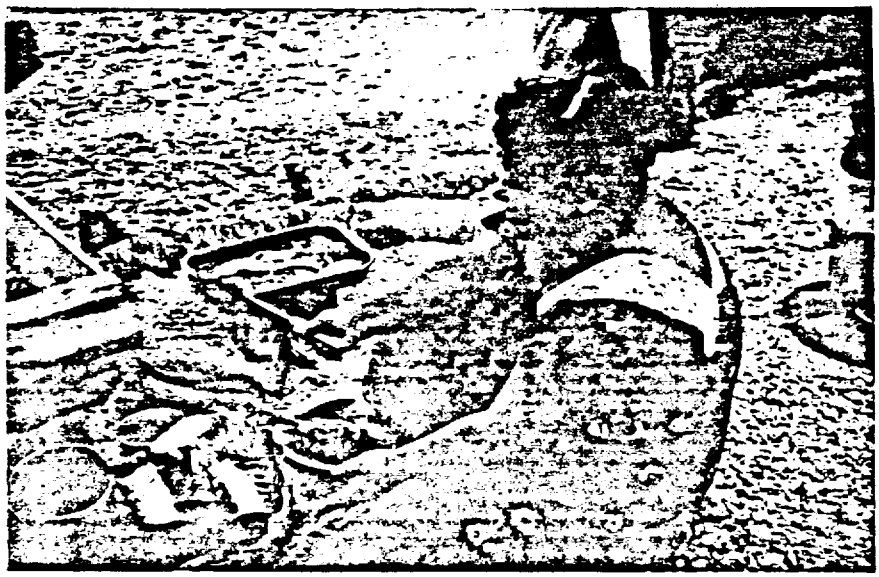


FIGURE IV-13

Food Prepared Outdoors

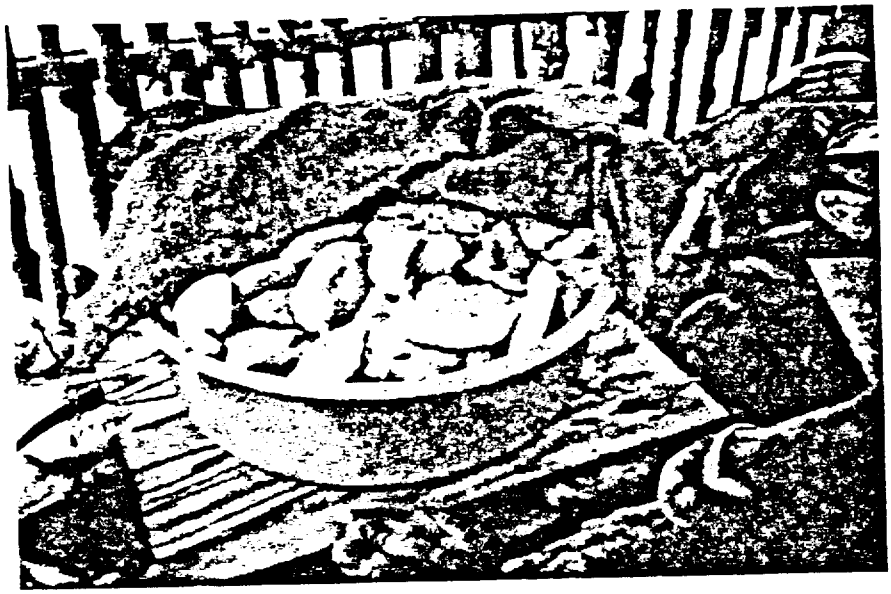


FIGURE IV-14

Food Prepared Outdoors

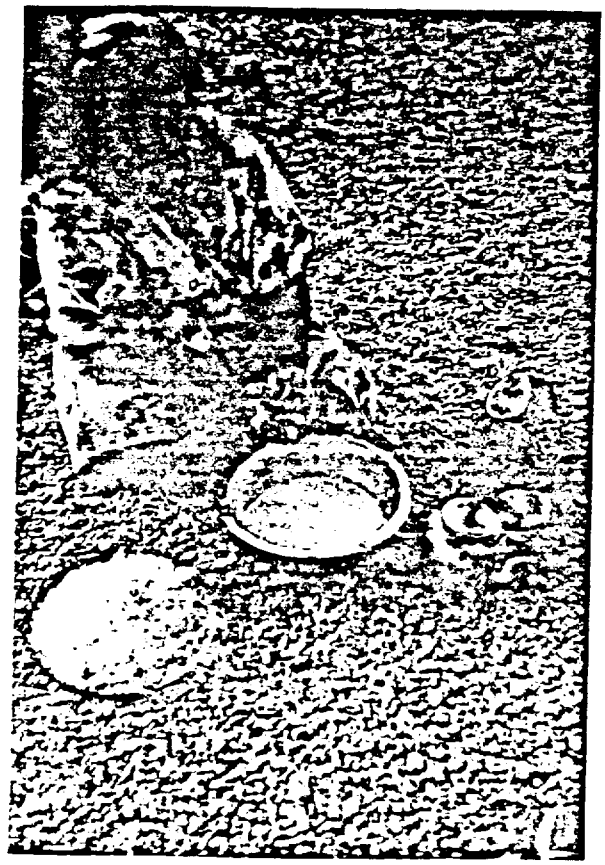


FIGURE IV-15

Food Prepared Outdoors

FIGURE IV-16

Food Prepared Outdoors

FIGURE IV-17

Food Consumed Outdoors

FIGURE IV-18

Food Prepared Outdoors

Question 1

Are there any components of your program which should be expanded, reduced, or eliminated in FY 1984 so as to aid the MIG in a transition program?

The Radiological Safety Program should be expanded in FY 1984 and 1985 to include periodic body-burden data collection and analyses for the Enewetak people at Ujelang. Should the Bikini people return to Bikini Atoll, the program should be expanded to evaluate these people annually. Assuming a whole-body counting unit is to be installed in Majuro, the 1985-1986 budget would have to increase to include costs of construction, installation, operation and calibration. Expanding the laboratory program to train a Marshallese Radiochemist and Health Physicist over a period of three years would aid in the transition to MIG at some future time. Dose reassessment should be expanded to include persons who resided at Likiep Atoll. Additional urine bioassay collection should be done for former Bikinians to define long-term retention of Pu. Reducing or eliminating any of the present elements of the Safety and Environmental Protection Division's Programs would be counter to responsibilities obligated in Public Laws 68-330, 78-598, 95-134 and 96-205. Reduction or elimination of program components would hinder the MIG in assuming its responsibility if required to do so by Agreement 177 of the Compact of Free Association.

Question 2

What components of your program would you suggest the Marshall Islands Government continue to carry out on its own? For how long? Why? Are there other organizations (U.S. or foreign) which you know to have the capability to carry out elements of your program?

The primary obligations, carried out by the Division were assigned by the AEC (now DOE) and they are (1) to diagnose and treat possible effects of radiation exposure at Rongelap and Utirik Atolls and (2) provide baseline and periodic radiological screening and dose assessment for persons who may reside at Bikini and Enewetak Atolls. Evaluating radiation exposure and potential health effects to persons who reside at these places requires (1) periodic body-burden data collection and analysis, (2) development and maintenance of a radiological data base, (3) retrospective dose assessment and (4) correlation of dose with incidence of disease. Carrying out a routine program of radiological protection at Rongelap, Utirik, Bikini or Enewetak requires these four elements because living patterns leading to exposure to radiological hazards are unique and unprecidented.

These program elements should definitely be continued at Enewetak, Rongelap, Utirik and Bikini (should Bikini Atoll be reinhabitated). Maintenance of these programs should continue until body burdens stabilize and doses are established for all radionuclides including Pu. This could be 1-3 years in the cases of Rongelap and Utirik, 2-4 years for Bikini and several years (up to 10) for Enewetak or 2-3 years past the time when all indigenous food products are available at Enewetak for daily consumption.

In addition, certain peoples at Rongelap and Utirik should be followed over their lifetime if they were exposed to high levels of radiation in 1954. A study of residual radiation and health effects from residual radiation has been performed since 1954 in order to meet the primary obligation assigned by the AEC. The dose since rehabitation of Utirik in 1954, and Rongelap in 1957 is known for most nuclides, however, data regarding Pu is being assembled now. Sequential sampling of urine for Pu will be required during the next few years in order to assess the intake regime and dose.

The Division's Marshall Islands Programs use state-of-the-art computers and radiation detection devices at the Laboratory and in the field. Multi-disciplinary scientists and technicians are employed to insure the success of remote and laboratory operations. At the Laboratory three radiochemistry laboratories, an anthropomorphic calibration facility, internal dose expertise and an ultra low-level alpha and gamma spectroscopy facility are maintained. Two portable whole-body counting systems with backup repair kits are maintained for field use. The Pu analysis program requires the use of the High Flux Beam Reactor and ultra-pure chemicals. A large computer data base is used to store records and clerical, graphic arts and publishing facilities are required often. The U.S. National Laboratories possess most of these elements. Foreign government laboratories such as the Institute of Atomic Energy, People's Republic of China possess similar elements which are used as a national resource like those in the U.S..

The following private organizations are capable of performing several elements of the program:

1. Whole Body Counting:

   Nuclear Data Incorporated, Schaumberg, Illinois

   Radiation Management Corporation, Philadelphia, Pennsylvania

   Helgeson, Plainville, California

2. Urine Bioassay (except Pu), a few of the many organizations are:

   Radiation Management Corporation, Philadelphia, Pennsylvania

   Eberline, Santa Fe, New Mexico

Controls for Environmental Pollution Incorporated, Sante Fe, New Mexico

3. Pu Analysis, the sensitivity requirement can be achieved by:

   Chem Nuclear Systems, Barnwell, South Carolina

4. Internal Dosimetry, the above organizations plus:

   K. W. Skrable, University of Lowell, Lowell, Massachusetts

   J. W. Poston, Georgia Institute of Technology, Atlanta, Georgia

5. Linking Medical and Dose Data:

   Epidemiology Resources, Berkeley, California

Question 3

What elements of your program are not directly related to statutory obligations? In your opinion, for each such element, should it be continued? By whom? Why?

There are no components of the Safety and Environmental Protection Division's Marshall Islands Programs which are not directly related to statutory obligations. Diagnosis and treatment of possible effects of radiation exposure require that the exposure be evaluated (see Public laws 68-330, 78-590, 95-134). The most recent statute, Public Law 96-205, is not free from ambiguity but the least it provides for is radiological screening, dose assessment, medical care and environmental research for people who may reside at Rongelap, Utirik, Bikini and Enewetak Atolls.

Question 4

What would you propose your FY 1985 program consist of and how does this differ from your 1984 plan?

The FY 1985 program would consist of a whole-body counting and a urine collection field program at Enewetak and Rongelap and a urine bioassay collection from former Bikini residents either at Majuro or Kili. Bioassay for Pu would continue at the Laboratory on about 1000 urine and stool samples. This differs from FY 1984 in regard to location of field work; that is, emphasis will shift from Utirik back to the former Bikini residents since current results confirm residual Pu activity due to living at Bikini Atoll, necessitating a dose assessment. The determination of long-term Pu retention in former Bikinians impacts on retrospective and prospective dose assessment for the residents at Rongelap, Utirik and Enewetak. Performing urine collection and analysis for Pu may be advisable also for residents of islands identified in the 13 atolls surveyed in 1978. During FY 1985, increased activity should occur in the areas of management training of the Marshallese and training for technical execution of the program to insure proper implementation of a radiation protection program by the MIG. Over the next few years it will be our intention to guide the Marshallese to the point where they will manage and execute the programs on their own.

Question 5

Is it feasible to transfer (a) management responsibility and (b) technical performance responsibility for your program elements to the MIG beginning in FY 1985? Reasons for your answer?

Management of the Marshall Islands Radiological Safety Program and the Rongelap and Utirik Thyroid Dose Reassessment Program are under the direction of Victor Bond, Charles Meinhold, John Baum and Edward Lessard. Technical performance is the responsibility of Edward Lessard, Robert Miltenberger, Anant Moorthy, Stephen Musolino and Carl Schopfer. Technical support is derived from eleven other members of the

Safety and Environmental Protection Division staff. A biographical sketch of the above people would include unique skills and hundreds of man-years of specialized education, training and experience. The MIG has no comparable management or technical staff. The MIG has no whole-body counting and bioassay facilities. It will not be feasible to transfer responsibility for radiological screening or dose assessment in FY 1985. A transfer would have to be between BNL and a comparable organization since it is a mutual interaction. Selected representatives of the MIG could be trained to do most of the work but not by the end of FY 1985. If training began in FY 1984, some elements of the program could be performed by MIG in FY 1985 if adequate consultation and equipment were also provided.

The MIG has only recently begun to tackle issues regarding community sanitation, unemployment, budget deficits, crime, etc. Although transfer is feasible, in light of other pressing problems, it is unlikely managment and technical performance of the radiological safety progam would be sustained by the MIG without first providing them with an intensive training program.

Question 6

Are there any program components that probably do not or would not directly benefit the affected peoples but are in your judgment necessary for our government or some other entity to carry forth for the possible long term benefit to science/mankind? Please discuss, and especially indicate what learned institution or society might agree.

Our investigations at Rongelap and Utirik are aimed at recording significant quantitative relationships between doses and observed incidence of any specific malignancy and this is of direct benefit to their health and safety. The radiation protection program for the people of Enewetak, Bikini, Rongelap and Utirik is designed

to prevent any unnecessary radiation exposure and this also directly benefits affected people.

Program accomplishments have benefited science/mankind because we developed relationships between thyroid dose and health effects from high levels of fallout, we developed a bioassay program to detect Pu due to exposures which occurred decades ago or due to long-term protracted exposure at very low levels, and we documented the development, implementation and dosimetric results of a radiation protection program following a nuclear weapons accident. These developments are particularly useful because thyroid and residual radiation dose modeling supports the DOE effort to assess fallout exposure in certain parts of the U.S.; the ultra-low level Pu measurement system would support a radiation protection program at U.S. weapons facilities; and the calibration techniques used over the years in the whole-body counting program illustrate changes in body-burden assessment practices, changes important for the protection of radiation workers. Carrying forth with new studies may prove beneficial, however, the basic radiation protection services approach does not give beforehand knowledge of the future benefits. The Marshall Islands situation is unique and further scientific inquiry would be encouraged by the Health Physics Society, United Nations Scientific Committee on the Effects of Atomic Radiation, National Academy of Sciences Committee on the Biological Effects of Ionizing Radiations, Radiation Research Society and other organizations which deal with questions on radiological health and safety.

Question 7

In general terms, under your 5-year plan, what are the estimated costs (in FY 1985 constant dollars) to DOE/Marshall Islands Government or some other funding entity? Also include a brief one paragraph summary of program content for every FY.

	Critical Program Components	FY 1985	FY 1986	FY 1987	FY 1988	FY 1989
1.	Materials, Supplies and Travel	88K	same as FY 1985	same as FY 1985	same as FY 1985	same as FY 1985
2.	Technical Services	17K	"	"	"	"
3.	Computer	13K	"	"	"	"
4.	Scientific and Professional Labor	203K	"	"	"	"
5.	Other Direct Labor	109K	"	"	"	"
6.	Overhead	190K	"	"	"	"
7.	Capital Equipment	80K	"	"	"	"
8.	Transition Costs	80K	580K	80K	40K	0

During FY 1985, a bioassay mission will occur at Rongelap, Enewetak, and at locations of the former Bikini residents. Body burdens for Bi-207, Cs-137, Co-60 and Pu will be assessed. Dose reassessment will expand to include persons who resided at Likiep Atoll during 1954. Equipment will be purchased to automate track etch analysis for Pu. Efforts to enhance the link between medical and dose data will continue. Information regarding radiological screening results and demographic data will continue to be computer based. Studies of long-term Pu retention in former Bikini residents will continue. Initial transition costs would support one year of training a Health Physicist and one year of training a Radiochemist.

During FY 1986 a bioassay mission will occur at Utirik, Ujelang, Enewetak and Likiep. Body burdens from Bi-207, Cs-137, Co-60, and Pu will be determined. Program costs (1-7 above) during FY 1986 through FY 1989 are estimated to be similar to FY 1985 (in FY 1985 constant dollars). Radiological results will be computer based. Dose

reassessment will be extended to appropriate locations based on results of previous Pu bioassays. A whole-body counting unit will be constructed at Majuro along with computer facilities to handle the data base. A radiochemistry lab will be constructed at Majuro for urine bioassays of gamma emitters. A Health Physicist and Radiochemist will continue to train. Costs for these transition items are indicated in Number 8 above. It is to be emphasized that these transition costs are in addition to 1985-1989 normal program costs (1-7 above).

During FY 1987 a summary of dose reassessment will be completed for Likiep and other atolls of interest. A bioassay mission to Enewetak and the locations of former Bikinians will be performed. Radiological experience at Enewetak and Bikini will be summarized. Training will continue and the Majuro radiation protection facilities made operational.

During FY 1988, a bioassay mission to Rongelap, Utirik, and Enewetak will be performed. Long-term retention exhibited by former Bikinians will be factored into dose assessment models. Whole-body counting calibration and comparison between the MIG unit and Laboratory units will be performed. Transition costs account for this intercomparison and calibration. Training will be finalized.

During 1989, a mission to Enewetak will occur. Whole-body counting, bioasssay of urine and computer updating will continue. Efforts to link medical and dose data will continue.

Advantages for MIG to exercise buy-back options include no startup costs, no transition costs, no hiring of permanent employees and availability of state-of-the-art research facilities. Advantages for the U.S. to maintain these programs include collection of long-term health and radiological data regarding exposure to fallout and no expenditure for transition costs. The techniques and expertise developed in the course of

U.S. supported studies could be used to assess doses to populations in other areas subjected to exposure from fallout or even those resulting from occupational situations. These studies also provide for upgrading long range predictive dose modeling activities such as those of Lawrence Livermore National Laboratories.

There are no non-critical program components. The number of full time employees supported by the FY 1985 program costs (1-7 above) in 6.5.

PROTRACTED EXPOSURE TO FALLOUT: THE RONGELAP AND UTIRIK EXPERIENCE

E.T. Lessard, R.P. Miltenberger, S.H. Cohn,

S.V. Musolino and R.A. Conard

Brookhaven National Laboratory

Upton, New York 11973

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. On March 1, 1954, BRAVO, an aboveground test in the Castle series, produced high levels of radioactive material, some of which subsequently fell on Rongelap and Utirik Atolls due to an unexpected wind shift. On March 3, 1954, the inhabitants of these atolls were moved out of the affected area. They were later returned, to Utirik in June 1954 and to Rongelap in June 1957. Comprehensive environmental and personnel radiological monitoring programs were initiated in the mid 1950's by Brookhaven National Laboratory to ensure that body burdens of the exposed Marshallese subjects remained within Atomic Energy Commission guidelines. Their body-burden histories and calculated activity ingestion rate patterns post return are presented along with estimates of internal committed effective dose equivalents. External exposure data are also included. In addition, relationships between body burden or urine activity concentration and declining continuous intake were developed. The implications of these studies are:

1) the dietary intake of ^{137}Cs was a major component contributing to the committed effective dose equivalent for the years after the initial contamination of the atolls,

2) for persons whose diet included fish, ^{65}Zn was a major component of committed effective dose equivalent during the first years post return,

3) a decline in the daily activity ingestion rate greater than that resulting from radioactive decay of the source was estimated for ^{137}Cs, ^{65}Zn, ^{90}Sr and ^{60}Co,

4) the relative impact of each nuclide on the estimate of committed effective dose equivalent was dependent upon the time interval between initial contamination and rehabitation, and

5) the internal committed effective dose equivalent exceeded the external dose equivalent by a factor of 1.1 at Utirik and 1.5 at Rongelap during the rehabitation period.

Few reliable ^{239}Pu measurements on human excreta were made. An analysis of the tentative data leads to the conclusion that a reliable estimate of committed effective dose equivalent requires further research.

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, 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 disclosedsed, 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, contractor or subcontractor thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency, contractor or subcontractor thereof.

Research carried out under the auspices of the U.S. Department of Energy, Contract No. DE-AC02-76CH00016.

INTRODUCTION

Subsequent to World War II, the United States carried out several series of atmospheric tests of nuclear weapons in the Northern Marshall Islands between the years 1946 to 1958. On March 1, 1954, at Bikini Atoll, BRAVO, the first of six nuclear weapons tests in the Castle series, was detonated. Due to an unanticipated wind shift, the BRAVO device produced substantial surface contamination on inhabited atolls up to 500 kilometers east of Bikini within a 5,000 square kilometer area. The contaminated region was cucumber shaped and falling bomb debris was visible on Rongelap Atoll from 5 to 10 hours after detonation (Gl62, Sh57).

Following a fallout alert by a Navy monitoring team stationed at nearby Rongerik Atoll, the 64 residents of Rongelap Atoll and an additional 18 Rongelapese who were gathering food nearby at Sifo Island, Ailinginae Atoll, were removed to Kwajalein Atoll, some 300 kilometers to the south on March 3, 1954. On March 3 and 4, removal of the more distant 157 Utirik Atoll residents was affected. 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 Atomic Energy Commission (and its successor organizations) and the Department of Defense has regularly conducted medical examinations to monitor the health and to evaluate the radiobiological status of persons affected by tropospheric fallout from the BRAVO nuclear test.

Reports of their findings including whole-body counting data and urine activity concentration data are available in Cr56, Du56, Du57, Wo59, Co56, 58, 59, 60, 62, 63, 65, 67, 70, 75, and Co80a. These reports may be consulted in order to easily follow the information presented here. Estimates of the initial body burdens of internal emitters were presented in Co55, Coh56 and Coh60 and will

not be discussed here. A reassessment of thyroid absorbed dose from the initial 1954 exposure is currently being made and will be reported in a separate study. Since April 1978, the bioassay program and whole-body counting studies have been performed by members of the Safety and Environmental Protection Division of Brookhaven National Laboratory. Reports of their findings may be found in Gr77a, Gr77b, Le80a, Le80b, Mi80, Mi81 and Na80. The report by Lessard (Le80b) contains more detail on the development of the equations used here.

The Utirik and Rongelap inhabitants were returned to their home atoll in June 1954 and in June 1957, respectively. The earlier repatriation of Utirik Atoll was based on the low measured level of external radiation exposure over a 3 month observation period. The Utirik population was subsequently examined by a Brookhaven medical team during 1957; 144 people received comprehensive physical examinations.

In 1957, the Rongelap inhabitants were also returned to the their atoll to occupy new homes, community structures and other facilities which had been constructed during their three year residence at Majuro and Kwajalein Atolls. Following the 1957 medical survey, measurements were made on two men from Utirik Atoll using the whole-body counter at Argonne National Laboratory. Radiochemical analyses of their urine samples were also made. Four persons from Rongelap Atoll also visited Argonne for whole-body counting in 1957. In addition, pooled urine samples from both atoll populations were analyzed radiochemically for ^{137}Cs and ^{90}Sr. The body burdens measured at Argonne National Laboratory were corrected for ten days of biologic elimination and radiologic decay in order to estimate the body burden while living on the atoll.

Starting in May 1958, Conard and Cohn (Co59), measured whole-body levels of ^{137}Cs, ^{65}Zn, and ^{60}Co in about 100 Rongelap adults, adolescents and juveniles

5

as part of the Brookhaven medical examination program. A portable whole-body counter with a standard chair geometry in a shielded steel room was employed (Coh63). Whole-body counts were obtained in the Rongelap and Utirik populations in 1959 (Co60), 1961 (Co62), 1965 (Co67), 1974 (Co75) and 1977 (Co80a). The counting geometry was converted to a scanning type shadow-shield geometry starting in 1965 (Co67). Urine samples were also collected in these surveys and in additional medical surveys conducted in intervening years. The samples were analyzed for their radiochemical content by both USNRDL and the NYO-AEC Laboratories.

From 1978 to the present time, whole-body counting measurements were performed with the bed type shadow shield whole-body counter (Co67). In 1980, a standard chair geometry was once again used. All three counting systems were intercalibrated and also calibrated against the large Brookhaven National Laboratory 54-detector whole-body counting facility to ensure consistency of the whole-body counting data over the past 28 years.

A summary of the sequence of events affecting the whole-body and urine activity measurements on the Rongelap and Utirik people is given in Fig. 1. The detonation of BRAVO in 1954 was followed by the evacuation of Rongelap Atoll at 2.2 days post detonation and then Utirik Atoll at 3.5 days post detonation. After a three month wait, the Utirik people returned in June 1954 and after three years Rongelap Atoll was rehabilitated and occupied in June 1957. Shortly after the Rongelap people's return, the first "in situ" whole-body counting survey was performed in 1958. The HARDTACK series of nuclear tests in 1958 were the final above-ground tests to be performed by the United States in the Marshall Islands. World-wide atmospheric testing of nuclear devices at other locations continued and peaked during the early 1960's. During the period 1958

through 1981 a total of eight whole-body counting surveys at Rongelap and five whole-body counting surveys at Utirik were performed.

METHODS

Body-Burden Data and Urine Activity Concentrations

Adult average body-burden data and urine activity concentration data were used as input quantities to equations which related them to activity intake rates. These input data were obtained from Conard's medical reports (Co56, 58, 59, 60, 62, 63, 67, 70, 75 and Wo59) and from recent surveys performed by members of the Safety and Environmental Protection Division of Brookhaven National Laboratory. The methods used to obtain the recent body-burden data were presented by Miltenberger (Mi80). The most recent average data obtained for adult body burden at Rongelap and Utirik are presented here. These data were obtained in April 1978, August 1979 and August 1981.

In the cases of ^{137}Cs, ^{60}Co and ^{65}Zn direct body-burden measurements were made. In the cases of ^{90}Sr and ^{239}Pu urine activity concentrations were measured and then converted to body-burden estimates. This was done by relating the activity in urine to the activity in the total body. For ^{90}Sr and ^{239}Pu this involved use of derived quantities which are developed in the next section.

Derived Quantities

An equation was developed to relate the activity in the urine or whole body to the activity taken in by ingestion of contaminated food and fluids. In order to select an appropriate model for this relationship, the body-burden history and the history of activity in vegetation and soil were examined. Activity concentrations of ^{137}Cs, ^{129}I, and ^{90}Sr in surface soil on Rongelap and Utirik Atolls were observed to decline with time at a rate greater than radioactive decay from 1954 to the present (Ne77, Ne79, Br82). Activity concentrations of ^{137}Cs and ^{90}Sr in vegetation were observed to decline at a rate greater than that predicted by radioactive decay alone (Ne77, Ne79). Body burdens and urine

activity concentrations were observed to increase rapidly and to decline slowly throughout the residence time of persons at Rongelap and Utirik Atolls (Co75, Le80b). These observations led to the selection of a declining continuous intake model.

An exponential decline in the amount of activity ingested each day from the dietary sources was assumed. The following general equations were derived (Le80b). They may be applied to each nuclide of concern:

$$\lambda P^{\circ} = \frac{\left(\frac{U\ U_s}{f_u}\right) - q^{\circ}\ \left(\Sigma_i\ k_i \chi_i'\ e^{-(\lambda+k_i)t}\right)}{f_1\ \left[\Sigma_i\ \frac{\chi_i k_i}{k_i - k}\ \left(e^{-(\lambda+k)t} - e^{-(\lambda+k_i)t}\right)\right]}\ , \qquad (1)$$

or

$$\lambda P^{\circ} = \frac{q - q^{\circ}\ \left(\Sigma_i \chi_i'\ e^{-(\lambda+k_i)t}\right)}{f_1\ \left[\Sigma_i\ \frac{\chi_i}{k_i - k}\ \left(e^{-(\lambda+k)t} - e^{-(\lambda+k_i)t}\right)\right]}\ , \qquad (2)$$

where

t ≡ time post onset of intake (time from day of return of each atoll population), d,

λ ≡ instantaneous fraction of atoms decaying per unit time, d^{-1},

P° ≡ initial daily atom ingestion rate on day of return, atoms s^{-1},

k_i ≡ instantaneous fraction of atoms removed from compartment i in the body by biological processes, d^{-1},

χ_i ≡ compartment i deposition fraction,

$\chi_i' \equiv$ the number of radioactive atoms in compartment i relative to the number in all compartments on the day of return (some persons returned with body burdens),

$U \equiv$ twenty-four hour or one liter urine activity concentration at any time post return, Bq ℓ^{-1},

$U_s \equiv$ subject urine excretion rate, $\ell\ d^{-1}$,

$f_1 \equiv$ fraction of element transferred from GI tract to blood,

$f_u \equiv$ fraction of element reaching extracellular fluid that is excreted through the urine pathway,

$k \equiv$ instantaneous fraction of atoms removed from the atom ingestion rate per unit time, d^{-1}, due to factors other than radioactive decay,

$q \equiv$ body burden at any time post return, Bq,

$q^\circ \equiv$ body burden on the day of return, Bq.

Using adult average data, two consecutive urine or body-burden measurements were used to estimate the unknown value of k, a rate constant describing removal of radioactivity in diet items. This yielded n-1 estimates of k where n was the number of measured adult average data points for body burden or urine activity concentration during the residence interval. An average value of k was assigned for the entire residence interval during which activity was measured. After the average k was obtained, an estimate of the atom ingestion rate on day of return was calculated based on a value for adult average body burden or urine activity concentration and the time since day of return. This generated n values of the atom ingestion rate on day of return where n was again the number of adult average data points for body burden or urine activity concentration.

As indicated by Eq. 1 or Eq. 2, a single exponential relationship was used to model the decline of radioactivity in diet items. Use of these equations led to an estimate of the dietary removal rate constant, k, over the entire residency interval. The average per cent decrease in the yearly activity ingested was determined from this dietary rate constant as follows:

$$\% = 100\ (1-e^{-(k+\lambda)t}) \qquad (3)$$

where

% ≡ average per cent decline in the atom ingestion rate during the residence interval.

The definitions of the other quantities in Eq. 3 were the same as previously given. The value of t was taken as 365 days and the % reflected the average yearly decline averaged throughout the interval over which a nuclide was observed in people. Thus for ^{137}Cs the average was for a period of 24 years at Rongelap and 27 years at Utirik.

In the development of the three equations several assumptions were made. For instance, decay of nuclides which were absorbed during transit through the stomach and small intestine was assumed to be negligible relative to their decay within the systemic organs. This was because of the long half-life of the nuclides relative to the transit time through the upper portion of the gastrointestinal tract. Urine activity and body-burden data were assumed to represent instantaneous values rather than incremental values. This was because the sampling periods for whole-body counting and urine collection were very short relative to the intake period. Additionally, one liter or 24 hour urine samples (which ever was less) were collected. This reduced the influence of biological variation of activity concentration between morning and evening voids. Since

urine activity concentration data were used in Eq. 1, urine excretion rates which were dependent on sex were adopted from data in ICRP Publication 23 (ICRP74).

Values for the quantities not measured directly and used in Eqs. 1 and 2 were taken from the literature (ICRP59, ICRP68, ICRP69, ICRP74, ICRP79, Ki78). Cobalt was assumed to be in the form of an organically complexed compound therefore f_1 was set at 0.3 (ICRP79). The value of f_1 for ^{239}Pu was taken as 10^{-4} (ICRP79). The longest term rate constant for ^{137}Cs was found to be a function of body mass. The value of this rate constant was adjusted for a sixty kilogram body mass according to formulas given by Miltenberger (Mi81). The single uptake whole-body retention functions given below for adults were based on ICRP models and were not corrected for radioactive decay. These functions, which were used for making an estimate of adult intake, were:

$$^{60}Co: \quad 0.5e^{-1.4t}+0.3e^{-1.2\times10^{-1}t}+0.1e^{-1.2\times10^{-2}t}+0.1e^{-8.7\times10^{-4}t},$$

$$^{137}Cs: \quad 0.1e^{-3.5\times10^{-1}t}+0.9e^{-8.3\times10^{-3}t},$$

$$^{65}Zn: \quad 0.24e^{-3.5\times10^{-2}t}+0.76e^{-1.7\times10^{-3}t},$$

$$^{90}Sr: \quad 0.73^{-3.3\times10^{-1}t} + 0.10e^{-2.3\times10^{-2}t} + 0.17e^{-2.5\times10^{-4}t},$$

$$^{55}Fe: \quad 1.0e^{-3.5\times10^{-4}t},$$

$$^{239}Pu: \quad 0.45e^{-1.9\times10^{-5}t}+0.45e^{-4.8\times10^{-5}t}+0.1e^{-0.33t},$$

where t was in days.

An average sixty kilogram adult body mass was chosen based on the values observed for male and female adult body weights in the study populations (Con56, Co58, 59, 60, 62, 63, 67, 70, 75 and Le80b).

An estimate of body burden for ^{239}Pu and ^{90}Sr was based on use of both Eqs. 1 and 2. The average dietary removal rate constant, k, was first determined using Eq. 1 and sequential urine activity concentration data. Once the average k was determined, Eqs. 1 and 2 were set equal to each other and the body burden was calculated for each urine measurement. After the body burden was determined, an estimate of P^{o} was made using Eq. 1 and the average value for k. In this way an average value for P^{o} was obtained from all the urine data.

In order to obtain the fifty-year cumulated intake, Eq. 2 was solved for q and the right hand side of the equation was integrated over an ingestion interval of fifty years. Total intakes were related to committed effective dose equivalents by using conversion factors "committed effective dose equivalent per unit activity ingested" given by the International Commission on Radiological Protection (ICRP79). Committed effective dose equivalent per unit activity ingested given by ICRP was multiplied by 1.17 to correct for body mass differences to yield committed effective dose equivalent per unit activity ingested by a Marshallese adult.

Statistical Analysis of Data

The adult average standard deviation for ^{137}Cs, ^{65}Zn or ^{90}Sr atom ingestion rate on the day of return, P^{o}, and the dietary removal rate constant, k, were determined from a set of calculated values derived from a set of adult body-burden measurements and Eq. 2. The standard deviation for the adult average fifty-year cumulated intake was determined by propagation of error techniques involving first and second order partial derivatives and partial cross de-

rivatives (Be69). To estimate the error, partial cross derivatives and partial derivatives were determined for k and P° with respect to the fifty-year cumulative intake.

Since only one measurement for adult average ^{55}Fe body burden was available, the relative standard deviation of the adult average P° was assumed to equal the relative standard deviation of individual adult P°'s which were determined from the 1970 individual adult ^{55}Fe body burdens. Only two values for the set of adult average ^{60}Co and ^{239}Pu body burdens were available and therefore the same method was employed to obtain adult average standard deviations for k and P°.

External Radiation Exposure

The external radiation exposure rate data were measured by many individuals and an explanation of their methods can be found in their reports (Ch60, He65, Gr77b, JCAE57, Ti81, USPHS59). A value of 2.8×10^{-8} Gy in tissue of interest per nC kg^{-1} (0.73 rad per R) measured in air at one meter above the surface was used to convert their data to absorbed dose in tissue. This factor was based on several considerations. First, the planar source represented by the flat atoll was assumed to be an exponential distribution of ^{137}Cs activity with depth in soil, typical of aged fallout (Be70). The nature of this source caused minimal variation of absorbed dose with depth of organ; however, the difference in the number of electrons per gram of air and per gram of tissue necessitated a correction. Secondly, since the atolls presented a varying exposure rate environment, absorbed dose was adjusted for living pattern variations. Both of these considerations combine to give the above factor used to convert external exposure to absorbed dose in tissue. Specific details on the adjustment for living pattern variation were given by Miltenberger and Greenhouse (Gr77b).

RESULTS

Body Burden Data and Urine Activity Concentrations

The average body-burden data for adults since their return to Rongelap and Utirik Atolls are presented in Tables 1 and 2. In these tables, the zero day or day of return for Utirik was nearly 1,000 days prior to the zero day or day of return for Rongelap. Directly measured body burdens were listed for ^{60}Co, ^{65}Zn and ^{137}Cs. For ^{137}Cs, an initial rise in body burden and a subsequent general decline was apparent. These data were plotted in Fig. 2 along with their standard deviation and standard error.

Conversion of adult average ^{90}Sr and ^{239}Pu urine activity-concentration data was done as indicated in the methods section in order to derive a body burden for these nuclides. Average data were listed in Tables 1 and 2 and plotted in the case of ^{90}Sr (see Fig. 3). The body burdens listed for ^{55}Fe were obtained from Beasley (Be72). The methods used to derive ^{55}Fe body burdens from blood measurements were given in Be72.

The most recent whole-body counting data available (1981) are presented in Table 3. Analysis of the data indicated that ^{137}Cs adult average body burdens at Rongelap and Utirik were from 40 to 90 times greater than those of a comparison population at Majuro, a southern atoll which received little fallout from testing (Le80c). The ^{40}K levels and corresponding potassium content were in close agreement with naturally occurring values developed from data in ICRP 23 (ICRP74).

Due to the paucity of early measurements of activity in Utirik residents (see Table 2), their ^{60}Co, ^{239}Pu, and ^{55}Fe body burdens were estimated by comparing nuclide ratios for Utirik and Rongelap residents. The measured body burdens for these nuclides in Rongelap residents and the observed atoll-to-atoll

ratios of adult average body burden for ^{65}Zn, ^{90}Sr, and ^{137}Cs were used in the calculation. Ratios were estimated for the period after the Rongelap adult body burdens reached a maximum value. The Rongelap-to-Utirik ratio, 2.6 ± 0.39, has been relatively constant since 1958.

The initial increase in 1958 in the ^{137}Cs average body burden for Rongelap adults (see Fig. 2) was due to dietary intake of ^{137}Cs and a small intake of ^{137}Cs from the air and water due to above ground nuclear tests in the Marshall Islands during 1958. The subsequent drop in the 1959 ^{137}Cs body burden may have been due to increased use of imported food and the conclusion of the testing. The reason for an increasing ^{137}Cs body burden at Rongelap during the 1960's was uncertain. Residual contamination from the Hardtack weapons testing program and subsequent incorporation of ^{137}Cs into diet items was one hypothesis.

The Hardtack Phase I series of tests was conducted during 1958, just prior to an increase in the exposure rate at Rongelap Atoll (Un59). Small amounts of fallout from the CACTUS, YELLOW WOOD, and HICKORY experiments in this series reached Rongelap. However, several observations support the conclusion that ^{137}Cs from this series was insignificant relative to ^{137}Cs from the Castle series. First, the peak ^{137}Cs body burden of a similar population at Utirik occurred three years after the initiating event (Castle BRAVO in 1954) while the 1965 peak ^{137}Cs body burden at Rongelap followed the Hardtack series by seven years. Secondly, the peak exposure rate on Rongelap which occurred during the Hardtack series in 1958 was about 10,000 times less than the peak exposure rate following BRAVO. These facts suggest that debris from the Hardtack series was not a major factor influencing the Rongelap ^{137}Cs body-burden pattern during the mid 1960's. In addition to Hardtack series fallout, the adult average body-burden pattern would have also been influenced by 1) world-wide fallout

fluctuations, 2) movement of adults in the study population to a clean island or atoll for a month's visit with family or friends and 3) to the initial success and subsequent failure of a food subsidy program which began at Rongelap in 1958 (Co80b).

Derived Quantities

The k values calculated for each nuclide in the Rongelap and Utirik adult populations are given in Table 4. In the cases of the Rongelap and Utirik people for whom sequential body-burden data was available, k was found to have a positive value for ^{137}Cs, ^{65}Zn, ^{60}Co, ^{239}Pu, and ^{90}Sr. The ^{239}Pu data for urine of three adult males at Rongelap in 1973 and 1976 provided a single tentative estimate of k. The value of k for ^{239}Pu was $7.5 \times 10^{-5} \pm 9.1 \times 10^{-5}\ d^{-1}$. For ^{55}Fe, only one bioassay estimate was published as a result of studies by the BNL medical program (Be72, Co75); thus an estimate of k was not possible. For the estimate of cumulated ^{55}Fe intake, k was assumed equal to zero which implies that radioactive decay was the only cause of reduced daily activity intake during residence.

Where data were available for comparison, the values for k for ^{137}Cs and ^{90}Sr were found to be similar for both males and females as well as for residents of both Rongelap and Utirik. The yearly per cent decrease in the atom ingestion rate was computed using Eq. 3 and the derived k value for each nuclide of interest. This intake relationship shows a 9% reduction in dietary ^{137}Cs for each year at Rongelap and Utirik. For dietary ^{90}Sr, an 8% reduction was estimated for each year at Rongelap and Utirik. The ^{60}Co and ^{65}Zn intakes were reduced rapidly during the first few years post return to Rongelap Atoll. An 80% per year reduction in dietary ^{65}Zn and a 60% per year reduction in dietary ^{60}Co were observed for adults. Also, for adult males at Rongelap, a

tentative value of 3% per year reduction in dietary ^{239}Pu was estimated from sparse data.

The derived quantity, daily activity ingestion rate on day of return to Rongelap (June 29, 1957), was calculated for many individuals for ^{137}Cs and was plotted as a function of age in Fig. 4. An example of the variation in ^{137}Cs values for male and female intake on day of rehabitation is shown in this figure. Differences in the daily ingestion rate of stable elements at the same geographic location have been shown to occur among subgroups of a population (ICRP74). As an example of the dietary variation at Rongelap, it was observed that coconut sap was used both as a major food supplement for infants, and then again (in a fermented form) in adult life by males as a component of daily fluid intake (Na80). Children and adolescents, however, were observed to receive a large portion of their daily fluid intake from two imported meals per day as part of the school lunch program. Studies indicated that coconuts and coconut tree sap provided the major source of ^{137}Cs in the diet (Le80a, Mi80). Thus, the undulating shape of Fig. 4 reflected this variation in the dietary intake of ^{137}Cs contaminated foods.

Adult average values for activity ingestion rate on day of return were calculated for all nuclides. Results are listed in Table 4. This information, together with the estimate of k for the nuclide of interest, was used in Eq. 2 to estimate adult body-burden histories based on the assumption of declining continuous intake (see Figs. 5 and 6).

The declining continuous intake equation (Eq. 3) provided a smooth body-burden function for Rongelap and Utirik adults. The equation was a tool to provide retroactive body-burden estimates during the early years post return to

Utirik. Few direct measurements were made at this time. The data plotted in Fig. 6 for ^{60}Co and ^{55}Fe were derived from Rongelap measurements.

Biological variation and errors in the collection and analysis of urine samples introduced larger errors in body-burden estimates than did direct whole-body counting. These variations can be observed in Fig. 5 where ^{90}Sr data vary widely from the theoretical curve. In contrast, the ^{137}Cs data fit the curve closely.

The method used to generate Figs. 5 and 6 was not chosen to minimize the weighted sum of squares of deviations of the body-burden estimates and measurements from the fitting function (Eq. 2). Instead average values of k and P° were selected to represent all the body-burden data. For Rongelap, the ^{137}Cs body burdens varied from the fitted function by a maximum factor of 1.7 and an average factor of 1.4.; the ^{90}Sr body burdens varied from the fitted function by a maximum factor of 3 and an average factor of 1.6. These factors reflect the quality of fit for directly measured body burdens and urine derived body burdens in general.

The integral intake for 50 years and the committed effective dose equivalent were derived quantities which depended on knowledge of k and P° for each population subgroup. The 50 year interval chosen for integral intake represented the years 1957 through 2007 for Rongelap residents. For Utirik residents, the fifty year interval represented the years 1954 through 2004. The committed effective dose equivalent was based on this cumulated intake and both values can be found in Table 4.

An important result of using the fitting function (Eq. 2) was that ^{65}Zn and ^{137}Cs were the largest contributors to dose equivalent for each population. The ^{65}Zn dose equivalent was greatest at Utirik because of a three month inter-

val separating the BRAVO event and day of rehabitation and because of the shorter half life of ^{65}Zn. The ^{137}Cs dose equivalent is important over the long term. It may be the chief nuclide of concern during an individuals life time post rehabitation of a fallout contaminated environment.

Statistical Analysis of Data

In the cases of ^{137}Cs, ^{65}Zn and ^{90}Sr, a large set of individual adult values for k and P° were available in addition to a set of adult average values. The whole-body counting techniques and urine bioassay techniques employed were similar throughout the programs' history. The short-term factors influencing the pattern of an individual's body burden, e.g. sickness, local diet changes, eating imported food, recent travel to uncontaminated areas, etc. were factors which influenced the pattern of adult average body burden throughout the entire residence interval. Therefore the ratio of the standard deviation to the adult average k's and P°'s should have been equal to the same ratio for individual adult values. This was in fact the case for ^{137}Cs, ^{65}Zn and ^{90}Sr. The standard deviations and the adult average k's and P°'s for these nuclides were listed in Table 4. Tables of individual adult values were not reproduced here, however, individual body-burden data obtained in sequence are found in the references given in the introduction. These body burdens may be used with a fitting function (Eq. 2) to generate individual adult, k's and P°'s.

The standard deviations for adult average k's and P°'s were used to estimate the standard deviations for adult average committed effective dose equivalents (see Table 4). Because the ratio of standard deviation to the average k and P° was the same for either adult average or individual adult k and P° data for ^{137}Cs, ^{65}Zn and ^{90}Sr, it was assumed to be true for ^{60}Co and ^{55}Fe. Thus, the standard deviations for the adult average k, P°, fifty-year cumulated intake

and committed effective dose equivalent were estimated and given in Table 4 for each of these nuclides as well.

The standard deviation for the fifty-year cumulated intake for each nuclide does not include the deviations due to the variation or uncertainty of biological removal rate constants, radioactive decay constants or the fraction of an element eliminated via the urine pathway. These variations plus the variation of specific absorbed fraction of photon energy would introduce even greater standard deviation than that indicated in Table 4 for the estimate of committed effective dose equivalent.

External Radiation Exposure

External exposure-rate history curves for periods following resettlement are plotted on Figs. 7 and 8. These exposure rates were many times less than the March 1, 1954 exposure rates 12 hours after detonation of BRAVO. At that time they were estimated to average 2.3×10^{6} nC kg^{-1} h^{-1} (8.9 R h^{-1}) for Rongelap Island, Rongelap Atoll and 8.9×10^{4} nC kg^{-1} h^{-1} (0.34 R h^{-1}) for Utirik Island, Utirik Atoll (Le80b). These estimates were extrapolated values based on survey measurements made several days after the BRAVO detonation (OC68).

The external exposure at Rongelap and Utirik Atolls since rehabitation varied due to radioactive decay of BRAVO fallout and the addition of low-level contamination from several other nuclear tests (see Figs. 7 and 8). The estimated total fifty-year background subtracted exposure post rehabitation was 5.9×10^{-4} C kg^{-1} (2.3 R) at Rongelap Island and 1.5×10^{-3} C kg^{-1} (5.6 R) at Utirik Island. These values were based on the exposure-rate history for each island and do not include the exposure contribution prior to rehabitation or from natural background radiation. The background exposure rate was measured by Miltenberger and Greenhouse (Gr77b) and was 9.6×10^{-1} nC kg^{-1} h^{-1} (3.7×10^{-6} R h^{-1}). The fifty-

year net external effective dose equivalent was estimated to be 1.7×10^{-2} Sv (1.7 rem) at Rongelap and 4.1×10^{-2} Sv (4.1 rem) at Utirik. The external exposure rate is expected to decline to nearly natural background levels by the year 2072.

The ratio of internal committed effective dose equivalent to fifty-years of net external dose equivalent was 1.1 for Utirik and 1.5 for Rongelap. The internal portion of these dose equivalent ratios does not include the contribution from ^{239}Pu due to the uncertainty in Pu bioassay data.

DISCUSSION

The body-burden and urine data indicated a definite decline with time from the day of return atom ingestion rate for ^{137}Cs, ^{65}Zn, ^{60}Co and ^{90}Sr. The data for ^{239}Pu were uncertain but indicated a decline. These measurements of internal levels of radionuclides used in conjunction with the declining continuous intake equations provided an estimate of the total intake, the committed effective dose equivalent and the rate of decline of radionuclides in the overall diet. The data for directly measured body burdens at Rongelap Atoll were the best quality data for determining derived quantities.

Based on a declining continuous intake due solely to radioactive decay and the 1970 ^{55}Fe adult average body burden for each atoll, an estimate of the daily activity ingestion rate for ^{55}Fe on the day of return was calculated. Based on this ingestion rate, it was estimated that ^{55}Fe contributed a negligible amount to the total committed effective dose equivalent (see Table 4). The assumption that k=0 for ^{55}Fe was made because sequential body-burden data were not available. Assigning $k=2.0\times10^{-3}\ d^{-1}$, the value determined for ^{60}Co, leads to an ^{55}Fe committed effective dose equivalent of 2.3×10^{-3} Sv (2.3×10^{-1} rem) for Rongelap adults. This is larger by a factor of 5 than the estimate for committed effective dose equivalent based on k=0.

Use of the body-burden extrapolation equation leads to the conclusion that ^{65}Zn could have been the major contributor to the ingested activity during the first year post rehabitation of Utirik Atoll (see Table 4). This was supported to some extent by a Japanese report (JCCRRER56) which indicated a rise in the photon count rate at the surface of various types of tuna retrieved from the Marshall Islands' fishing grounds from March to August 1954 (100 cpm to 10,000 cpm). Fish with count rates greater than 100 cpm at the surface were discarded.

Radiochemical techniques indicated the prominence of ^{65}Zn in the tuna's edible flesh. If it was assumed 1) that ^{65}Zn was the principal contributor to the external photon count rate, 2) that a self-sufficient living pattern existed on Utirik in which adults consumed 300 gms of fish each day (Na80), and 3) that 1% of the fish eaten was tuna, then the daily activity ingestion rate might have been $7x10^3$ Bq d^{-1} ($2x10^{-1}$ μCi d^{-1}) in May and June and $7x10^4$ Bq d^{-1} ($2x10^0$ μCi d^{-1}) in July and August of 1954. This method of estimating ^{65}Zn daily activity ingestion rates yields a ten times greater estimate of total intake than the total intake suggested by body-burden extrapolation techniques (see Eq. 2). Although the ^{65}Zn total intake estimate indicated for Utirik adults in Table 4 was based on scanty data, it was made with fewer assumptions than was the above estimate using Japanese fishing data.

The validity of the ^{239}Pu data used to estimate the body burden at Rongelap Atoll (see Table 1) in 1973 had been considered by an Energy Research and Development Agency ad hoc committee. The committee concluded that, because of the possibility of contamination of the urine samples, these data were uncertain. This may indeed have been a factor since a radiochemical analysis of BRAVO debris indicated Rongelap Atoll was contaminated with ^{239}Pu (Ts55). No special precautions had been taken when the urine samples were collected in the field, therefore, not much credence could be given to these data.

In 1976, three male adults at Rongelap Atoll provided urine samples for ^{239}Pu analysis. Two yielded results below the minimum detection limit of $3.7x10^{-4}$ Bq ℓ^{-1} (10 fCi ℓ^{-1}) and one yielded $3.3x10^{-3}$ Bq ℓ^{-1} (90 fCi ℓ^{-1}). The average of these values along with the 1973 adult average data that was reported by Conard (Co75) were used to derive potential body burdens. The results were listed in Table 1.

The estimates for ^{239}Pu adult body burden were not used to derive values of intake and committed effective dose equivalent since they may be have been the result of erroneous urine collection technique and not the result of internal deposition. The potential for contamination also existed for ^{90}Sr, however the impact of contamination on dose assessment was much greater for Pu.

Questions concerning the ^{239}Pu estimates have led to a study of the sampling and analysis procedures which indicated that some ^{239}Pu in urine may not have been chemically recovered along with the tracer (Ry82). The extent of sample contamination during collection and the fundamental reasons for variation in recovery of ^{239}Pu from urine samples remain unanswered at this time. Several investigations are underway. In August 1981, fecal and urine samples were obtained from Rongelap and Utirik residents and are to be analyzed after complete dissolution followed by a liquid solvent extraction technique used in conjunction with a photon-electron rejecting liquid scintillation spectrometer developed by McDowell for low-level alpha spectroscopy (Mc72). The question of initial sample contamination will be answered following additional analysis of urine collected in 1980 from former Bikini Atoll residents.

CONCLUSION

The principle results of this investigation were that: ^{137}Cs and ^{65}Zn were major contributors to the committed effective dose equivalent; the overall body burden pattern was one of initial increase followed by continuous decline over a period of years; the daily intake pattern was probably one of continuous decline, this conclusion was based on the fitting of sequential body-burden data to Eq. 2; the impact of each nuclide on internal committed effective dose equivalent was dependent upon the time between contamination and rehabitation; and the internal committed effective dose equivalent exceeded external dose equivalent during the rehabitation period. The sparse ^{239}Pu data indicated further research was necessary in order to estimate accurately the activity intake and committed effective dose equivalent from this nuclide.

For committed effective dose equivalent, the impact of nuclides with a short mean residence time in the diet (^{65}Zn, ^{60}Co) was greater at Utirik because the population reinhabited within months of the BRAVO event. The impact of nuclides with a long mean residence time in the diet (^{137}Cs, ^{90}Sr, ^{55}Fe) was greater at Rongelap because of greater initial contamination.

ACKNOWLEDGMENTS

The authors fully appreciate the fine efforts of Michael Ryan of Oak Ridge National Laboratory, Nathanial A. Greenhouse of Lawrence Berkeley Laboratory, Lee V. Kaplan, formerly from Yale University, Humbilena Manalastas, from the Philippine Atomic Energy Commission, William Adams, Jan Naidu, John Baum, Victor Bond, Donald Borg, Eugene Cronkite, Andrew Hull, and Charles Meinhold, from Brookhaven National Laboratory and Thomas McCraw from the Department of Energy Headquarters in helping to prepare a scientific document. We gratefully acknowledge their contributions of ideas and procedures.

REFERENCES

Be69 Bevington P.R., 1969, Data Reduction and Error Analysis for the Physical Sciences (New York: McGraw-Hill Book Company).

Be70 Bennett B.G., 1970, "Estimation of Gonadal Absorbed Dose Due To Environmental Gamma Radiation," Health Phys. 19, 757-767.

Be72 Beasley T.M., Held E.E. and Conard R.A., 1972, "Iron-55 in Rongelap People, Fish and Soils," Health Phys. 22, 245-250.

Br82 Brauer F.P. and Naidu J.N., 1982, "I-129 Analysis of Marshall Island Environmental Samples Analytical and Quality Assurance Procedures," Battelle Pacific Northwest Laboratories, Richland, WA, and Brookhaven National Laboratory, Upton, NY, unpublished manuscript.

Ch60 Chakravarti D. and Held E.E., 1960, Potassium and Cesium-137 in Birgus Latro (Coconut Crab) Muscle Collected at Rongelap Atoll, University of Washington Fisheries Laboratory Report, Seattle WA, UWFL-64.

Co55 Cohn S.H., Rinehart R.W., Gong J.K., Robertson J.S., Milne W.L. and Bond V.P., 1955, Nature and Extent of the Internal Radioactive Contamination of Human Beings and Animals Exposed to Fallout Material in Operation Castle, U.S. Naval Radiological Defense Laboratory Report, San Francisco, CA, USNRDL-TR-86.

Co56 Conard R.A., Cannon B., Huggins C.E., Richards J.B. and Lowery A., 1956, Medical Survey of Marshallese Two Years After Exposure to Fallout Radiation, Brookhaven National Laboratory Report, Upton, NY, BNL 412.

Co58 Conard R.A., Meyer L.M., Rall J.E., Lowery A., Suen A.B., Cannon B., Carter E.L., Eicher M. and Hechter H., 1958, March 1957 Medical Survey of Rongelap and Utirik People Three Years After Exposure to Radioactive Fallout, Brookhaven National Laboratory Report, Upton, NY, BNL 501.

Co59 Conard, R.A., et al., 1959, Medical Survey of Rongelap People, March 1958, Four Years After Exposure to Fallout, Brookhaven National Laboratory Report, Upton, NY, BNL 534.

Co60 Conard R.A., et al., 1960, Medical Survey of Rongelap People Five and Six Years After Exposure to Fallout (With an Addendum on Vegetation), Brookhaven National Labortatory Report, Upton, NY, BNL 609.

Co62 Conard R.A., et al., 1962, Medical Survey of Rongelap People Seven Years After Exposure to Fallout, Brookhaven National Laboratory Report, Upton, NY, BNL 727.

Co63 Conard R.A., et al., 1963, Medical Survey of Rongelap People Eight Years After Exposure to Fallout, Brookhaven National Laboratory Report, Upton, NY, BNL 780.

Co65 Conard R.A., et al., 1965, Medical Survey of the People of Rongelap and Utirik Islands Nine and Ten Years After Exposure to Fallout Radiation (March 1963 and March 1964), Brookhaven National Laboratory Report, Upton, NY, BNL 908.

Co67 Conard R.A., et al., 1967, Medical Survey of the People of Rongelap and Utirik Islands Eleven and Twelve Years After Exposure to Fallout Radiation (March 1965 and March 1966), Brookhaven National Laboratory Report, Upton, NY, BNL 50029.

Co70 Conard R.A., et al., 1970, Medical Survey of the People of Rongelap and Utirik Islands Thirteen, Fourteen and Fifteen Years After Exposure to Fallout Radiation (March 1967, March 1968, and March 1969), Brookhaven National Laboratory Report, Upton, NY, BNL 50220.

Co75 Conard R.A., et al., 1975, A Twenty-Year Review of Medical Findings in a Marshallese Population Accidentally Exposed to Radioactive Fallout, Brookhaven National Laboratory Report, Upton, NY, BNL 50424.

Co80a Conard R.A., et al., 1980, Review of Medical Findings in a Marshallese Population Twenty-Six Years After Accidental Exposure to Radioactive Fallout, Brookhaven National Laboratory Report, Upton, NY, BNL 51261.

Co80b Conard R.A., 1980, private communication, Brookhaven National Laboratory, Upton, NY, 11973.

Coh60 Cohn S.H., Robertson J.S. and Conard R.A., 1960, "Radioisotopes and Environmental Circumstances: Internal Radioactive Contamination of a Pacific Island Community Exposed to Local Fallout," in: Radioisotopes in the Biosphere, (Minneapolis: University of Minnesota Press).

Coh63 Cohn S.H., Conard R.A., Gusmano E.A. and Robertson J.S., 1963, "Use of a Portable Whole Body Counter to Measure Internal Contamination in a Fallout Exposed Population," Health Phys. 9, 15-23.

Coh56 Cohn S.H., Rinehart R.W., Gong J.K., Robertson J.S., Milne W.L., Bond V.P. and Cronkite E.P., 1956, "Internal Deposition of Radionuclides in Human Beings and Animals", in: Some Effects of Ionizing Radiation on Human Beings, U.S. Atomic Energy Commission Report, Washington, D.C., USAEC-TID 5358.

Cr56 Cronkite E.P., Bond V.P. and Dunham C.L., 1956, A Report on the Marshallese and Americans Accidentally Exposed to Radiation from Fall-out and a Discussion of Radiation Injury in the Human Being, U.S. Atomic Energy Commission Report, Washington, D.C., TID 5358.

Du56 Dunning G.M. and Hilcken J.A., Editors, 1956, The Shorter-Term Biological Hazards of a Fallout Field, Symposium, 12-14 December, U.S. Atomic Energy Commission and Department of Defense Report, Washington, D.C.

Du57 Dunning G.M., 1957, Radioactive Contamination of Certain Areas in the Pacific Ocean from Nuclear Tests, United States Atomic Energy Commission Report, Washington, D.C.

Gl62 Glasstone S., Editor, 1962, The Effects of Nuclear Weapons, Defense Atomic Support Agency Report, Department of Defense, Published by U.S. Atomic Energy Commission, Washington, D.C.

Gr77a Greenhouse N.A., Miltenberger R.P. and Cua F.T., 1977, Radiological Analyses of Marshall Islands Samples 1974-1976, Brookhaven National Laboratory Report, Upton, NY, BNL 50796.

Gr77b Greenhouse N.A. and Miltenberger R.M., 1977, External Radiation Survey and Dose Predictions for Rongelap, Utirik, Rongerik, Ailuk and Wotje Atolls, Brookhaven National Laboratory Report, Upton, NY, BNL 50797.

He65 Held E., 1965, Gamma Dose at Rongelap Atoll, 1954-1963, Laboratory of Radiation Biology Report, University of Washington, Seattle, WA, UWFLO-91.

ICRP59 Recommendations of the International Commission on Radiological Protection, 1959, "Report of Committee II on Permissible Dose for Internal Radiation," ICRP Publication 2 (London: Pergamon Press).

ICRP68 Recommendations of the International Commission on Radiological Protection, 1968, "Report of Committee IV on Evaluation of Radiation Doses to Body Tissues from Internal Contamination Due to Occupational Exposure," ICRP Publication 10 (London: Pergamon Press).

ICRP69 Recommendations of the International Commission on Radiological Protection, 1969, "Report of Committee IV on the Assessment of Internal Contamination Resulting from Recurrent or Prolonged Uptakes," ICRP Publication 10A (London: Pergamon Press).

ICRP74 Recommendations of the International Commission on Radiological Protection, 1974, "Report of the Task Group on Reference Man," ICRP Publication 23 (London: Pergamon Press).

ICRP79 Recommendations of the International Commission on Radiological Protection, 1979, "Report of Committee II on Limits for Intakes of Radionuclides by Workers," ICRP Publication 30 (Oxford: Pergamon Press).

JCAE57 Joint Committee on Atomic Energy, 1957, The Nature of Radioactive Fall-out and Its Effects on Man, Part 1, Washington, D.C.

JCCRRER56 Japan Committee for Compilation of Reports on Research in the Effects of Radioactivity, 1956, "Research in the Effects and Influences of the Nuclear Bomb Test Explosions," (Published by the Japan Society for Promotion of Science, Ueno, Tokyo).

Ki78 Killough G.G., Dunning D.E., Bernard S.R. and Pleasant J.C., 1978, Estimates of Internal Dose Equivalent to 22 Target Organs for Radionuclides Occurring in Routine Releases from Nuclear Full-Cycle Facilities, Oak Ridge National Laboratory Report, Oak Ridge, TN, NUREG/CR-0150, ORNL/NUREG/TM190.

Le80a Lessard E.T., Miltenberger R.P. and Greenhouse N.A., 1980, "Dietary Radioactivity Intake from Bioassay Data: A Model Applied to ^{137}Cs Intake by Bikini Island Residents," Health Phys. 39, 177-83.

Le80b Lessard E.T., Greenhouse N.A. and Miltenberger R.P., 1980, A Reconstruction of Chronic Dose Equivalents for Rongelap and Utirik Residents - 1954 to 1980, Brookhaven National Laboratory Report, Upton, NY, BNL 51257.

Le80c Lessard E.T. and Miltenberger R.P., October 1980, "July-August 1980 Field Trip Report to Thomas McCraw, U.S. Department of Energy," Brookhaven National Laboratory, Upton, NY, 11973.

Mc72 McDowell W.J. and Henley L.C., 1972, An Evaluation of the Possibility of Detecting and Identifying Alpha Emitters in Low-Count Rate Samples, Oak Ridge National Laboratory Report, Oak Ridge, TN,ORNL-TM-3676.

Mi80 Miltenberger R.P., Greenhouse N.A. and Lessard E.T., 1980, "Whole Body Counting Results from 1974 to 1979 for Bikini Islands Residents," Health Phys. 39, 395-407.

Mi81 Miltenberger R.P., Lessard E.T. and Greenhouse N.A., 1981, "^{60}Co and ^{137}Cs Long Term Biological Removal Rate Constants for the Marshallese Population," Health Phys. 40, 615-623.

Na80 Naidu J.R., Greenhouse N.A., Knight G. and Craighead E.C., 1980, Marshall Islands: A Study of Diet and Living Patterns, Brookhaven National Laboratory Report, Upton, NY, BNL 51313.

Ne77 Nelson U.A., 1977, Radiological Survey of Plants, Animals and Soil at Christmas Islands and Seven Atolls in the Marshall Islands, Laboratory of Radiation Ecology Report, University of Washington, Seattle, WA, NUO-269-32.

Ne79 Nelson U.A., 1979, Radiological Survey of Plants, Animals and Soil at Five Atolls in the Marshall Islands, Laboratory of Radiation Ecology Report, University of Washington, Seattle, WA, NUO-269-36.

OC68 O'Connor J.D. and Crocker G.R., 1968, Local Fallout from Nuclear Test Detonations, Defense Atomic Support Agency Report, Naval Radiological Defense Laboratory, San Fransciso, CA, DASA 1251.

Ry82 Ryan M.T., Case G.N., McDowell W.J. and Henley L.C., 1982, A Preliminary Comparison of Two Techniques for Bioassay of Urine for Plutonium, Oak Ridge National Laboratory Report, Oak Ridge, TN, ORNL/TM-8531.

Sh57 Sharp R. and Chapman W., 1957, Exposure of Marshall Islanders and American Military Personnel to Fallout, Naval Medical Research Institute Report, Bethesda, MD, WT-938.

Ti81 Tipton W.J. and Melbaum R.A., 1981, An Aerial Radiological and Photographic Survey of Eleven Atolls and Two Islands within the Northern Marshall Islands, DOE Remote Sensing Laboratory Report, Las Vegas, NV, E66-1183-1758.

Ts55 Tsuzuki M., 1955, "Erfahrungen uber Radioaktive Schadigung der japanische Fisher durch Bikini-asche," Muench. Med. Wochsch. 31, 988-994.

USPHS59 United States Public Health Service, 1959, Report of Public Health Service Off-Site Radiological Monitoring Data, Operation Hardtack Phase I 1958, Publisher Unknown, Manuscript attached to letter from Lt. Colonel Belmont Evans, USA to Robert Conard, M.D., Brookhaven National Laboratory, Upton, NY.

Wo59 Woodward K., Schrodt A., Anderson J., Claypool H. and Hartgering J., 1959, The Determination of Internally Deposited Radioactive Isotopes in the Marshallese People by Excretion Analysis, Defense Atomic Support Agency Report, Walter Reed Army Institute of Research Report, Washington, D.C., DASA 1180.

List of Table Captions

Table 1	Average Radionuclide Burden and Time Since Rehabitation for Rongelap Adults
Table 2	Average Radionuclide Burden and Time Since Rehabitation for Utirik Adults
Table 3	Summary - Whole Body Counting Results - August 1981
Table 4	Summary of Estimates of Committed Effective Dose Equivalent

Table 1

Average Radionuclide Burden And Time Since Rehabitation For Rongelap Adults

	Adult Males (>15a)		Adult Females (>15a)		Adults (>15a)			
	Body Burden Bq	Number of Individuals	Body Burden Bq	Number of Individuals	Body Burden Bq	Number of Individuals	Time Post Rehabitation Days	Year
^{60}Co	1.1×10^{0}	(A)	6.3×10^{-1}	(A)	9.3×10^{-1}	(A)	0	1957
	3.7×10^{2}	37	2.9×10^{2}	37	3.3×10^{2}	74	1370	1961
	9.3×10^{1}	45	7.4×10^{1}	45	8.1×10^{1}	90	2831	1965
^{65}Zn	1.9×10^{3}	4(B)	(C)	(C)	(C)	(C)	0	1957
	2.3×10^{4}	17	6.4×10^{3}	8	1.8×10^{4}	25	244	1958
	1.6×10^{4}	30	1.4×10^{4}	12	1.5×10^{4}	42	304	1958
	2.3×10^{4}	32	1.9×10^{4}	27	2.1×10^{4}	59	639	1959
	3.5×10^{3}	38	3.1×10^{3}	23	3.4×10^{3}	61	1370	1961
^{55}Fe	1.6×10^{4}	28	1.5×10^{4}	32	1.5×10^{4}	60	4626	1970
^{90}Sr	7.0×10^{0}	(A)	5.2×10^{0}	(A)	6.3×10^{0}	(A)	0	1957
	1.7×10^{1}	11	1.1×10^{1}	4	1.4×10^{1}	15	304	1958
	4.7×10^{1}	24	2.9×10^{1}	16	4.1×10^{1}	40	639	1959
	6.3×10^{1}	9	2.5×10^{1}	4	5.1×10^{1}	13	1370	1961
	3.0×10^{2}	13	1.8×10^{2}	15	2.4×10^{2}	28	1696	1962
	2.1×10^{2}	12	1.9×10^{2}	13	1.9×10^{2}	25	2100	1963
	2.1×10^{2}	11	2.0×10^{2}	7	2.1×10^{2}	18	2466	1964
	7.7×10^{1}	12	1.6×10^{2}	12	1.3×10^{2}	24	3561	1967
	1.5×10^{2}	11	1.2×10^{2}	11	1.3×10^{2}	22	3927	1968
	1.6×10^{2}	11	1.3×10^{2}	13	1.5×10^{2}	24	4292	1969
	5.5×10^{1}	9	1.5×10^{2}	11	1.1×10^{2}	20	4657	1970
	1.4×10^{2}	8	1.2×10^{2}	7	1.3×10^{2}	15	5022	1971
	9.6×10^{1}	5	8.7×10^{1}	7	9.6×10^{1}	12	5388	1972
	3.2×10^{2}	4	2.1×10^{2}	7	2.5×10^{2}	13	5753	1973
	1.7×10^{2}	10	8.5×10^{1}	4	1.5×10^{2}	14	6118	1974
	2.5×10^{2}	26	(C)	(C)	(C)	(C)	7579	1978
	3.7×10^{1}	25	2.8×10^{1}	19	3.3×10^{1}	44	8057	1979
^{137}Cs	5.2×10^{2}	(A)	3.1×10^{2}	(A)	4.1×10^{2}	(A)	0	1957
	2.9×20^{4}	38	1.9×10^{4}	13	2.7×10^{4}	51	304	1958
	2.9×10^{4}	47	1.5×10^{4}	49	2.1×10^{4}	96	639	1959
	3.5×10^{4}	37	1.7×10^{4}	37	2.5×10^{4}	74	1370	1961
	3.5×10^{4}	44	1.8×10^{4}	45	2.5×10^{4}	89	2831	1965
	1.8×10^{4}	22	1.1×10^{4}	24	1.4×10^{4}	46	6118	1974
	1.1×10^{4}	30	7.0×10^{3}	21	9.3×10^{3}	51	7213	1977
	6.7×10^{3}	19	5.6×10^{3}	18	6.3×10^{3}	37	8057	1979
	6.7×10^{3}	36	7.0×10^{3}	30	6.7×10^{3}	66	8813	1981
^{239}Pu	6.4×10^{1}	3	3.8×10^{2}	8	3.2×10^{2}	11	5753	1973
	4.1×10^{1}	3	(C)	(C)	(C)	(C)	7030	1976

A ≡ Number of individuals not recorded.
B ≡ Measured at Argonne National Laboratory.
C ≡ No females measured.

Table 2

Average Radionuclide Burden And Time Since Rehabitation for Utirik Adults

	Adult Males (>15a)		Adult Females (>15a)		Adults (>15a)			
	Body Burden Bq	Number of Individuals	Body Burden Bq	Number of Individuals	Body Burden Bq	Number of Individuals	Time Post Rehabitation Days	Ye
^{60}Co	$3.6x10^1$(A)	-	$2.8x10^1$(A)	-	$3.1x10^1$(A)	-	3926	19
^{65}Zn	$1.4x10^4$	2(B)	(C)	(C)	(C)	(C)	1039	19
	$1.0x10^4$	14	$5.9x10^3$	15	$7.8x10^3$	29	1734	19
^{55}Fe	$6.0x10^3$(A)	-	$5.8x10^3$(A)	-	$5.8x10^3$(A)	-	5721	19
^{90}Sr	$1.8x10^1$	5	$2.2x10^1$	2	$1.9x10^1$	7	1734	19
	$4.0x10^1$	5	$3.8x10^1$	6	$3.9x10^1$	11	7213	19
	$6.1x10^0$	17	(C)	(C)	(C)	(C)	8669	19
	$5.6x10^0$	16	$5.0x10^0$	16	$5.4x10^0$	32	9225	19
^{137}Cs	$1.5x10^4$	(D)	$1.0x10^4$	(D)	$1.2x10^4$	(D)	1039	19
	$1.1x10^4$	15	$7.4x10^3$	15	$9.3x10^3$	30	1734	19
	$9.6x10^3$	9	$4.8x10^3$	13	$6.8x10^3$	22	7213	19
	$4.4x10^3$	27	$2.9x10^3$	21	$3.7x10^3$	48	8309	19
	$2.3x10^3$	19	$1.6x10^3$	17	$2.0x10^3$	36	9225	19
	$3.7x10^3$	61	$2.5x10^3$	65	$3.1x10^3$	126	9935	19
^{239}Pu	$2.4x10^1$(A)	-	$1.5x10^2$(A)	-	$1.2x10^2$(A)	-	6848	19

A ≡ Adapted from Rongelap data, see text.
B ≡ Measured at Argonne National Laboratory.
C ≡ No females measured.
D ≡ Number of individuals not recorded.

Table 3

Summary - Whole Body Counting Results - August 1981

Island	Population Sub-Group	Number Counted	Average or Average ± 1 s.d. Age, a	Height, m	Weight, kg	Cs-137, Bq	K, kg	Range Cs-137, Bq	K, kg	Comparison Data Average or Average ± 1 s.d. Cs-137, Bq (A)	K, kg (B)
Rongelap	Adult Males	34	32±14	1.6±.063	67±11	6,700±3,600	.15±.028	220-17,000	.030-.21	85	.13±.020
Rongelap	Adult Females	30	34±16	1.5±.045	59±11	7,000±4,200	.12±.027	1,500-25,000	.048-.17	78	.096±.020
Rongelap	Adoles. Males	14	12±.97	1.4±.083	34±7.5	6,100±2,300	.075±.026	2,800-10,000	.018-.11	52	.083±.011
Rongelap	Adoles. Females	8	13±1.5	1.5±.070	38±6.0	9,400±3,100	.10±.046	3,400-13,000	.033-.18	52	.071±.011
Rongelap	Child Males	18	7.6±1.6	1.2±.080	22±2.8	3,900±2,100	.060±.031	1,300- 8,200	(C)-.089	48	.048±.006
Rongelap	Child Females	13	7.7±1.4	1.2±.087	22±3.0	3,600±1,800	.062±.022	1,800- 7,800	.018-.10	48	.046±.006
Utirik	Adult Males	61	36±17	1.6±.057	66±12	3,700±1,500	.15±.030	340- 7,400	.095-.22	85	.13±.020
Utirik	Adults Females	65	37±18	1.5±.048	62±15	2,500±1,100	.092±.024	370- 5,900	.044-.15	78	.099±.020
Utirik	Adoles. Males	21	12±1.1	1.4±.11	33±8.7	2,500±1,400	.076±.033	560- 5,200	.011-.15	52	.083±.011
Utirik	Adoles. Females	16	13±1.4	1.4±.080	38±7.0	2,300±1,000	.078±.021	850- 4,800	.047-.13	52	.071±.011
Utirik	Child Males	31	8.2±1.6	1.2±.12	23±5.1	1,900± 800	.051±.020	930- 4,300	.024-.096	48	.052±.006
Utirik	Child Females	20	8.3±1.7	1.2±.12	24±6.3	1,700± 800	.044±.019	590- 3,200	.017-.086	48	.049±.006
Rongelap	All Adults	64	33	1.6	63	6,800	.12	220-25,000	.030-.21	81	.12
Rongelap	All People	117	23	1.4	48	6,300	.094	220-25,000	(C)-.21	60	.090
Utirik	All Adults	126	37	1.6	64	3,100	.12	340-7,400	.044-.22	81	.12
Utirik	All People	214	25	1.4	49	2,700	.095	340-7,400	.011-.22	60	.093

A ≡ May 1979 - Comparison population at Majuro, minimum detection limit 37 Bq.
B ≡ Adapted from ICRP23 and adjusted according to mean age.
C ≡ Minimum detection limit, .01 kg.

Table 4

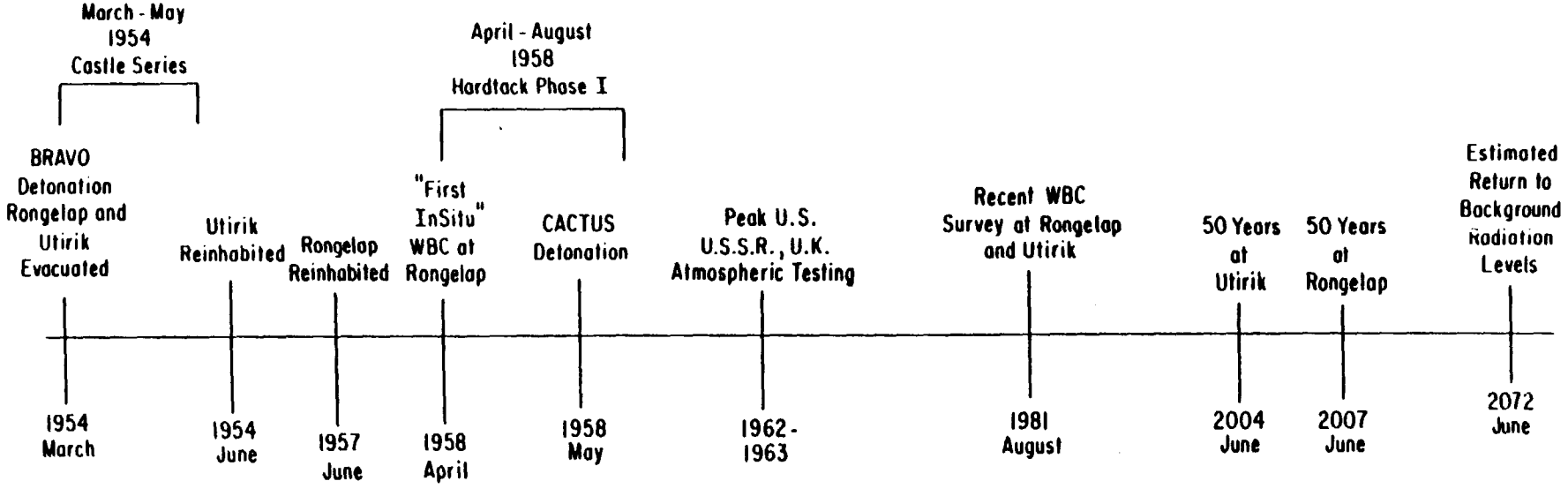
Summary of Estimates of Committed Effective Dose Equivalent

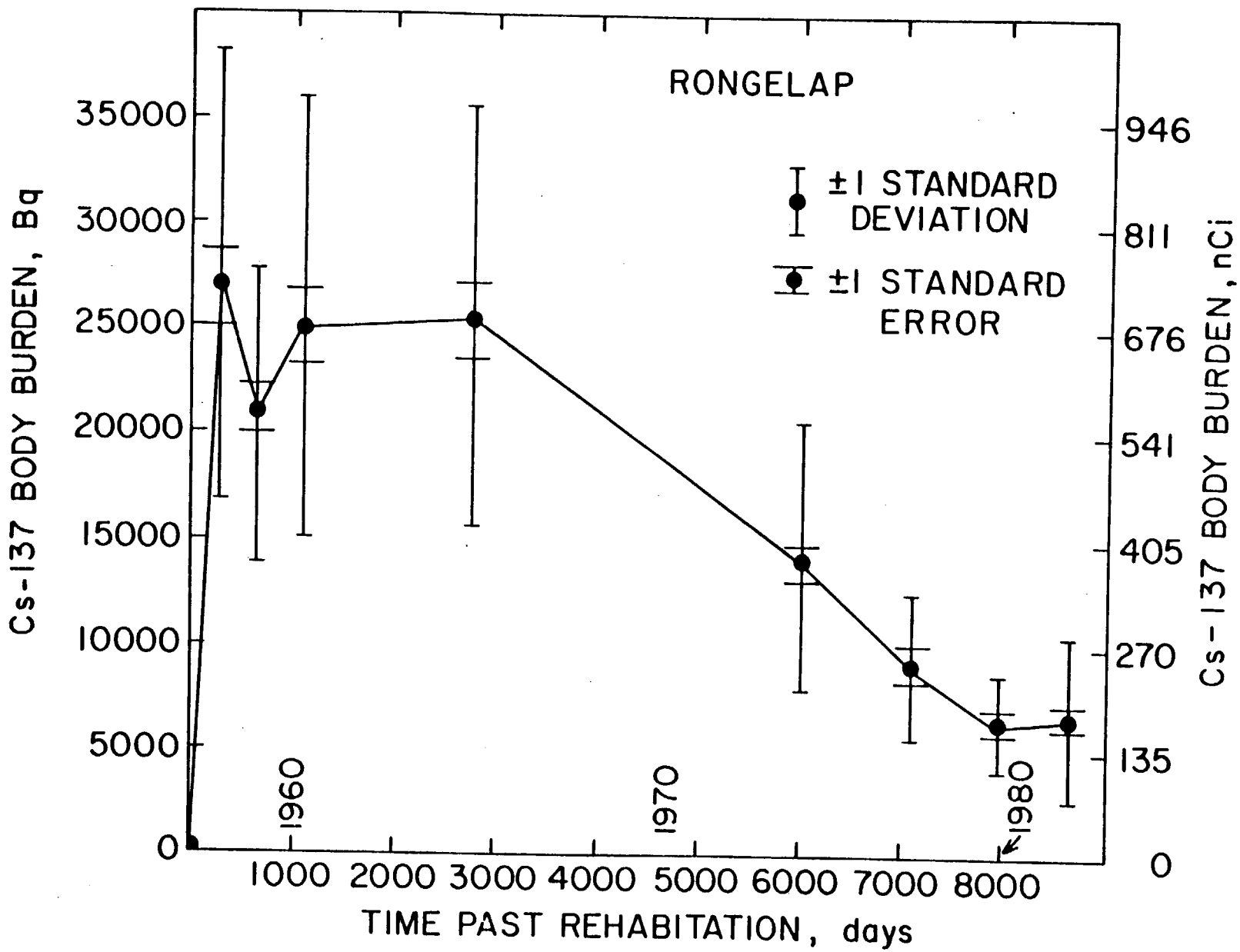
Nuclide	Atoll	Ingestion Rate on Day of Rehabitation, λP^{o} Bq d^{-1} ± s.d.	Decay Constant, λ d^{-1} ± s.d.	Dietary Removal Rate Constant, k d^{-1} ± s.d.	Fifty-Year Cumulated Intake Bq ± s.d.	60 kg Adult Ave Committed Effec Dose Equival Sv ± s.d.
^{60}Co	Rongelap	$9.5\times10^{1}\pm 3.2\times10^{1}$	$3.6\times10^{-4}\pm7.5\times10^{-8}$	$2.0\times10^{-3}\pm1.9\times10^{-3}$	$4.0\times10^{4}\pm2.8\times10^{4}$	$3.4\times10^{-4}\pm2.3\times1$
^{137}Cs	Rongelap	$3.9\times10^{2}\pm 1.3\times10^{2}$	$6.3\times10^{-5}\pm7.1\times10^{-8}$	$2.0\times10^{-4}\pm4.6\times10^{-4}$	$1.5\times10^{6}\pm2.2\times10^{6}$	$2.2\times10^{-2}\pm3.2\times1$
^{65}Zn	Rongelap	$1.3\times10^{3}\pm 9.4\times10^{2}$	$2.8\times10^{-3}\pm2.3\times10^{-6}$	$1.3\times10^{-3}\pm5.3\times10^{-3}$	$3.1\times10^{5}\pm3.4\times10^{5}$	$1.9\times10^{-3}\pm2.0\times1$
^{90}Sr	Rongelap	$2.1\times10^{0}\pm 1.1\times10^{0}$	$6.6\times10^{-5}\pm3.2\times10^{-7}$	$1.7\times10^{-4}\pm1.5\times10^{-3}$	$9.0\times10^{3}\pm5.5\times10^{4}$	$5.3\times10^{-4}\pm3.2\times1$
^{55}Fe	Rongelap	$1.7\times10^{3}\pm 9.3\times10^{2}$	$7.1\times10^{-4}\pm2.6\times10^{-6}$	(A)	$2.4\times10^{6}\pm1.3\times10^{6}$	$4.8\times10^{-4}\pm2.5\times1$
^{60}Co	Utirik	$1.3\times10^{2}\pm 4.4\times10^{1}$	$3.6\times10^{-4}\pm7.5\times10^{-8}$	$2.0\times10^{-3}\pm1.9\times10^{-3}$(B)	$5.4\times10^{4}\pm4.0\times10^{4}$	$4.4\times10^{-4}\pm3.3\times1$
^{137}Cs	Utirik	$2.1\times10^{2}\pm 1.1\times10^{2}$	$6.3\times10^{-5}\pm7.1\times10^{-8}$	$1.8\times10^{-4}\pm5.7\times10^{-4}$	$8.6\times10^{5}\pm1.7\times10^{6}$	$1.3\times10^{-2}\pm2.5\times1$
^{65}Zn	Utirik	$2.1\times10^{4}\pm 1.6\times10^{4}$	$2.8\times10^{-3}\pm2.3\times10^{-6}$	$1.3\times10^{-3}\pm5.3\times10^{-3}$(B)	$5.2\times10^{6}\pm7.5\times10^{6}$	$3.0\times10^{-2}\pm4.4\times1$
^{90}Sr	Utirik	$4.0\times10^{-1}\pm3.0\times10^{-1}$	$6.6\times10^{-5}\pm3.2\times10^{-7}$	$1.6\times10^{-4}\pm2.1\times10^{-4}$	$1.7\times10^{3}\pm1.7\times10^{3}$	$1.0\times10^{-4}\pm1.0\times1$
^{55}Fe	Utirik	$1.3\times10^{3}\pm 7.1\times10^{2}$	$7.1\times10^{-4}\pm2.6\times10^{-6}$	(A)	$1.9\times10^{6}\pm1.0\times10^{6}$	$3.6\times10^{-4}\pm2.0\times1$

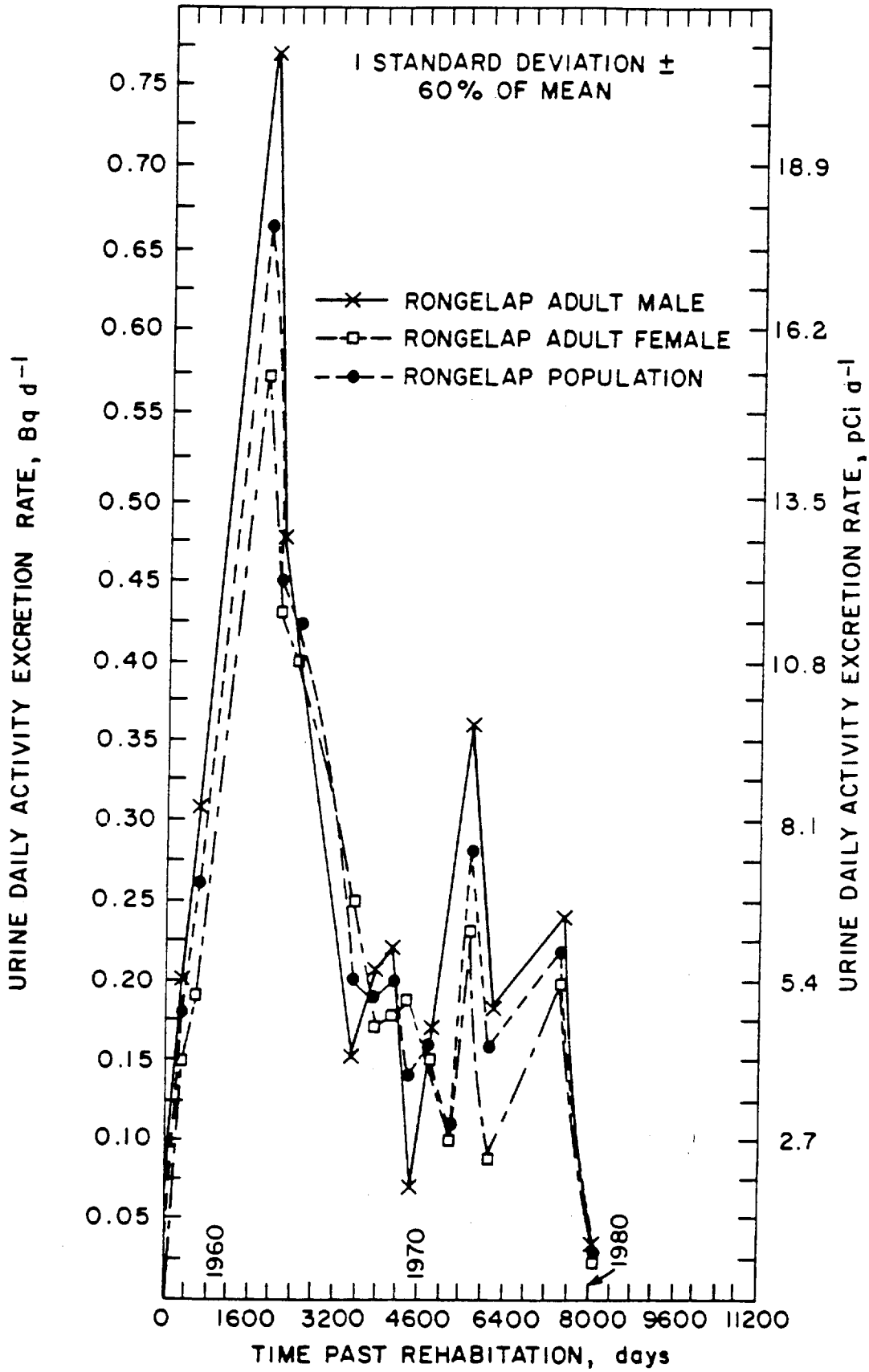
(A) Assumed to equal zero.
(B) Rongelap values were used.

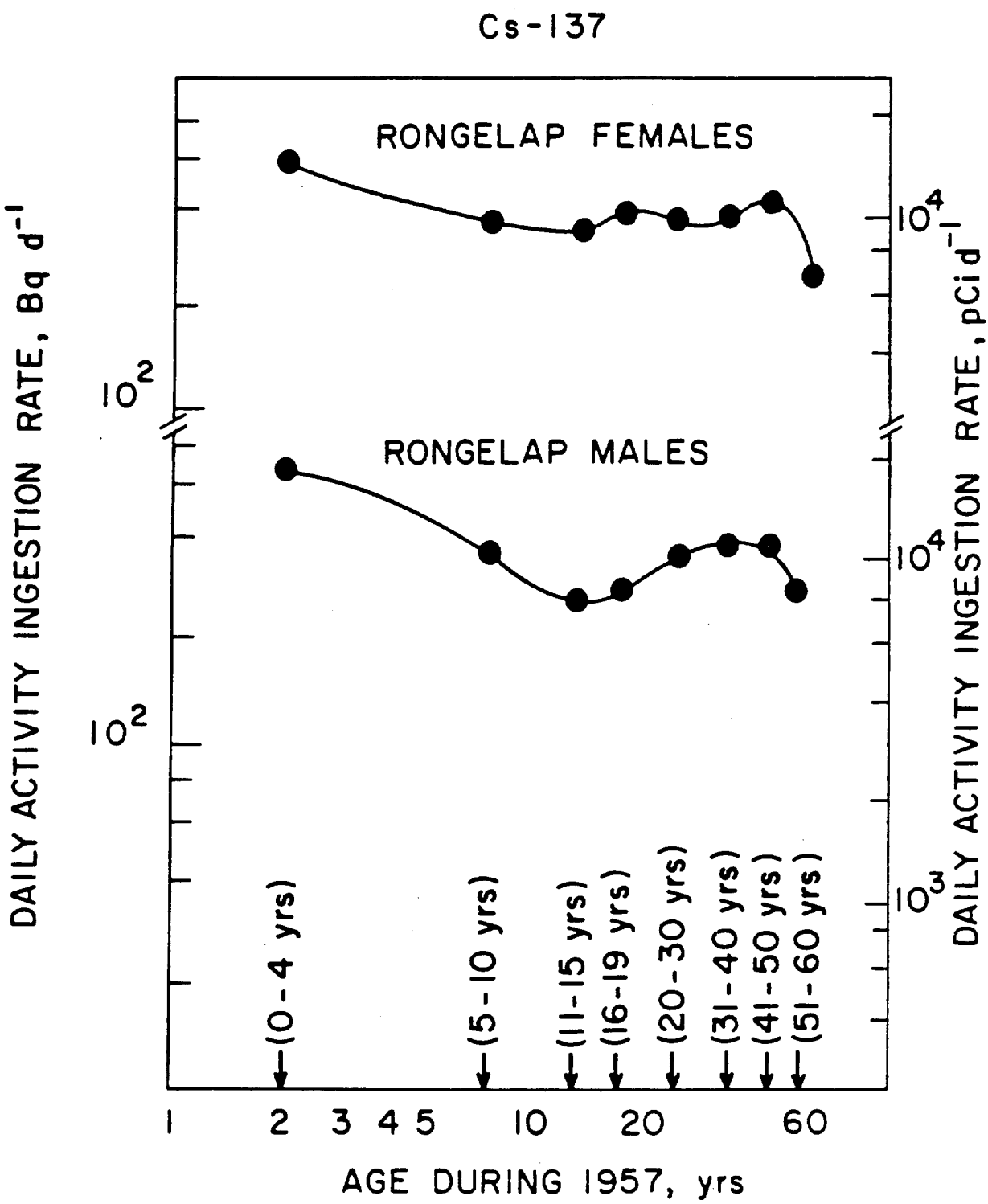
List of Figure Captions

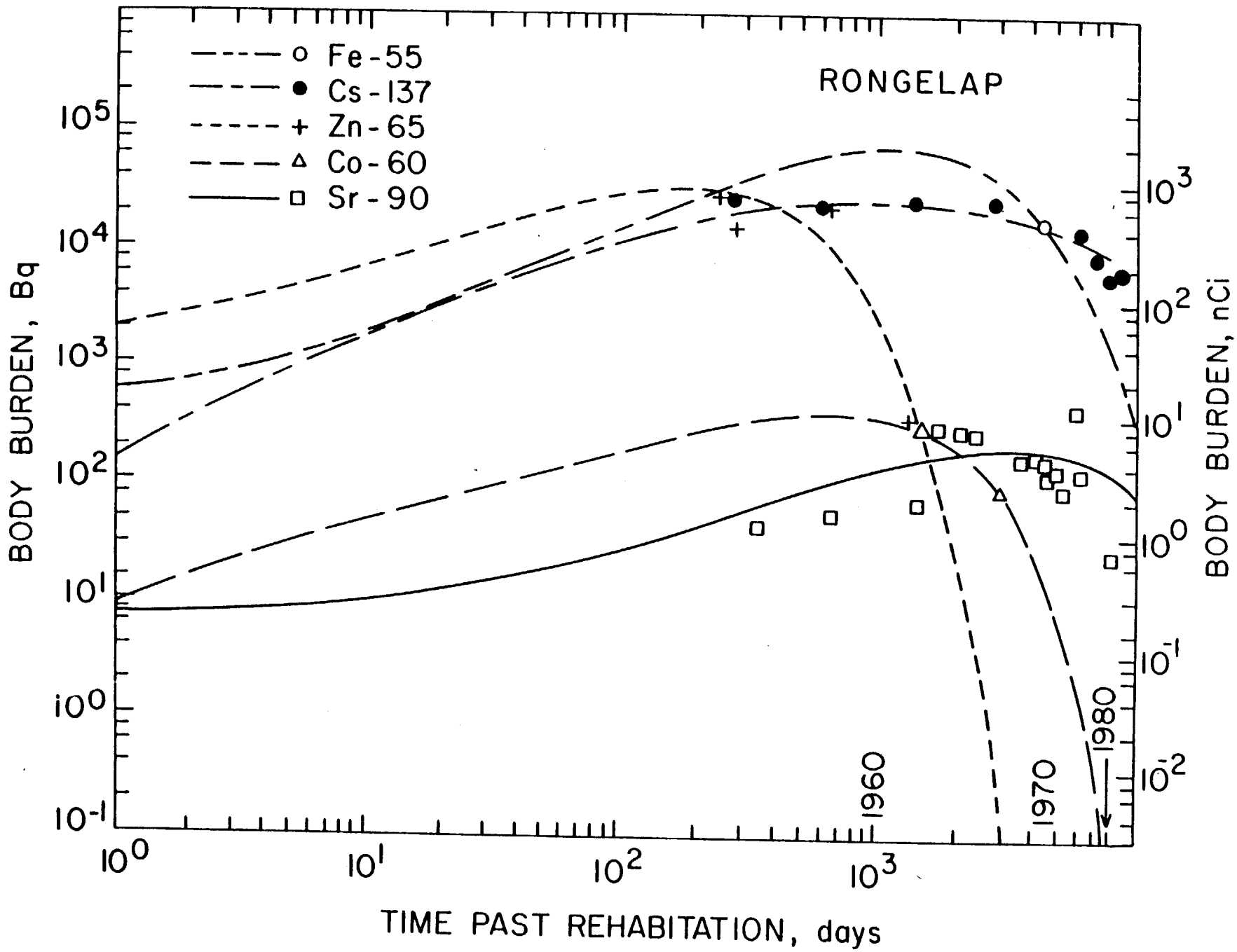
Figure 1	Sequence of Events at Rongelap and Utirik Atolls
Figure 2	Cs-137 Body Burden For Rongelap Adults
Figure 3	Sr-90 Urine Activity Excretion Rate for Rongelap Adults
Figure 4	Daily Activity Ingestion Rate for Day of Return to Rongelap Atoll
Figure 5	Body-Burden History for Rongelap Adults
Figure 6	Body-Burden History for Utirik Adults
Figure 7	Exposure-Rate History at Rongelap Atoll
Figure 8	Exposure-Rate History at Utirik Atoll

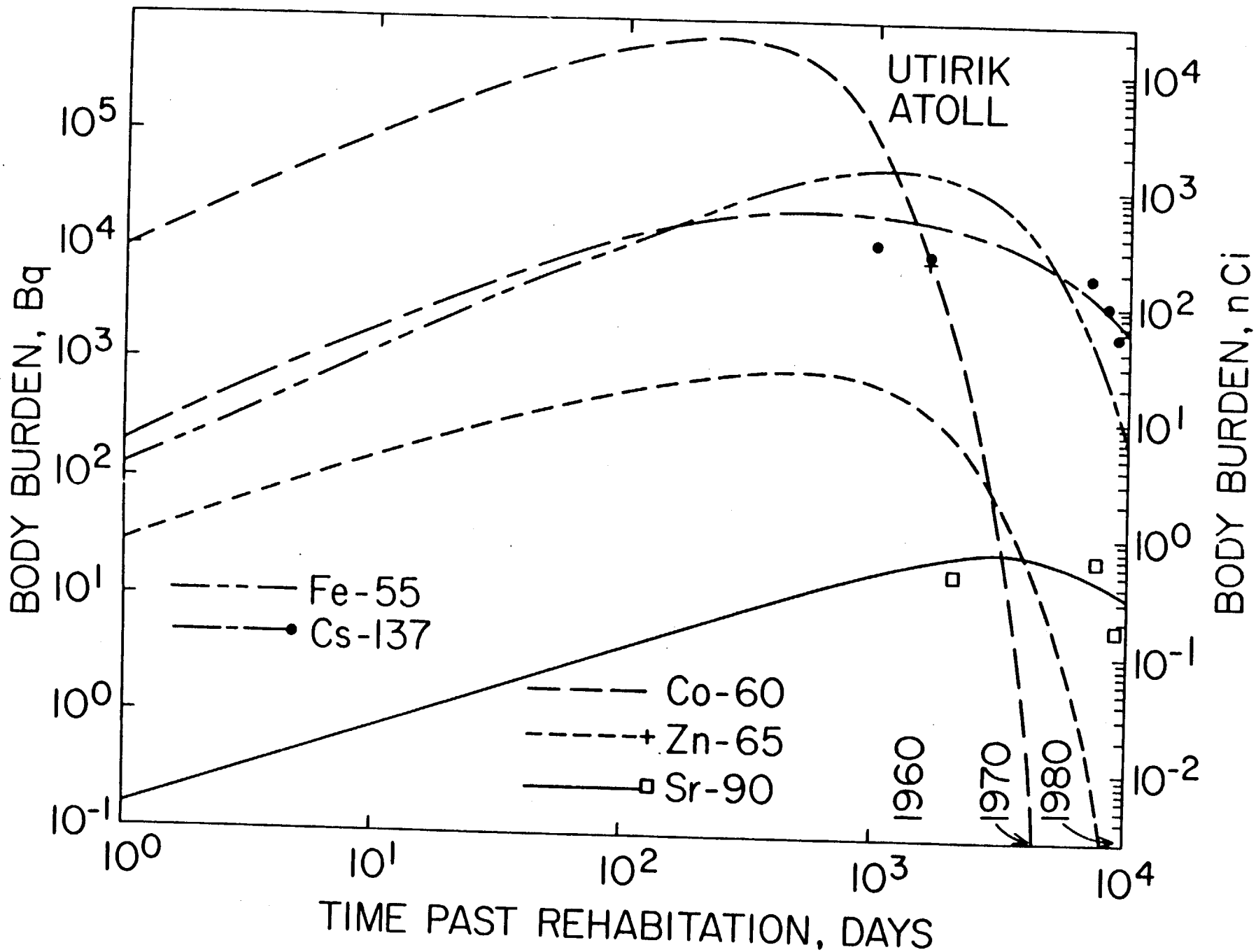

March - May
1954
Castle Series
BRAVO
Detonation
Rongelap and
Utirik
Evacuated
1954
March
Utirik
Reinhabited
1954
June
Rongelap
Reinhabited
1957
June
April - August
1958
Hardtack Phase I
"First
InSitu"
WBC at
Rongelap
1958
April
CACTUS
Detonation
1958
May
Peak U.S.
U.S.S.R., U.K.
Atmospheric Testing
1962 -
1963
Recent WBC
Survey at Rongelap
and Utirik
1981
August
50 Years
at
Utirik
2004
June
50 Years
at
Rongelap
2007
June
Estimated
Return to
Background
Radiation
Levels
2072
June

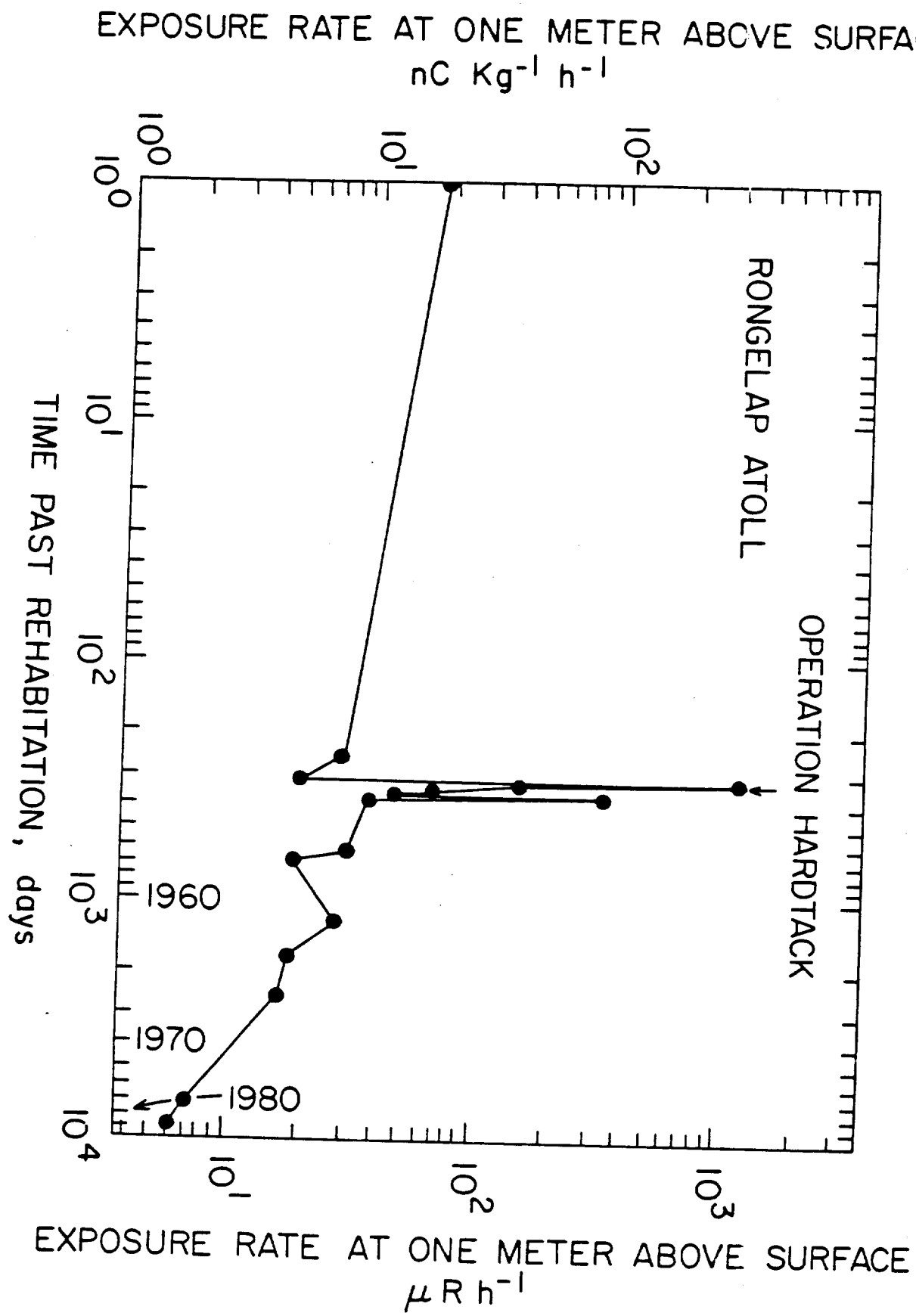

RONGELAP
±1 STANDARD DEVIATION
±1 STANDARD ERROR
Cs-137 BODY BURDEN, Bq
35000
30000
25000
20000
15000
10000
5000
0
Cs-137 BODY BURDEN, nCi
946
811
676
541
405
270
135
0
1960
1970
1980
1000 2000 3000 4000 5000 6000 7000 8000
TIME PAST REHABITATION, days

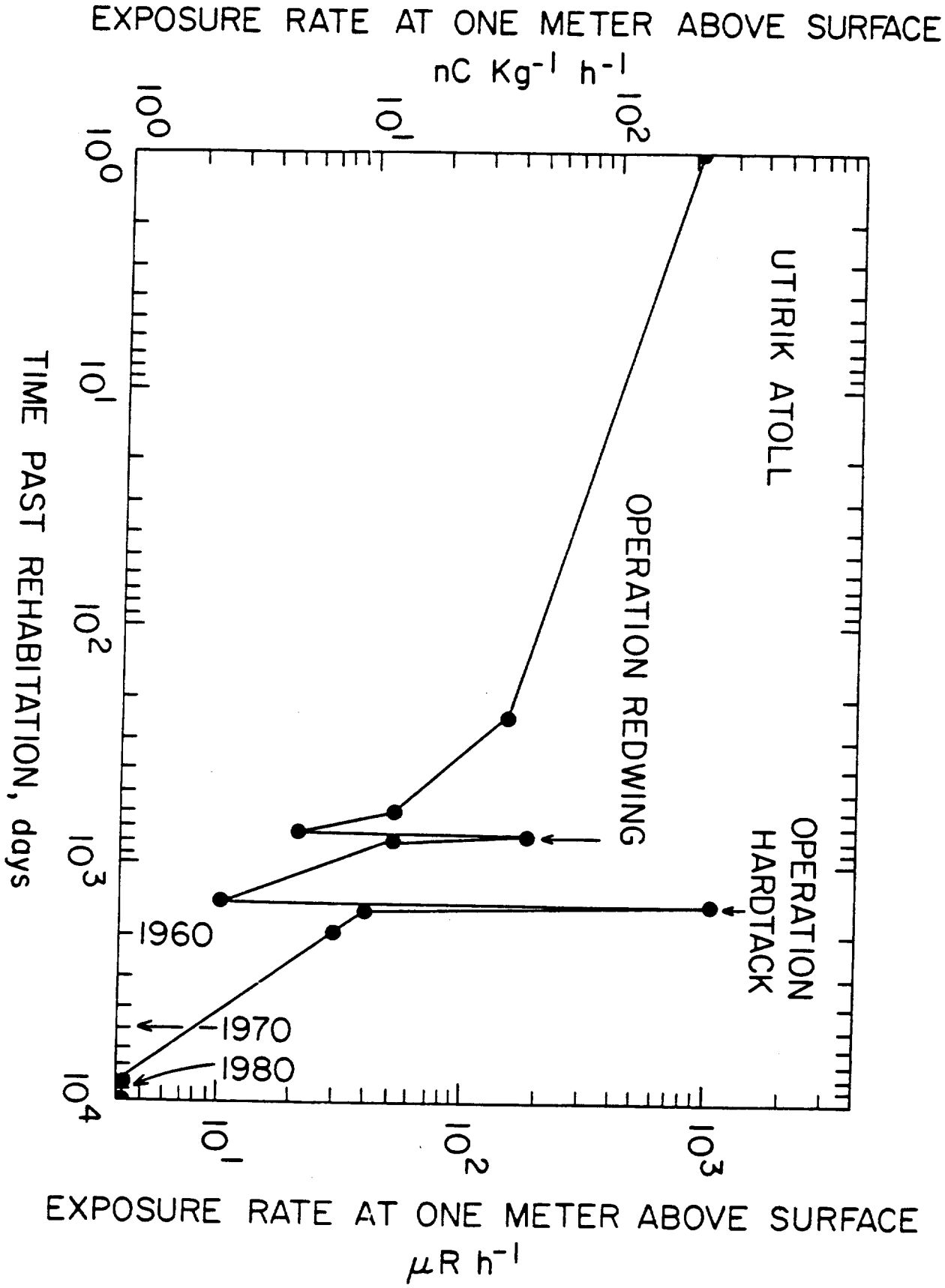

I STANDARD DEVIATION ±
60% OF MEAN
RONGELAP ADULT MALE
RONGELAP ADULT FEMALE
RONGELAP POPULATION
URINE DAILY ACTIVITY EXCRETION RATE, Bq d⁻¹
URINE DAILY ACTIVITY EXCRETION RATE, pCi d⁻¹
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
18.9
16.2
13.5
10.8
8.1
5.4
2.7
1960
1970
1980
0
1600
3200
4600
6400
8000
9600
11200
TIME PAST REHABITATION, days


Cs-137
RONGELAP FEMALES
RONGELAP MALES
DAILY ACTIVITY INGESTION RATE, Bq d^{-1}
DAILY ACTIVITY INGESTION RATE, pCi d^{-1}
10^2
10^4
10^3
(0-4 yrs)
(5-10 yrs)
(11-15 yrs)
(16-19 yrs)
(20-30 yrs)
(31-40 yrs)
(41-50 yrs)
(51-60 yrs)
1
2
3
4
5
10
20
60
AGE DURING 1957, yrs


Fe-55
Cs-137
Zn-65
Co-60
Sr-90
RONGELAP
BODY BURDEN, Bq
BODY BURDEN, nCi
TIME PAST REHABITATION, days
1960
1970
1980


UTIRIK
ATOLL
BODY BURDEN, Bq
BODY BURDEN, nCi
TIME PAST REHABITATION, DAYS
Fe-55
Cs-137
Co-60
Zn-65
Sr-90
1960
1970
1980
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{-2}


EXPOSURE RATE AT ONE METER ABOVE SURFACE
nC Kg-1 h-1
10^0
10^1
10^2
RONGELAP ATOLL
OPERATION HARDTACK
TIME PAST REHABITATION, days
10^0
10^1
10^2
10^3
10^4
1960
1970
1980
10^-1
10^2
10^3
EXPOSURE RATE AT ONE METER ABOVE SURFACE
μR h-1


EXPOSURE RATE AT ONE METER ABOVE SURFACE
nC Kg⁻¹ h⁻¹
10⁰
10⁻¹
10⁻²
UTIRIK ATOLL
OPERATION REDWING
OPERATION HARDTACK
TIME PAST REHABITATION, days
10⁰
10¹
10²
10³
10⁴
1960
1970
1980
10⁻¹
10⁻²
10⁻³
EXPOSURE RATE AT ONE METER ABOVE SURFACE
μR h⁻¹