410400

REVIEW OF MARSHALL ISLANDS FALLOUT STUDIES

Presented by

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Summary

Persons who were present on March 1, 1954, at Rongelap Island, Rongelap Atoll, Sifo Island, Ailingnae 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. Medical specialists have reported short-term effects exhibited over a period of many months and possible long-term effects exhibited over many years. A study was undertaken to reexamine thyroid-absorbed dose estimates for people who were exposed accidentally at Rongelap, Sifo, and Utirik Islands. The study included: 1) reevaluation of radiochemical analysis to relate results from pooled urine to intake, retention, and excretion functions, 2) analysis of neutron irradiation studies of archival soil samples to estimate areal activities of the iodine isotopes, 3) analysis of source term, weather data, and meteorology functions predicting atmospheric diffusion and fallout deposition to estimate airborne concentrations of the iodine isotopes, and 4) reevaluation of radioactive fallout contaminating a Japanese fishing vessel in the vicinity of Rongelap Island on March 1, 1954, to determine fallout components. The relative location of the exposed people is given as Figure 1.

The original estimates of external whole-body dose from the acute exposure were 1.75 gray (175 rad) at Rongelap and 0.14 gray (14 rad) at Utirik (Cr56). The first estimate of thyroid dose from internal emitters in Rongelap people was 100 to 150 rep (Cr56). Thus the first estimate of total thyroid absorbed dose was 2.68 to 3.15 gray (268 to 315 rad) for Rongelap people in general and for internal plus external exposure.

In 1964, three teenage girls who were exposed in 1954 underwent surgery for benign thyroid nodules. In 1964, 3 to 4-year-old child thyroid dose was reexamined by James on the basis of 1) urine bioassy results and 2) a range of values for thyroid burden of ^{131}I, thyroid mass, and uptake retention functions for iodine (Ja64). In addition two modes of intake were considered, inhalation and ingestion. For 3 to 4-year-old girls the extreme range of thyroid dose from internal emitters was estimated at 2 to 33 gray (200-3300 rad). The most probable total thyroid dose was in the range of 7 to 14 gray (700-1400 rad). The James estimate of most probable total thyroid absorbed dose to the child was 2 to 5 times higher than the estimate reported by Cronkite for Rongelap people.

The value for the James estiamte of total thyroid dose was extrapolated to other ages and to the Utirik people and reported along with medical effects by Conard (Co74). The number of radiation-induced thyroid lesions per million person-rad-years at risk was tabulated by Conard for the Rongelap and Utirik exposed populations. It was clear that the risks of radiation induced benign and cancerous lesions were not comparable between the two atolls for any age grouping. The thyroid cancer risk for the Japanese population exposed at Nagasaki and Hiroshima, as reported by the National Research Council's Committee on the Biological Effects of Ionizing Radiation, was 1.89 excess cases per million person-rad-years of tissue dose (CBEIR80). This parameter was 7.0 at Rongelap and 17.8 at Utirik for the 10-year and older age grouping in 1974 (Co74).

Variation between atolls in risk of radiation-induced thyroid cancer and the difference when compared to other irradiated groups had become an important scientific and health-related question with the considerable political overtones. Early in 1977, Bond, Borg, Conard, Cronkite, Greenhouse, Naidu, and Meinhold, all members of Brookhaven National Laboratory (BNL), and Sondhaus, University of California, College of Medicine, initiated a reexamination of the technical issues. In 1978, formal program objectives and funding were supplied to BNL by the Department of Energy's Division of Biological and Environmental Research.

In June 1978, the Meteorology Division at Lawrence Livermore National Laboratory was subcontracted to provide a computer simulation of the dispersion, transport, and deposition of fallout from the 1954 atmospheric nuclear test, BRAVO. A subcontract to provide neutron activation analysis of archival soil samples was given to the Radiological Sciences Department, Battelle-Pacific Northwest Laboratory. Soil samples were provided by Seymour, the director of the University of Washington's Laboratory of Radiation Ecology.

Thyroid absorbed dose tabulated here was estimated from results on ^{131}I activity excreted in urine and the specific nuclide composition of BRAVO fallout. Surface and airborne activity, fallout granule size, and exposure rate at times after the detonation were developed for 142 nuclides at Rongelap and Utirik on the basis of the reported nuclide composition on day 26 post-detonation. Over 70 documents were reviewed for information regarding exposure-rate readings, film-badge readings, fallout composition, dose and dose rate, body burdens, urine analyses, gastrointestinal tract contents, bone marrow and thyroid dose estimates, and activity measurements in soil, water, marine life, and land animals. Results from the meteorology study and archival soil study were also reexamined and compared to fallout composition results.

A tabulation of the estimates of thyroid absorbed dose, age at exposure and specific nuclides was done for each location. For an adult male, the thyroid absorbed dose from iodine and tellurium nuclides was 7.7 times the absorbed dose due to ^{131}I at Rongelap, 10 times at Sifo Island and 4.7 times at Utirik Island. James assumed the total thyroid absorbed dose was 2.6 times the absorbed dose due to ^{131}I (Ja64). The factor 2.6 would be appropriate for slightly older fallout than that experienced at Rongelap, Utirik or Sifo Islands. Thryoid absorbed dose was based on ingestion intake. Inhalation intake and absorption through skin could not be reconciled with measurements of ^{131}I in urine or with external exposure rate measurements.

Observations of the range of ^{137}Cs body burdens during protracted exposure (Mi79) and the range associated with the contents of the stomach in cases of sudden death (Ev66) were used to estimate maximum thyroid absorbed dose. The average internal thyroid dose at Rongelap Island was based on the average ^{131}I activity collected in urine. The contribution to thyroid dose from external sources was estimated from the air exposure created by 142 nuclides which were estimated from results of BRAVO fallout composition. The external dose was similar to original estimates by Sondhaus for persons exposed at Rongelap and Utirik Islands. The original external dose estimates at these islands, 1.75 gray and 0.14 gray (175 rad and 14 rad) respectively, were derived from survey instrument readings taken after evacuation and film badge data from a nearby military outpost (So55). Our external dose value at Sifo Island, 1.1. gray (110 rad) was greater than the 0.69 gray (69 rad) originally estimated by Sondhaus from post-evacuation surveys of exposure rate. The difference was due to the presence of very short-lived activation and transuranic nuclides which, according to the nuclide composition, must have been present during exposure at Sifo Island.

Medical observations concerning thyroid abnormalities have been tabulated along with the new thyroid dose estimated for each person. From these results, the mean cancer risk rate in the exposed population of 251 people was 150 thyroid cancers per million person-gray-years at risk (1.5 ± 2.5 thyroid cancers per million person-rad-years at risk). The mean time at risk for thyroid cancer was 19 years. The uncertainity derived for the estimate of risk was based on the standard deviation in adult mean urine activity concentration, the standard deviation in thyroid absorbed dose per unit intake, and the standard deviation in the spontaneous frequency of thyroid lesions in the unexposed comparison group.

In order to avoid unwarrented external and internal dose from the deposited radioactivity, the inhabitants of these atolls were relocated out of the affected area. They returned to Utirik in June 1954 and to Rongelap in June 1957. Environmental and personnel radiological monitoring programs were initiated in the mid 1950's by Brookhaven National Laboratory. The objective was to maintain a comprehensive radiological safety program. Post-return body-burden histories and activity-ingestion rate patterns were determined as were estimates of internal committed effective dose equivalent. External exposure rate and living pattern data were also collected. Relationships between body burden or urine activity concentration and a declining continuous intake scenario were developed in order to model retrospective and prospective dose equivalent. The dosimetric conclusions for the protracted exposure are summarized in Table 1 (Le84).

Table 1. Dosimetric conclusions for the protracted exposure of Rongelap and Utirik Adults from day of return to 50 years.

Nuclide	Rongelap Committed Effective Dose Equivalent, Sv±S.E.	Utirik Committed Effective Dose Equivalent, Sv±S.E.
Fe-55	$4.8\times10^{-4} \pm 2.5\times10^{-4}$	$3.6\times10^{-4} \pm 2.0\times10^{-4}$
Co-60	$3.4\times10^{-4} \pm 1.3\times10^{-4}$	$4.4\times10^{-4} \pm 3.3\times10^{-4}$
Zn-65	$1.9\times10^{-3} \pm 1.0\times10^{-3}$	$3.0\times10^{-2} \pm 4.4\times10^{-2}$
Sr-90	$5.3\times10^{-4} \pm 8.0\times10^{-4}$	$1.0\times10^{-4} \pm 5.0\times10^{-5}$
Cs-137	$2.2\times10^{-2} \pm 1.1\times10^{-2}$	$1.3\times10^{-2} \pm 1.0\times10^{-2}$
External	$1.7\times10^{-2} \pm 3.4\times10^{-3}$	$4.1\times10^{-2} \pm 8.2\times10^{-3}$

A decline in the daily activity ingestion rate greater than that due solely to radioactive decay was estimated to be 9% per year for ^{137}Cs, 8% per year for ^{90}Sr, 80% per year for ^{65}Zn and 60% per year for ^{60}Co. A tentative value of 3% per year for Pu was estimated from sparse data. Current studies are aimed at determining the dosimetric impact of Pu. These values for the % per year decline in activity ingestion rate were observed at both atolls and do not account for the additional decline due to radioactive decay.

During the mid 1940s through 1958, the U.S. conducted high yield weapons tests at Bikini and Enewetak Atolls. These areas were contaminated with fallout from the tests. A restoration program, concentrating on the main residence islands of Bikini and Eneu Islands at Bikini Atoll, began in 1969. Approximately 30 Trust Territory residents including some former Bikini Atoll inhabitants participated in the initial cleanup and redevelopment of the Atoll. During subsequent years, the Bikini population increased to some 140 individuals at the time of their departure in August 1978.

Between 1969 and 1974, scrub vegetation on Bikini and Eneu Islands was cleared and indigenous food crops were planted. These crops consisted mainly of coconut, pandanus and breadfruit trees, but included a garden development where squash, papaya, bananas and other crops were grown (Ro77). During the maturation interval for most of the tree crops (5-7 years), the majority of the food consumed on Bikini Island was imported. As the local vegetation developed, the diet became less restricted to imported foods so that by 1978, the diet contained sustantial quantities of locally grown items.

Bioassay and external exposure monitoring programs were initiated for Bikini Island residents in anticipation of the changing dietary situation, and with the realization that it was essential to do personnel monitoring on those individuals living on Bikini Island.

From the period 1974 to 1978 the Bikini people exhibited ever increasing body burdens of ^{137}Cs and ^{90}Sr. Based on the intake pattern exhibited by adults we estimated a committed effective dose equivalent of 8.4×10^{-3} Sv (0.84 rem) from internally deposited ^{137}Cs, 2.0×10^{-3} Sv (0.20 rem) from ^{90}Sr and 3.2×10^{-5} Sv (0.0032 rem) from ^{60}Co.

External radiation exposure minus natural background was 5.5×10^{-3} Sv (0.55 rem). The average time the exposed adults were at Bikini Atoll was 4.5 years. The people were removed to Kili Island in August 1978 and we are anticipating further cleanup activities at Bikini Atoll.

ACUTE EXPOSURE
INTRODUCTION

The subject of this presentation is a description of the major health physics aspects of fallout exposure of the inhabitants of Rongelap, Utirik and Sifo Islands on March 1, 1954. External exposure was estimated based on gamma radiation measurements. In order to estimate thyroid dose, an estimate was made of the amount of fallout activity taken into the body. This was done by reexamining the ^{131}I excreted from persons who were at Rongelap. The other components of fallout taken into the body had to be inferred from studies on fallout composition. Initially, fallout composition was assumed and nuclide activity concentrations in air, water and food were established on the basis of meteorological and archival soil study results. Further study led to dose estimates based on actual BRAVO fallout composition, rather than estimates based on hypothetical compositions. Finally, knowledge was gathered about the intake pathway and the time post detonation at which intake was likely to have occurred and this was factored into the thyroid absorbed dose estimate.

The limitations of this work are 1) thyroid dose estimates have a large standard error 2) thyroid dose estimates apply for a unique situation and should not be extrapolated to other fallout exposures and 3) the medical observations quoted are not infallible, that is, a reevaluation of medical results may result in other cancer sites, different classifications for thyroid lesions or additional thyroid lesions.

The sources of information were many and varied. Discussions with persons initially involved, eg. Stan Cohn, Vic Bond, and Eugene Cronkite led to documents which have been cited in the reference section. A search for records at DOE headquarters led to the many files currently held by Tom McCraw. Mr. McCraw has acted as a repository for many Atomic Energy Commission documents. Some of these documents related directly to this study and were not easily located anywhere else. An abundance of environmental results have been published by the University of Washington's Laboratory of Radiation Ecology (also known as Applied Fisheries Laboratory). Medical information was published by Brookhaven National Laboratory's Medical Department and dietary information was published by both the Medical Department and the Safety and Environmental Protection Division. Much of the early and detailed observations about the accident were recorded in documents published by the U.S. Naval Radiological Defense Laboratory and by the naval Medical Research Institute.

The conclusions of the acute exposure study were that the population mean thyroid absorbed dose at Rongelap was 21 gray (2,100 rad). It was 6.7 gray (670 rad) at Sifo and 2.8 gray (280 rad) at Utirik. The overall thyroid cancer risk was in agreement with results published for Japanese exposed at Nagasaki and Hiroshima. The major route for intake of fallout was by direct ingestion. This resulted from outdoor food preparation and consumption practices during the period fallout clouds passed over the islands.

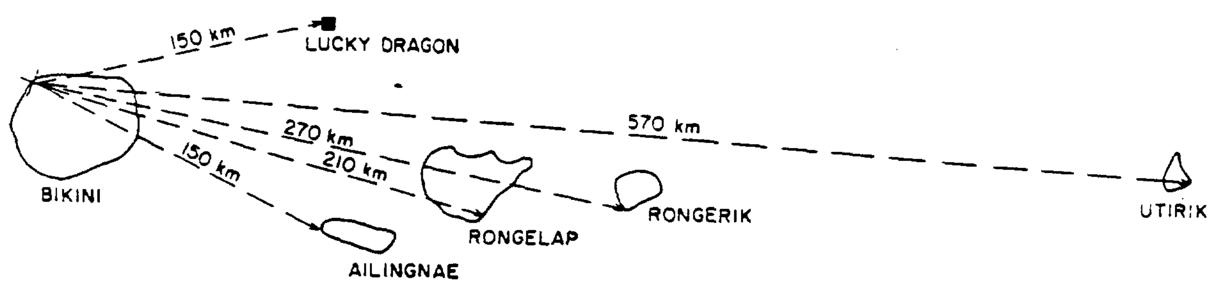
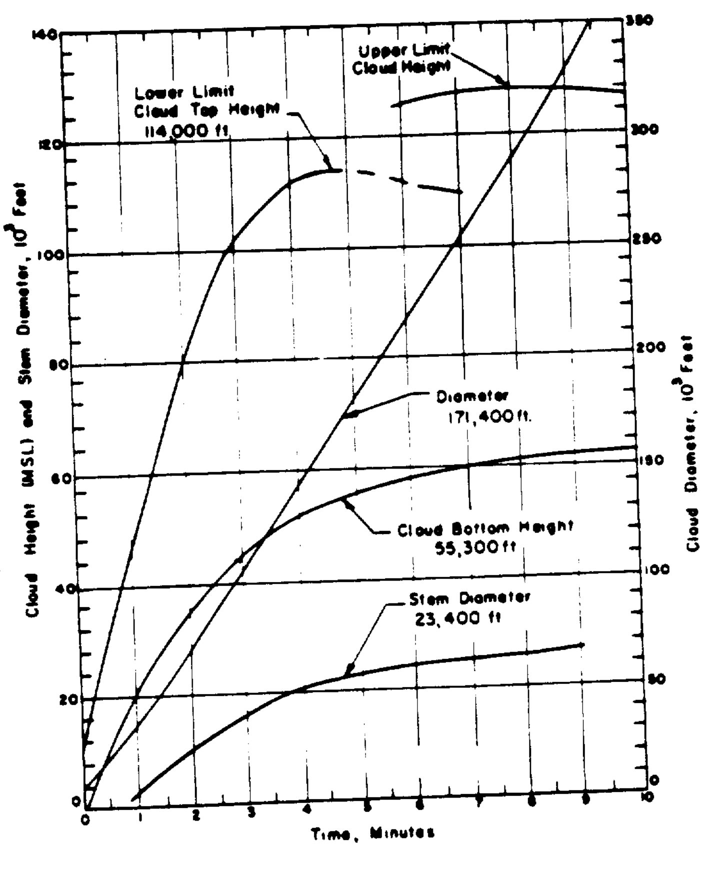


FIGURE 1. Relative location of the exposed people.

SLIDE 1

BRAVO Cloud Dimensions. The BRAVO device was detonated on a sandspit near Namu Island, Bikini Atoll at 0645 March 1, 1954 (28/2/54 1845 GCT). It was a 17 MT thermonuclear yield. The upper limit to cloud height was 40 km (25 miles). The diameter 10 minutes after the burst was 110 km (70 miles). The fission/fusion ratio was estimated to be 0.47. It was the first in the Castle series of experiments. The second shot was 100 KT and occurred 30 days later. The next three shots were 150 KT, 9.5 MT and 10 MT respectively. The 9.5 and 10 MT shots may have contributed some fallout at Rongelap and Utirik, perhaps as much as a 8% of the surface activity. These later shots occurred after persons were evacuated.



Cloud Dimensions: Operation CASTLE - Shot 1 - Bravo.

SLIDE 2

Acute Exposure. In order to estimate acute exposure, meteorology and fallout dispersion models were used to calucate external exposure rate and air activity concentrations. Archival soil measurments were used to calculate surface activity levels of the iodine isotopes. The meteorology results and archival soil results were not used in the final thyroid dose estimate becuase they could not satisfy the basic criteria that new results must be related to previously known facts. Two approaches 1) the estimate of ^{131}I intake from urine results and 2) the estimate of particle size and nuclide composition by Japanese scientists who examined fallout collected from a Japanese fishing vessel near Rongelap, could both be related to each other and be related to the know facts about fallout arrival and duration, external exposure rate measurements and gross beta measurements.

Once the nuclide composition was assessed, the composition was normalized to external exposure rate measurements. Exposure rate histories were constructed for each island. Estimates of intake of radioiodines and radiotelluriums were normalized to the ^{131}I intake estimate which was based on Rongelap urine results and related to external exposure rate. The time and mode of intake were based on diet and living pattern observations. The population mean and individual thyroid absorbed dose were based on the age and location of the exposed people. Age dependent values of thyroid absorbed dose per unit activity intake were obtained from the scientific literature.

The final results were internal and external thyroid absorbed dose estimates for 251 exposed people.

ACUTE EXPOSURE

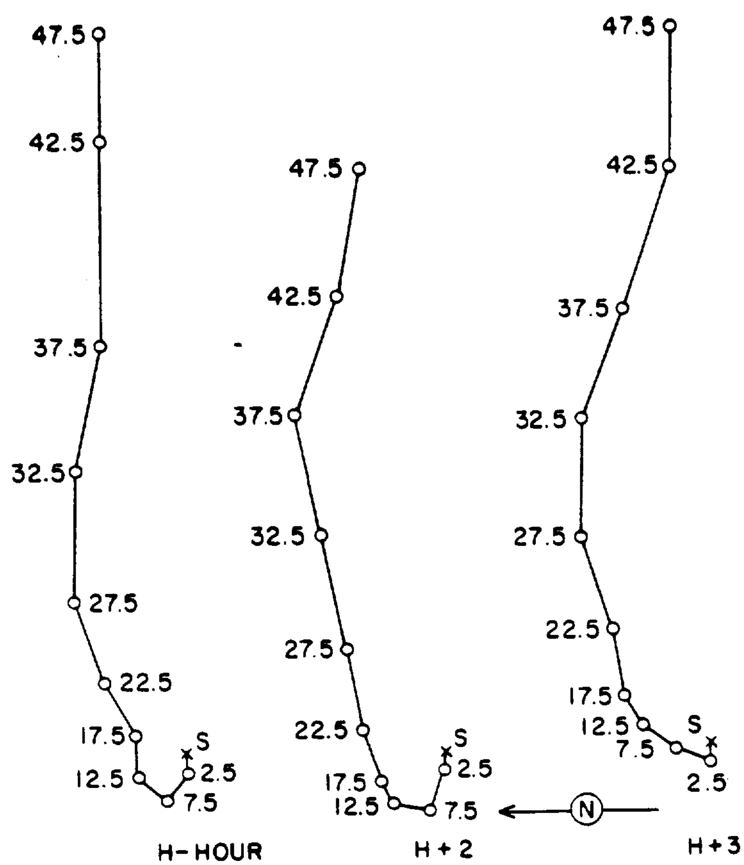
Meteorology
Archival Soil Measurements
Composition of Fallout
Activity Excreted
Activity Intake
Absorbed Dose

SLIDE 3

Meteorology. Downwind expsoure rate contours were estimated by several groups (Armed Forces Special Weapons Project, Rand Corporation, Naval Radiological Defense Laboratory) for the BRAVO detonation (Ha79). These contours were based on observations of BRAVO cloud dimensions and hodographs for 3 hours, 6 hours and 9 hours post detonation. These contours do not all agree but are within a factor of two for any specific location at Rongelap and Utirik Atolls. Significant departure in exposure rate contours occurs 32 to 190 km (20 to 120 miles) north of Rongelap Atoll out to a distance of 480 km (300 miles) east of the detonation site.

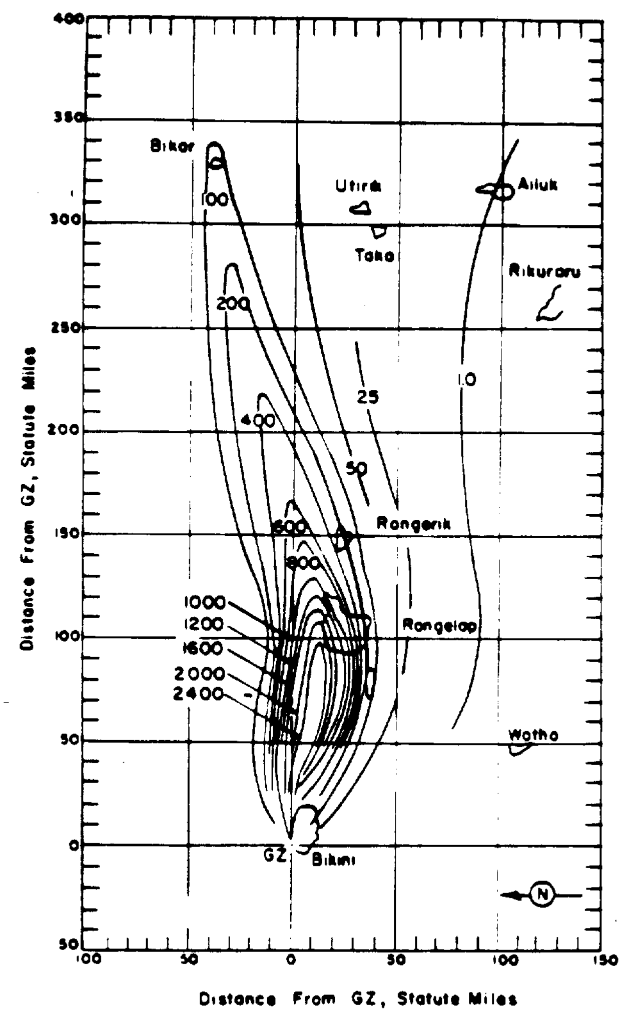
Kendall Peterson estimated downwind exposures using the MATHEW-ADPIC modified code suite (Pe81). Additionally, Peterson developed instantaneous activity concentrations for ^{129}Te, ^{131}I, ^{135}I, ^{137}Cs, and ^{155}Eu for Ailingnae Atoll and the southeastern part of Rongelap Atoll in proximity to Rongelap Island. The computer codes were developed for the Atmospheric Release Advisory Capability of the Department of Energy. They were modified to include a large number of upper-air wind levels which was thought by Peterson to be important. Additional modification included a turbulent wake correction to large granules falling from the stratosphere. Parameters for a tropical atmosphere were incorporated into granule fall velocity calculations. An assumption that the activity per granule increased as the cube of granule radius was made. Further description of the analytical approach has been given by Peterson (Pe81).

METEOROLOGY



SLIDE 4

BRAVO fallout patterns based on meteorology. This contour of exposure rate was estimated by the Armed Forces Special Weapons Project (AFSWP). The contour was cucumber shaped. Exposure rates were hypothetical values at one hour after the shot. The contaminated region was an area of more than 70,000 km^2 (27,000 square miles) extending 50 km (30 miles) upwind and over 540 km (340 miles) downwind. The width of the crosswind direction was variable, the maximum being over 220 km (140 miles).



Operation CASTLE - Shot 1 - Bravo.
Off-site dose rate contours in r/hr at H+1 hour (AFSWP).

SLIDE 5

Whole-body dose estimates. On Rongerik Atoll, a military outpost, a set of film badges were present and readings were obtained (So55). Monitoring instrument readings and the film badge results led Sondhaus to postulate total gamma exposures, from the time fallout began up to the time of evacuation, of 0.027, 0.022 and 0.018 C kg^{-1} (106, 86 and 70 R) based on three assumed fallout durations of 8, 12 and 16 hours, respectively. One film badge remained outdoors at Rongerik from the time of fallout to evacuation and recorded 0.025 C kg^{-1} (98 R).

The values for whole-body dose estimated by Dunning, Sondhaus and those estimated by Lessard who used fallout composition studies, are in reasonable agreement. These last two approaches were different from each other in that Sondhaus derived the estimate of whole-body dose from actual measurements of total exposure (film badges at Rongerik) and exposure rate, while the estimate by Lessard depended upon measurements of the composition of fallout, living pattern corrections, and exposure rate measurements made by survey teams during evacuation efforts. The approach used by Peterson depended on upper-air wind level patterns and the fallout was estimated by him to drift in a southerly fashion. This was not in agreement with assumptions used in three previous and independent approaches (Ha79). The Peterson results for whole-body dose were, therefore, radically different from other estimates for persons located at Rongerik and Utirik and do not coincide with measured values for exposure and exposure rate (Sh57).

It was not clear which exposure rate measurements were accepted by Peterson for normalizing his meteorology based results. It is clear that he accepted one measurement at some location. He may have purposely overlooked measured exposure rates in deference to upper-air wind patterns (Pe81).

ESTIMATES OF WHOLE-BODY ABSORBED DOSE

	Grays			
Location of People	1955 Sondhaus	1957 Dunning	1981 Peterson	1984 Lessard
Rongelap	1.75	1.70	1.10	1.9
Ailingnae	0.69	0.75	0.24	1.1
Utirik	0.14	0.15	0.0033	0.11
Rongerik	0.78	—	3.4	0.81

SLIDE 6

Duration of fallout. Duration of fallout is defined as the time fallout begins up to the time of cessation. This should not be confused with the time fallout begins up to the time of evacuation which is much longer. Peterson's estimated duration of fallout of about 19 hours at Rongelap, appears to be too long relative to the known wind velocity moving the cloud past Rongelap (Cr56) and relative to the first-hand accounts of fallout duration given by the Marshallese evacuated from Rongelap Island (Sh57). Rongerik Atoll was 65 km (40 miles) further away from the detonation than wan Rongelap Atoll. An upper limit of 16 hours duration at Rongerik Atoll was estimated by Sondhaus.

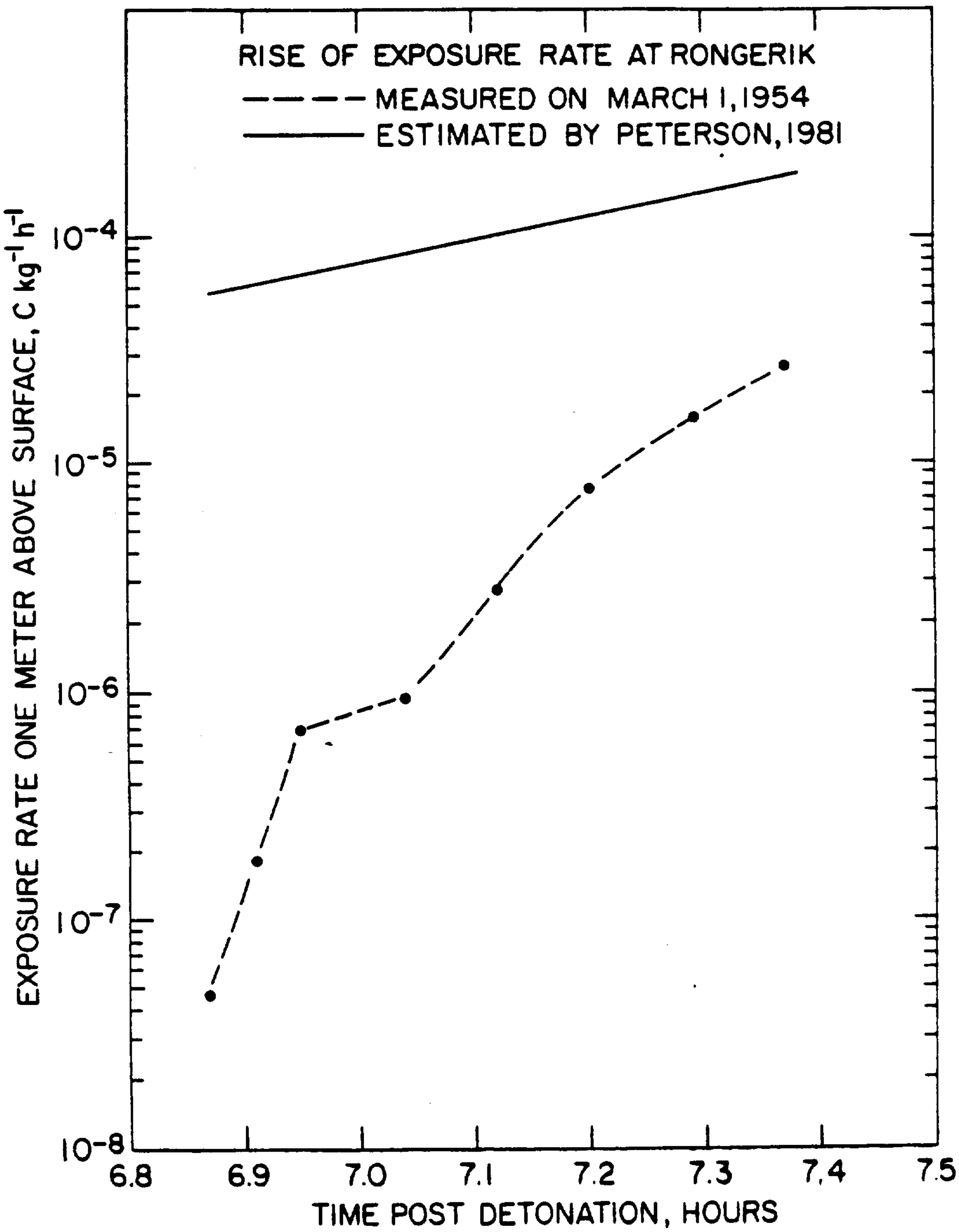
Fallout at the location of Sifo Island, Ailingnae Atoll was at the same distance from the detonation site as the Japanese vessel which was contaminated by BRAVO fallout. This fallout was named Bikini Ash by the Japanese. Bikini Ash granule size was visible to the eye (Su56) and was observed to fall for 5 hours (Ts55). Bikini Ash granule size is consistent with reports that fallout was visible at Rongelap, Rongerik and Ailingnae. Fallout would not have been visible at Utirik based on distance vs granule size extrapolations and fall velocity considerations. Visual observations of fallout arrival and cessation time were reported by many persons at each of these locations, (Sh57, Ts55) except Utirik, and were in reasonable agreement with Dunning's values. Lessard estimated duration time based on granule size of Bikini Ash, the relative positions of the atolls and the fishing vessel, and granule fall velocity estimates (Le84b).

DURATION OF FALLOUT

Location of People	Distance from Ground Zero	Hours			
		1956 Sondhaus	1957 Dunning	1981 Peterson	1984 Lessard
Ailingnae	150 km	12	5.5	10	5
Rongelap	210 km	12	5.5	19	7
Rongerik	270 km	12	—	17	9
Utirik	570 km	12	17	3	19

SLIDE 7

Rate of rise of exposure rate. The rate at which exposure rate rises to the peak value has an impact on estimates of whole-body dose. Rate of rise of exposure rate at Rongerik Atoll was estimated from monitoring instrument readings taken for one-half hour (So55). Rate of rise was determined also from results supplied by Peterson (Pe81). Exposure rate contours from graphs provided by Peterson were evaluated for different times for the Rongerik location. A best fit of the data yielded an exponential rise in exposure rate. A comparison of the two, measured versus that based on Peterson's work, indicated wide discrepancy in rate of rise, the measured data being much steeper.



SLIDE 8

Estimates of airborne activity concentrations. Air activity concentration at Rongelap and Sifo Island were tabulated from the meteorology results provided by Peterson for ^{131}I and ^{133}I (Pe81). Also, results for air activity concentrations of ^{131}I and ^{133}I were estimated from the Bikini Ash composition and tabulated for comparison. Details on this method are given by Lessard (Le84b). The cumulated activity agree somewhat, however the instantaneous airborne activity concentrations do not agree well. In summary, the Peterson approach towards estimating dose to the exposed Marshallese requires further refinement in order to achieve correspondence with all available information regarding external exposure and exposure rate.

AIR ACTIVITY CONCENTRATIONS AT RONGELAP

Time Post Detonation, Hours	Bq M^{-3} 1981, Peterson ^{131}I	1981, Peterson ^{133}I	1984, Lessard ^{131}I	1984, Lessard ^{133}I
5	7.4	250	3,700	110,000
7	250	7,400	1,100	25,000
10	15,000	110,000	19	330
14	74	1,500	0	0
17	11	250	0	0

SLIDE 9

Surface activity based on soil analysis. Surface soil activity measurements are important because they may be related to activity on the ground at the cessation of fallout if the soils are undisturbed, or if disturbances can be accounted for.

Surface soil samples were removed from Rongelap, Utirik and other atolls in the Marshall Islands during the period 1955 to 1977. Samples were stored at the University of Washington's Applied Fisheries Laboratory. The surface soil samples were taken at depths up to two inches. Soil sample tests for ^{129}I were either mid-island soils with humus, sandy soils from all parts of the island, black and white beach sands, grey powdery soils, randomly collected composites or humus-seedy mixtures. Out of the thousands of samples of this type stored at the University, several hundred were identified for neutron activation analysis by persons from BNL. Samples were packed and sent to Battelle Northwest Laboratory and analyzed by Brauer (Br80).

ARCHIVAL SOIL MEASUREMENTS

PNL ANALYSIS

Date	I-129 PCI/G	PCT ERR	I-127 NG/G	PCT ERR	CS-137 PCI/G	PCT ERR	EU-155 PCI/G	PCT ERR	Comment
102255	8.5E−03	3	1.5E+04	5	3.5E+00	1	2.7E−01	7	Utirik soil, very fine, dark grey, powdery
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	

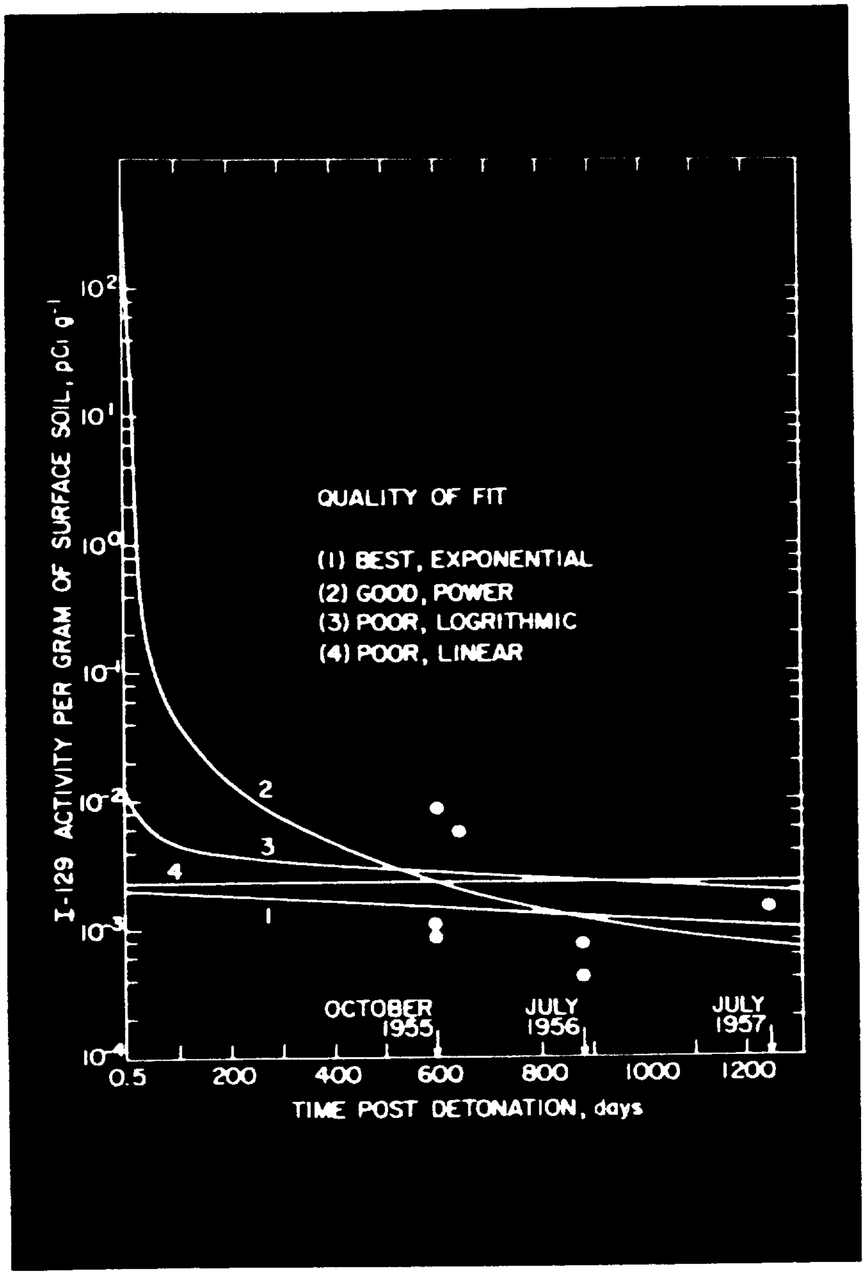
OVER 50 SOIL SAMPLES WERE ANALYZED FOR ^{129}I, ^{127}I, ^{125}Sb, ^{137}Cs, ^{155}Eu, ^{60}Co,

SLIDE 10

Analysis of samples. Soil samples were analyzed for ^{127}I, ^{129}I, ^{125}Sb, ^{137}Cs, ^{155}Eu, and ^{60}Co. The methods used for neutron activation analysis were described by Brauer (Br74) and Keisch (Ke65). Iodine was separated from soils according to the method of Studier (St62). Once separated, the iodine was irradiated with neutrons in a nuclear reactor, purified to reduce levels of interfering nuclides and then measured by gamma spectroscopy (Br80). In order to perform quality control, comparison samples containing known amounts of ^{125}I, ^{127}I and ^{129}I were irradiated with each set of iodine samples isolated from Marshall Islands' soil.

Following irradiation the iodine samples were further purified and then precipitated onto the detecting media. The number of atoms of activated nuclide were determined by gamma spectroscopy measurements of the radioactivity produced in the soil sample and in a comparison sample. The number of initial comparison atoms and resulting comparison activity were used to determine a production ratio. The production ratio was applied to the soil sample activity and the number of atoms of activated nuclide per gram of soil was estimated. Corrections to the soil activity were made based on results for soil sample blanks, comparison sample blanks and method yield. Individual counting errors were normally less than 5% although a few samples approached 20%. A least squares fitting was performed on results for nuclide soil activity per unit soil mass vs days post detonation using linear, exponential, logarithmic and power function models. Sample results varied from their best fit value by as much as a factor of 9 and by an average factor of 2.5 over the period 1955 to 1977.

The best fitting function was determined based on a comparison of the coefficient of determination for each model. Functions used with ^{129}I results for Rongelap soil are plotted here. For ^{129}I soil results, the best fitting function was exponential. All four fitting functions were generally useful in predicting soil activity per gram at times after 600 days post BRAVO for all nuclides. Significant departure between functions occurs during the period several hours out to one year post BRAVO. For example, at 0.5 days the difference between the exponential and power function estimates spans 5 orders of magnitude for ^{129}I.



QUALITY OF FIT
(1) BEST, EXPONENTIAL
(2) GOOD, POWER
(3) POOR, LOGRITHMIC
(4) POOR, LINEAR
I-129 ACTIVITY PER GRAM OF SURFACE SOIL, pCi g⁻¹
TIME POST DETONATION, days
OCTOBER 1955
JULY 1956
JULY 1957

SLIDE 11

Ratio of nuclide to total fallout activity. The ratio of ^{129}I activity to total fallout activity would help in determining if the archival soil analysis for radioiodine corresponded to other measured or hypothetical ratios. The surface-soil activity of each nuclide measured by Brauer was estimated for 0.5 days post detonation. This was the assumed time of cessation of fallout at Rongelap. The value for the nuclide activty per unit mass of soil at the cessation of fallout was estimated from the best fit of archival soil results. The value of the denominator used in the ratio was based on measured gross beta activity. Gross beta analysis was done on soil samples taken on March 8, 1954 (OC68) from Rongelap Atoll.

Hypothetical nuclide activity relative to total fission product activity was estimated from data on thermonuclear fission of ^{238}U given by Crocker (Cr65). Total activity values given by Crocker do not account for chemical and physical deletion or enhancement of fission products, production of activation products or production of transuranics. Total acitivity per 10,000 fissions at 0.5 days was taken from Table 3 of Crocker's report (Cr65). Individual nuclide activities were calculated by Crocker's methods and the original inupt data (Cr63).

The ratio derived from BRAVO fallout measurements was based on Bikini Ash activity.

For ^{125}Sb, the ratios were not similar however sample size was small. For ^{155}Eu and ^{137}Cs, results were in accord at both Rongelap and Utirik. The archival soil results for ^{129}I at Rongelap and Utirik were distinctly different from the thermonuclear fission results and Bikini Ash results.

SURFACE ACTIVITY RATIOS 0.5 DAYS POST DETONATION

Nuclide	Archival Soil Measurements Nuclide Activity / Gross Beta Activity	BRAVO Fallout Measurements Nuclide Activity / Bikini Ash Beta Activity	Hypothetical Thermonuclear Fission ^{238}U Nuclide Activity / Fission Product Activity
^{125}Sb	1.8×10^{-7}	3.5×10^{-6}	4.6×10^{-6}
^{129}I	2.6×10^{-10}	4.5×10^{-12}	3.5×10^{-12}
^{137}Cs	7.6×10^{-6}	7.1×10^{-6}	5.5×10^{-6}
^{155}Eu	8.3×10^{-7}	7.1×10^{-7}	9.6×10^{-7}

Iodine activity on the surface. Based on archival soil measurements the iodine isotope activity per unit area of soil at the cessation of fallout at Rongelap was tabulated. It was assumed that iodine isotopes were enriched in the same amount as ^{129}I, as indicated to us by archival soil results. The total radioiodine soil activity per unit area, based on archival soils from Rongelap, exceeded the measured total activity per unit area by a factor of ten! The total activity per unit area was based on four soil samples taken and measured for gross beta activity on March 8, 1954 (OC68). Conversion of the iodine surface activity (derived from archival soils) to exposure rate one meter above a plane source yields an estimated exposure rate 12 times greater than what was measured. Because of this disparity, the assumption could not be made that iodine isotopes reflected the behavior of ^{129}I in archival soils.

The level of ^{129}I in archival soil may be real, an artifact of the neutron activation technique, or the residue from other weapons tests occurring near the time of soil collection. Comparison of Bikini Ash ^{129}I to the hypothetical ^{129}I leads one to believe that some enrichment of occurred but not to the extent indicated by our extrapolation of archival soil measurements.

ACTIVITY PER UNIT AREA AT RONGELAP
0.5 DAYS POST DETONATION

Nuclide	Bq m^{-2} Archival Soils	Exposure Rate One Meter Above Plane of Activity / Measured Total Exposure Rate
^{129}I	5.2×10^{0}	—
^{131}I	7.0×10^{9}	0.14
^{132}I	2.2×10^{10}	2.5
^{133}I	7.4×10^{10}	2.4
^{134}I	7.4×10^{8}	0.098
^{135}I	9.3×10^{10}	7.0

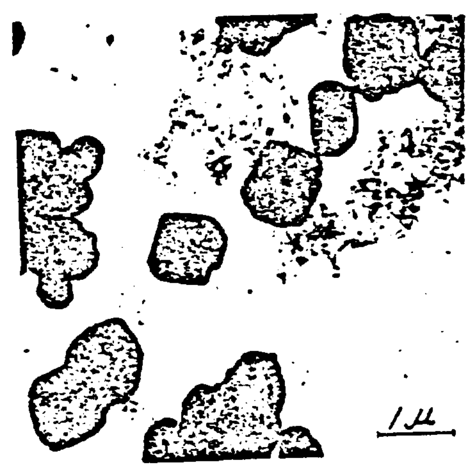
SLIDE 13

Analysis of BRAVO fallout. Bikini Ash fell on the Japanese fishing vessel, the 5th Lucky Dragon, on the day of the test. Its gross beta activity was measured and standarized to day 26, and individual nuclide beta-activity was identified and quantified by Japanese scientists (Ya56, Ts55).

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, was deposited while the ship was located about 150 km (90 miles) from the detonation site (Ta55). From the size and shape distribution it was determined the mean volume diameter of Bikini Ash granules was 320 μm ± 70 μm (Su56). The mean volume diameter was defined by them as the diameter corresponding to the mean volume. The mean mass of a granule was 0.039 mg (Su56). The specific gravity was 2.4 (Su56), less than the specific gravity of $CaCo_3$, 2.7-2.9. The granules were aggregates of smaller unit particles with shapes that varied from spindles to cubes to spheres (Su56). The size of these smaller unit particles making up the granules varied from 0.1 to 3.0 μm (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.

ANALYSIS OF BRAVO FALLOUT

CaO	55%
MgO	7%
CO_2	12%
H_2O	26%



Microscopic Detail of BRAVO Fallout

SLIDE 14

Comparison of Bikini Ash to unfractionated fallout. The per cent of fallout beta activity due to fission products present on day 26 after formation was tabulated. The hypothetical beta activity was based on a fallout composition which was unaltered due to chemical or physical mechanisms which affected certain fission product nuclides. This unaltered composition was referred to as unfractionated. This unfractionated fallout was calculated from thermonuclear neutron fission data given by Crocker for ^{238}U (Cr65).

The comparison between per cents, based on the measured values of Bikini Ash beta activity and unfractionated fission product beta activity, required conversion of the Yamatera and Tsuzuki data sets (Ya56, Ts55) into percent fission product beta activity. That is, we exclude the beta activity of the activation products ^{35}S, ^{45}Ca and the transuranic nuclide ^{237}U for comparison purposes. It was assumped by us that ^{237}U, which represented 20% of the beta activity on day 26 in the Tsuzuki results represented 20% of the beta activity in the Yamatera data.

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 ^{95}Zr (Fr61). To quantify fractionation between two nuclides, the beta activity ratios were compared by Freiling (Fr61). The term "degree of fractionation" was used by him and represented the range of variability of the nuclide ratio.

A review of the Japanese results indicted to us that the activity ratios for ^{132}Te, ^{132}I, ^{131}I, ^{141}Ce, $^{106}RuRh$ and $^{144}CePr$ (ratioed to measure $^{95}ZrNb$ beta activity) did not differ by a factor greater than about 1.5 from the unfractionated ratios. Ratios for $^{140}BaLa$, ^{147}Nd, ^{91}Y, ^{90}SrY, ^{103}Ru and ^{143}Pr differed by about a factor of 2, and ^{89}Sr and ^{129m}Te, ^{129}Te differed by about a factor of 3 relative to the unfractionated ratios. The nuclides ^{91}Y, $^{106}RuRh$, ^{128m}Te ^{129}Te, ^{132}Te, ^{132}I, $^{144}CePr$, ^{143}Pr and ^{147}Nd were in greater abundance relative to unfractionated debris.

DAY 26 COMPOSITION OF BRAVO FALLOUT

Nuclide	% Bikini Ash Beta Activity	Hypothetical Thermonuclear Neutron Fission, % Total Beta Activity
^{90}Y	0.013	0.031
^{91}Y	8.0	4.1
^{35}S	0.05	—
^{45}Ca	0.20	—
^{237}U	20	—
^{239}Pu (α)	0.0004	—

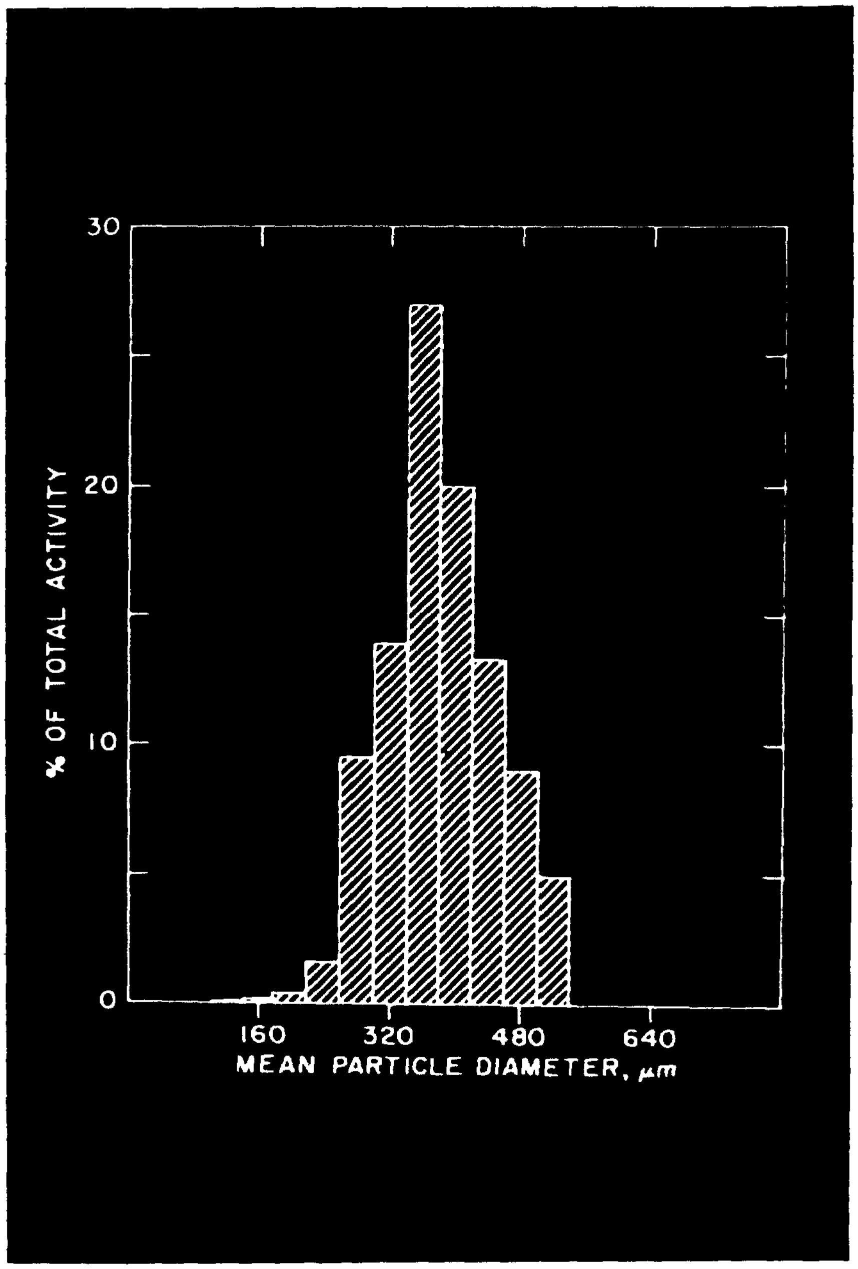
Greater Than Hypothetical
^{91}Y, ^{106}Ru, ^{106}Rh, ^{129}Te, ^{129m}Te, ^{143}Pr, ^{147}Nd

Less Than Hypothetical
^{89}Sr, ^{90}Sr, ^{90}Y, ^{103}Ru, ^{131}I, ^{140}Ba, ^{140}La

Approximately Same As Hypothetical
^{95}Zr, ^{95}Nb, ^{132}Te, ^{132}I, ^{141}Ce, ^{144}Pr

SLIDE 15

Granule size distribution and activity. The granule size distribution of Bikini Ash was used to estimate the time over which the bulk of the 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 Bikini Ash activity versus granule size distribtuion in % of total activity as a function of granule size was plotted here. In order to construct this histogram, the activity of a granule was assumed proportional to the 3.5 power of its size. Lavrenchik reported measurements varied such that the activity of a granule was proprotional to the 3rd or 4th power of the size (La65). A generalization observed by him was that the activity and volume were proportional. The number of granules in each size class was taken from Suito (Su56). The size at median activity was 370 μm for Bikini Ash.



SLIDE 16

Granule fall time. Information regarding granule fall time as a function of granule size was derived from the deposition models which were reviewed by Norment (No66). Four models of fallout settling were presented as a function of granule size 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 complexity of each model varied, however, each investigator accounted for the aerodynamic properties of irregularly shaped fallout granules. The granule fall time result versus granule size was best described by a power function in each case.

Tsuzuki indicated the observed fallout arrival time, cessation time and granule size distribution for Bikini Ash (Ts55). This data was used to model a power function relationship which related granule size to granule fall time specifically for BRAVO fallout as follows:

$$T = 79.5 \ D^{-0.524}$$

where

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

It was assumed that the largest granules in the Bikini Ash fell upon arrival and smallest granules fell upon cessation of fallout.

The times of arrival and cessation of fallout were observed at Rongelap and Sifo Islands and at Rongerik Atoll. The above equation was used to estimate granule size at these locations. The times of arrival and cessation at Utirik were based on linear extrapolation of known arrival and cessation times versus distance from detonation site. Thus, granule size at Utirik could be estimated using the above equation.

BRAVO FALL TIME

Location	Fall Time of Size At Median Activity Hours
5th Lucky Dragon	3.5
Rongelap Island	5.7
Sifo Island	3.5
Utirik Island	12

SLIDE 17

BRAVO fallout characteristics. 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 500 km (300 miles) 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 possible adsorbed 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 valid assumption due to the proximity of Rongelap and Sifo islands to the 5th Lucky Dragon. The granule size distribution was assumed to have the same shape as Bikini Ash as given by Suito (Su56). Assuming the activity of a granule was proportional to the 3.5 power of the size of the granule (La65), the per cent of total activity versus granule size was estimated. The size at median activity is given here for each location. Granules of a given size were spread throughout the stem, the base of the cloud and up to the cloud top at 40 km (24 miles). In fact, the entire distribution of granule sizes would reach the surface at any point in time, not just one size at one time. The simple model was assumed here for the purpose of estimating the rate of rise of exposure rate, the rate of accumulation of activity at the surface, and accumulated internal exposure during the period of rising exposure rates. This period was very short relative to the total exposure interval. The simple model was in agreement with measurements of rate of rise of exposure rate for weapons tests made during the Hardtack Series in 1957 (USPHS57) and with the rate of rise of exposure rate measured for one-half hour at Rongerik Atoll on March 1, 1954 (So55).

BRAVO FALLOUT CHARACTERISTICS

Location	Size At Median Activity μm	Distance From Ground Zero km
5th Lucky Dragon	370	150
Rongelap Island	150	210
Sifo Island	370	150
Utirik Island	15	570

Specific Gravity : 2.4
Solubility : 20-50% Iodine in Seawater
Relative Activity : $(\text{Size/Largest Size})^{3.5}$
Unit Particle Size : 0.1 – 3 μm

SLIDE 18

Exposure rate measurements. Mean values for the external exposure rate were based on many measurements reported at the time of the evacuations. A Radsafe Officer plus a 3-man team took readings in the air, throughout the islands and especially in the village areas with Army, Navy catalogue AN/PDR-27E instruments. Readings tended to be the same with and without the beta shield (OC68). Readings were interpreted to be taken at waist level, about 1 meter (3 ft) from the surface (OC68).

Held (He65) indicated a mean exposure rate at Rongelap Island of 2.9 x 10^{-9} C kg^{-1} s^{-1} (40 mR h^{-1}) at 26 days post detonation. He reported a storm with heavy rain two weeks post detonation (He65). This was followed by a reduction in exposure rate greater than what would have been expected from decay of BRAVO fallout. Glasstone (Gl62) repored a 40% reduction in the exposure rate, attributed to weathering alone, during the first 25 days post BRAVO in certain areas of the Marshall Islands.

We estimated the reduction in exposure rate due to weathering at Rongelap Island based on measurement taken 2.2 days post detonation by the USS PHILIP radsafe team. It was assumed to be a measurement on unweathered fallout and to decay with decay at a rate based on the nuclide mixture present at Rongelap 2.2 to 26 days post detonation. This decline was based on the gamma decay of 142 nuclides. For the estimate of decline, we accounted for the contribution to exposure rate from: 1) the transuranic nuclides ^{237}U and ^{239}Np, 2) the neutron induced nuclides ^{35}S and ^{45}Ca, 3) the day 26 fission products which had fractionated according to Japanese results (Ya56, Ts55) and 4) the fission product and transuranic product precursors. The day 26 value of the exposure rate extrapolated from the 2.2 day measurement made by the radsafe team was 18 per cent over that reported by Held. Thus, 3.4 x 10^{-9} C kg^{-1} s^{-1} (47 mR h^{-1}) was the mean unweathered exposure rate estimated to have existed on day 26 had the rain storm not occurred.

EXPOSURE RATE MEASUREMENTS

Time Post Detonation	Rongelap Island $R\ h^{-1}$ Mean	Rongelap Island Maximum	Sifo Island Mean	Sifo Island Maximum	Utirik Island Mean	Utirik Island Maximum
54 hours	1.5	1.9	—	—	—	—
78 hours	—	—	0.41	0.48	—	—
62 hours	—	—	—	—	0.10	0.13
26 days	0.047	—	—	—	—	—

Normalization of fallout activity to exposure rate. Beck recorded activity per unit area per unit exposure rate factors for a number of particulate gamma-emitting fission products and for a number of particulate activation products and residual nuclear materials as the ground as a result of weapons tests (Be80). The exposure rates at one meter above the surface of a planar source of unit area of Bikini Ash activity were calculated for each nuclide based on the data of Beck (Be80) and nuclide composition of the ash.

By summing the product of each nuclide's exposure rate (relative to unit activity per unit area) and fraction of total activity represented by each nuclide in Bikini Ash, the exposure rate from Bikini Ash per unit areal activity was estimated to be 1.12×10^{-17} C kg^{-1} s^{-1} Bq^{-1} m^2 (5.8×10^{-3} R h^{-1} mCi^{-1} km^2). By inverting this sum and multiplying by the fraction of each nuclide activity relative to the total Bikini Ash activity and the Rongelap exposure rate on day 26, we estimated the beta activity of each nuclide per unit area due to BRAVO fallout on the surface of Rongelap Island.

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. The 0.5 day post detonation time was chosen by us as the point in time at which the fallout at Rongelap Island had effectively ceased (Sh57). First order linear kinetics for serially related nuclide species (Ba10, Sk75) 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 any short-lived precursor nuclide, not present on day 26 but on the ground at the end of fallout at 0.5 days, was also calculated.

AREAL ACTIVITY RELATED TO EXPOSURE RATE

$$\sum \frac{(\mathrm{R\,h^{-1}})_{\mathrm{Nuclide}}}{(\mathrm{Ci\,m^{-2}})_{\mathrm{Nuclide}}} \times \frac{(\mathrm{Ci})_{\mathrm{Nuclide}}}{(\mathrm{Ci})_{\mathrm{Bikini\ Ash}}} = \frac{(\mathrm{R\,h^{-1}})_{\mathrm{Bikini\ Ash}}}{(\mathrm{Ci\,m^{-2}})_{\mathrm{Bikini\ Ash}}}$$

$$\frac{(\mathrm{Ci\,m^{-2}})_{\mathrm{Bikini\ Ash}}}{(\mathrm{R\,h^{-1}})_{\mathrm{Bikini\ Ash}}} \times (\mathrm{R\,h^{-1}})_{\mathrm{Measured}} \times \frac{(\mathrm{Ci})_{\mathrm{Nuclide}}}{(\mathrm{Ci})_{\mathrm{Bikini\ Ash}}} = (\mathrm{Ci\,m^{-2}})_{\mathrm{Nuclide}}$$

SLIDE 20

<u>Radioactivity in excreta.</u> 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 Harris at Los Alamos Scientific Laboratory and an estimate of thyroid absorbed dose from internal emitters was reported by Cronkite (Cr56). The 64-person composite urine sample was 75% adult urine (18 ℓ, >16 years of age), 20% adolescent and child urine (4.8 ℓ, 5-16 years of age) and 4.8% child and infant urine (1.2 ℓ, <5 years of age) (Ja64). Harris indicated a mean activity of 0.48 kBq (1.31 x 10^{-2} μCi) of ^{131}I in the Rongelap adult 24-hour urine taken on the 17th day post detonation (Co72). The adult mean peak thyroid content of ^{131}I was estimated by Harris to be 414 kBq (11.2 μCi) based on these urine samples (Ha54). This estimate was calculated on the assumption that 0.1% of stable iodine burden on the first day would be eliminated via the urine between the 15th and 17th days (Co72).

Cronkite (Cr56) reported ^{89}Sr and ^{140}Ba urine activity excretion on day 45 post detonation for six adults from Rongelap Island. The mean urine activity excreted for ^{89}Sr was 8.9 Bq (2.4 x 10^{-4} μCi) on day 45 and for ^{140}Ba, 2.2 Bq (6.0 x 10^{-5} μCi) on day 45.

RADIOACTIVITY IN EXCRETA
(RONGELAP)

Nuclide	Day Post Detonation Urine Was Collected	Adult Mean Activity Excreted In One Day Bq
^{131}I	17	480
^{89}Sr	45	8.9
^{140}Ba	45	2.2

SLIDE 21

Radioactivity intake estimated from excreta. The fraction of an initial ^{131}I activity intake by ingestion that would be eliminated by an adult on a given day post the intake was calculated by two methods. One was a model by Johnson (Jo81) and the other was a model used by ICRP (ICRP79). Both models had feedback incorporated into the estimate of the fraction of initial intake. Both were solved using catenary compartment kinetics and both led to similar values for elimination of ^{131}I by a reference man. Based on 0.48 kBq (1.32 x 10^{-2} μCi) in adult urine on the 17th day post intake, a 3,440 kBq (93 μ Ci) intake was estimated for ^{131}I.

The intake of 3,440 kBq (93 μCi) was used as a normalization point. That is, once the relationship between ^{131}I and other nuclides in fallout was determined by us, then the contribution to thyroid dose from all radioiodines was estimated while keeping the ^{131}I intake at 3,440 kBq (93 μCi).

Whole-body retention functions were given by ICRP (ICRP72) for strontium and barium as follows:

$$R_{Sr}(t) = 0.60e^{-0.25t}+0.299(t+0.20)^{-0.18}(0.555e^{-6.5x10^{-5}t}+0.445e^{-2.6x10^{-4}t}),$$

$$R_{Ba}(t) = 0.38e^{-0.75t}+0.191(t+0.007)^{-0.237}(0.564e^{-1.09x10^{-4}t}+0.436e^{-4.36x10^{-4}t}),$$

where t is in days and R(t) is the absorbed fraction remaining on day t. The fecal to urine ratios for excretion of absorbed Sr and Ba were 0.25 and 9.0, respectively (ICRP72) Correcting for 45 days of decay, the ^{89}Sr activity absorbed was estimated to be 2.3 x 10^4 Bq (0.62 μCi) and the ^{140}Ba activity absorbed was 6.1 x 10^5 Bq (16.4 μCi). If fallout was directly ingested as a single intake of dust at 0.5 days post detonation, then the intake of ^{140}Ba, ^{90}Sr or ^{131}I should be in a ratio similar to one estimated by us by a different approach. The fraction of ingested iodine absorbed into blood was taken as 1.0, the fraction of ingested strontium absorbed into blood was taken as 0.2 and the fraction of ingested barium absorbed into blood was taken as 0.06 (ICRP68). The intake ratios we obtained from urine results for ^{131}I relative to ^{89}Sr or ^{140}Ba are 28 and 0.34, respectively. The hypothetical ratios are 8.5 and 1.2 based on unfractionated thermonuclear fission data. Thus the urine derived ratio of activity is a factor of 3 lower than the hypothetical ratio for ^{89}Sr and a factor of 3 higher for ^{140}Ba.

ESTIMATE OF ACTIVITY INGESTED
(RONGELAP)

Nuclide	Activity Ingested Bq	Iodine Activity[a] / Nuclide Activity
^{131}I	3.4×10^6	1.0
^{89}Sr	1.2×10^5	8.5
^{140}Ba	1.0×10^7	1.2

[a]Thermonuclear neutron fission and 5 hours post detonation.

Radioactivity intake through food, water supplies and air. Preparation and consumption of food in the open was and still is a common practice among the Marshallese people and fallout was ingested directly with food. Food was reported to taste strange by persons interviewed at Rongelap following 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 outdoor 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.

The majority of activity fell at Rongelap Island during preparation of the mid-day and evening meals. Fallout was visible on peoples skin; it caused itching, sneezing and coughing (Sh57). The living pattern of the Marshallese led to direct ingestion of BRAVO fallout in amounts which can be estimated based roughly on meal intake but more accurately if the ^{131}I activity measured in urine is taken into account. The living patterns at Utirik and Sifo were similar to those at Rongelap (Na80). No alteration in daily routine was thought to occur and no attempt at removing visible fallout from food was reported by persons evacuated from Rongelap or Sifo Islands (Sh57).

The outside area used to prepare food for the mid-day or evening meals at Rongelap may have been several square meters for a family. 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 or 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 prepartion and cooking modes allowed significant amounts of BRAVO debris to be mixed with food.

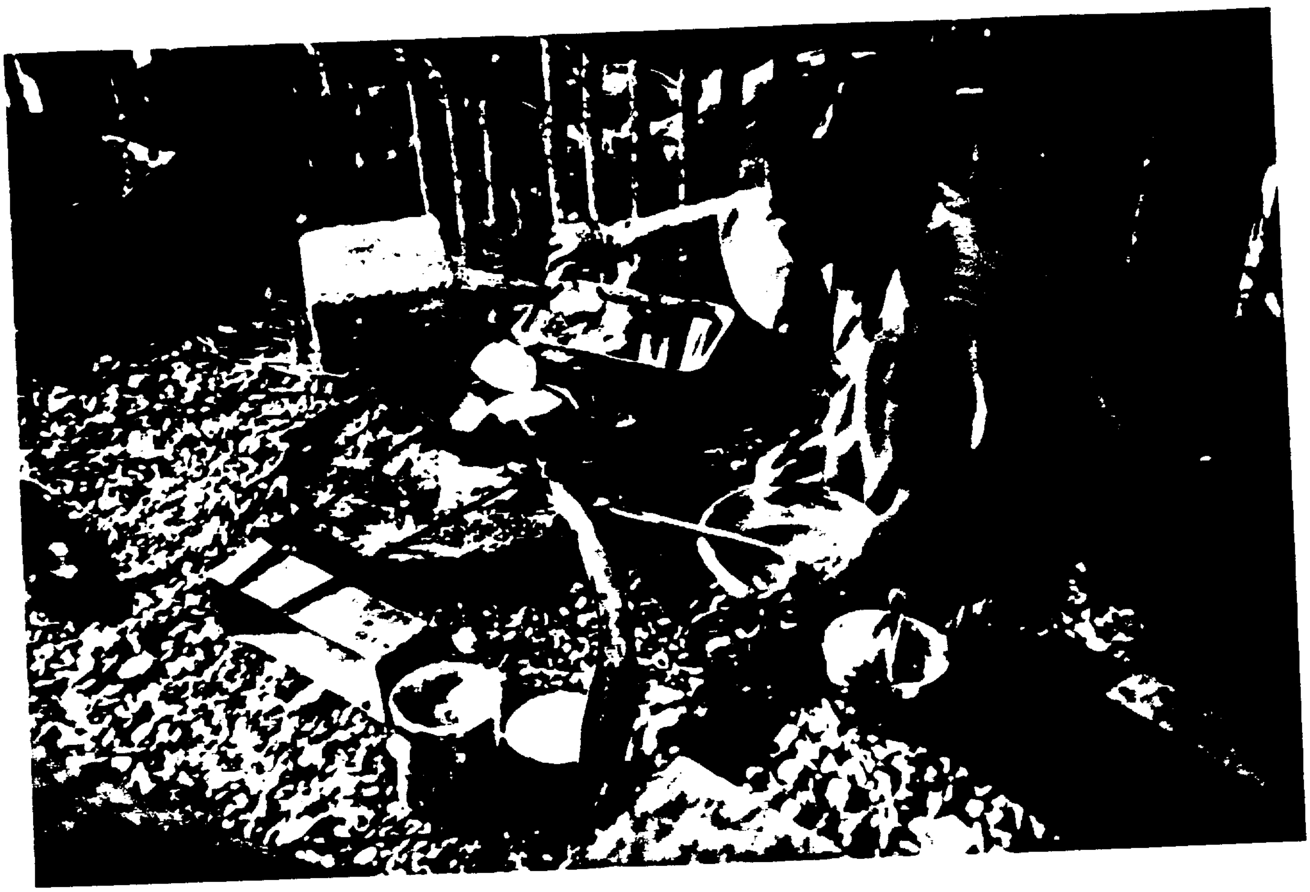
The amount of fallout dust ingested per meal would be dependent upon the amount that fell into utensils and plates during preparation and during consumption. Resuspension and subsequent deposition on food, and preparation of food on dusty surfaces would be secondary pathways. During the mid-day meal 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 exposure interval to dust, then about 40 mg (about 4/1000th of a teaspoon) would fall on this eating area at Rongelap Island. During the preparation of an evening meal about 0.1 m^2 surface area could be assumed as the family food preparation area. 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. This corresponds to a total per person ingestion of about 3.1×10^6 Bq (90 μCi) of ^{131}I; 1.1×10^6 Bq (30 μCi) at 5.5 hours post detonation and 2.2×10^6 Bq (60 μCi) at 12 hours post detonation. This corresponds to the intake based on the urine bioassay result and indicates to us that direct ingestion of fallout was a reasonable pathway to assume.

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 resulted in release of radioiodines trapped in the granules due to the acid enviroment of the stomach. The mass and volume of BRAVO fallout granules were insignificant relative to the normal amount of food eaten per meal, the normal amount being about 400 g for adult meals (Ev66). The mass of BRAVO fallout per m^2 at Rongelap Island was 4.4 g. The volume corresponding to this mass 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 per unit area estimates were for the point in time at which all fallout was on the ground. The values for Utirik and Sifo Islands were estimated by ratio of the exposure rate to that at Rongelap Island with the ratio being estimated after the cessation of fallout.

The main water supplies at Rongelap, eight cisterns, each contained a height of 0.23 m of water during the later part of March and early April 1954 (Sh57). Water was drawn from six of these cisterns at Rongelap for gross beta analysis on March 2, 1954 (see report of the radsafe team, USS PHILIP, OC68), and one other cistern was reported as out. Each cistern opening was about 0.65 m^2 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). It was assumed that the additional cistern catchment area did not contribute water or activity to the cistern. Results of the analysis for gross beta activity concentration in cistern water ranged from 1.8×10^5 to 2.0×10^6 Bq ℓ^{-1} (0.005 to 0.054 μCi ml^{-1}) with a mean of 5.0×10^5 Bq ℓ^{-1} (0.027 μCi ml^{-1}) at 50 hours post detonation (OC68). The fallout from Castle series coral surface bursts including BRAVO was barely soluble in water (Ka66). Estimates of solubility were based on 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). Therefore, most BRAVO activity probably remained with fallout granules at the bottom of a cistern.

Mean air concentration estimates of the activity of selected nuclides were based on the deposition rates of fallout granules and total activity deposited. The air activity concentration at a point in time was assumed 1) directly proportional to the fraction of total activity deposited per minute, 2) directly proportional to the total activity on the ground at the end of fallout (decay corrected back to that point in time) and 3) inversly proportional to fall velocity of granules. The cumulated air activity concentrations for Rongelap Island which were derived by us from Bikini Ash activity results were about three times less than the cumulated air activity concentrations given by Peterson (Pe81).



SLIDE 27

Estimated activity intake from cistern water. Based on 1) Bikini Ash radioiodine activity per unit area estimates, 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. These concentrations were in agreement with gross beta analysis of cistern water.

Prior to evacuation of Rongelap, many weeks of drought were reported by Sharp (Sh57). 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 were distributed and regulated by village officials. This water was used to make tea and coffee and was directly ingested (Sh57). One hundred fifty cm^3 of water were 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.

These assumed cistern water intakes led us to estimate the ingested activity tabulated here. 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.

ESTIMATED ACTIVITY INTAKE FROM CISTERN WATER

Rongelap Island

Nuclide	Activity Intake[a], M Bq
^{135}I	0.75
^{134}I	0.14
^{133}I	1.0
^{132}I	0.41
^{131}I	0.078

[a]Normalized to exposure rate and fallout composition.

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<u>Ingestion with meals</u>. An adult male was assumed to take in 3.4 x 10^6 Bq (93 μCi) of ^{131}I in order to correspond to urine data. The intakes of other iodines and telluriums were based on the relationship between ^{131}I and these nuclides in Bikini Ash. Meal intake and thus activity intake 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 which was derived by us from data tabulated in the ICRP Publication Reference Man (ICRP74). 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 intake per unit volume of breast milk was assumed to be the fraction of mother's intake of iodine transferred to newborns (Ma81). Decay of the iodine between the time of intake for the mother and the time of intake for the newborn was neglected. Radioiodine excreted from the long-term clearance compartments of the mother's body was considered insignificant relative to radioiodine cleared in the short term (Ma81).

ACTIVITY INTAKE BY INGESTION WITH MEALS

	Body Weight kg	M Bq						
		^{135}I	^{134}I	^{133}I	^{132}I	^{131}I	^{132}Te	^{131m}Te
Rongelap Adult Male	70	130	44	78	20	3.4[a]	20	3.0
Rongelap Child	30	85	30	52	14	2.3	14	2.0
Utirik Adult Male	70	5.2	—	10	3.7	0.74	3.7	0.55
Utirik Child	30	3.5	—	7.0	2.5	0.48	2.5	0.37
Sifo Adult Male	70	44	29	21	4.4	0.74	4.8	0.89
Sifo Child	30	30	19	14	3.0	0.48	3.2	0.59

[a]Normalized to urine excretion result.

SLIDE 29

Activity intake by inhalation. Airborne activity intakes were dependent upon the breathing rate of individuals during fallout cloud passage. Breathing rate was assumed proportional to body mass. We arrived at this conclusion based on reference data given by ICRP for persons less than 58 kg (ICRP74). Adult reference values for breathing rates (ICRP74) were assumed for all Marshallese adults regardless of 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 resting. At Sifo Island a period of light physical activity was assumed in order to estimate breathing rate during the morning they were exposed. On the basis of urine results and breathing rate, it was determined that inhalation could not account for the estimated activity intake for ^{131}I. Less than 1% of the intake could be attributed to inhalation. In fact lethal external exposure rates would have to accompany significant radioiodine intakes if inhalation was assumed to be the dominant intake pathway leading to the urine activity excreted on day 17.

ESTIMATE OF INHALED ACTIVITY[a]

	Body Weight kg	KBq						
		^{135}I	^{134}I	^{133}I	^{132}I	^{131}I	^{132}Te	^{131m}Te
Rongelap Adult Male	70	890	370	410	97	18	110	20
Rongelap Child	30	520	220	240	55	10	59	12
Utirik Adult Male	70	70	—	1200	410	78	410	59
Utirik Child	30	41	—	700	230	44	230	35
Sifo Adult Male	70	81	85	85	4.4	0.85	5.5	1.1
Sifo Child	30	48	48	48	2.5	0.48	3.2	0.59

[a] Air concentrations normalized to exposure rate measurements and fallout composition.

Absorption through skin. According to Glasstone (Gl62) fallout will enter the body through the digestive tract, through the lungs, or through wounds or abrasions. No direct absorption through skin is written about in JCAE57, JCCRREF56, Gl62, Cr56 or Du56. Beta burns appeared on the skin of Rongelap people many weeks after exposure. Skin was thought by us to be intact at the time of contamination. Harrison (Ha63) measured the extend to which gaseous $^{131}I_2$ and aqueous solutions of $K^{131}I$ and $^{131}I_2$ were absorbed through human skin. For aqueous $K^{131}I$ the mean absorption rate was 7.8×10^{-4} h^{-1} and for $^{131}I_2$ it was less. Use of stable I carrier with the gas was found to irritate and blister skin which may have led to increased absorption reported for gaseous $^{131}I_2$ (Ha63). Assuming 0.17 m^2 of skin surface was exposed, a surface activity of 110 MBq m^2 (3.1×10^3 μCi m^{-2}) and 49 hours of exposure at Rongelap Island, leads us to estimate 0.7 MBq (19 μCi) ^{131}I intake based on an absorption rate $7.8 \times 10^{-4} h^{-1}$. This was a conservative estimate since the skin surface was not likely to be as contaminated as the ground surface due to swimming, bathing and sloughing off of fallout granules. Assuming the urine bioassay results (Ha54) were accurate, the conservative estimate of intake through skin represent 20% of the total intake for ^{131}I.

About half the Rongelap adults had skin lesions on the scalp, neck and feet 12 to 14 days post detonation. It was not likely, therefore, that all adults had 10% of skin surface exposed to ground contamination levels continuously, although it was assumed for the above estimate. Also, the iodine was in a solid calcium carbonate matrix and was not likely to be as transportable across the skin as was aqueous $K^{131}I$. Therefore, it was assumed by us that absorption through skin was not important.

ABSORPTION THROUGH SKIN

	10% Skin Surface Exposed m^2	Maximum Hours Exposed	I Absorption Rate[a] h^{-1}	^{131}I Surface Activity M Bq m^{-2}	^{131}I Intake M Bq
Rongelap Adult Male	0.17	49	7.8×10^{-4}	100	0.72
Utirik Adult Male	0.17	59	7.8×10^{-4}	12	0.094
Sifo Adult Male	0.17	59	7.8×10^{-4}	37	0.29

[a] Aqueous KI on skin surface.

SLIDE 31

Absorbed dose estimates. External thyroid absorbed dose estimates were based on integrated photon exposure and based on an adjustment for living pattern in a variable exposure rate environment.

External beta radiation penetrating to the depth of the thyroid was not thought by us to be important. The thickness of tissue overlying the thyroid ranges from 0.4 to 2.0 cm (0.2 to 0.8 in), average 0.82cm (0.3 in), and does not correlate with age or body weight very well (ICRP74). The minimum beta energy for penetration of 0.82 cm (0.3 in) of tissue was estimated to be 1.8 MeV. At Rongelap Island about 70% of the population had skin lesions on some part of the neck appearing about 21 days post exposure (Cr56). This would imply a skin surface dose of tens of gray (several thousand rad). 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 (0.3 in) of tissue and deposit energy in the thyroid. Thus thyroid dose from this pathway was considered insignificant.

For internal emitters, thyroid absorbed dose per unit intake was compiled from values generated by Johnson (Jo82). An exponential interpolation of non-adult values was performed. Thyroid absorbed dose commitment was calculated because the nuclides of interest had half-lives much shorter than 50 years. Absorbed dose was generated based 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). The values for the tellurium isotopes were generated from reference man data contained in Limits for Intakes of Radionuclides by Workers (ICRP79). Tellurium isotope values 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 per unit intake of any tellurium isotope was assumed directly proportional to the product of the adult value and the ratio of the iodine value.

ABSORBED DOSE

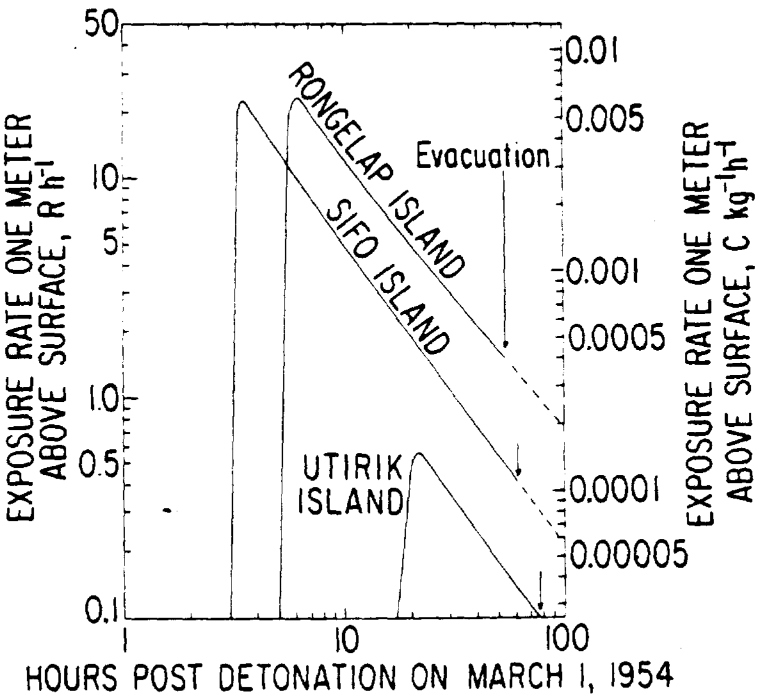
ESTIMATES

SLIDE 32

External absorbed dose adjusted for living pattern. The Marshallese reported no significant deviation from routine living patterns (see interview's recorded by Sharp Sh57). In a previous document by Greenhouse and Miltenberger (Gr77), it was shown by them that external exposure inhomogeneties due to various living patterns (such as fishing in the lagoon, standing on the beach, etc.) could be accounted for by multiplying the mean exposure rate for the island by a factor to obtain whole-body absorbed dose rate. Another multiplicative factor used by us was a correction for the electron density difference between air and tissue. Another factor used by us was one which accounted for attenuation and build-up of the photon flux as it traversed the body. The energy spectra assumed by us was that given by Borg (Bo56) for BRAVO fallout at four days. The total multiplicative factor used by us, to convert the average island exposure during the acute phase to whole-body absorbed dose, was 0.7.

SLIDE 33

External exposure rate. Rate of rise in exposure rate at Rongerik Atoll was measured by a monitoring instrument for one-half hour. A best fit of the results yielded an exponential rate of rise in exposure rate. The exposure rate peaked within an hour after the arrival of fallout at Rongelap and Sifo Islands. Arrival time and peak exposure rate were estimated by us based on granule size considerations and the rate of activity deposition. The estimate of rate of rise was in agreement with the rate of rise observed at Rongerik. The exposure rate peaked within 3 hours at Utirik. Decline of exposure rate was based on the decay of 142 nuclides which precursed the Bikini Ash. The exposure rate histories at Rongelap, Utirik and Sifo Islands were normalized to the results of the radsafe survey teams of the USS PHILIP and USS RENSHAW (OC68). The mean exposure rate at Rongelap was estimated to peak at 5.7×10^{-3} C kg^{-1} h^{-1} (22 Rh^{-1}). At Utirik the peak was 1.5×10^{-4} C kg^{-1} h^{-1} (0.59 Rh^{-1}) and at Sifo 5.2×10^{-3} C kg^{-1} h^{-1} (20 Rh^{-1}). After the cessation of fallout 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.

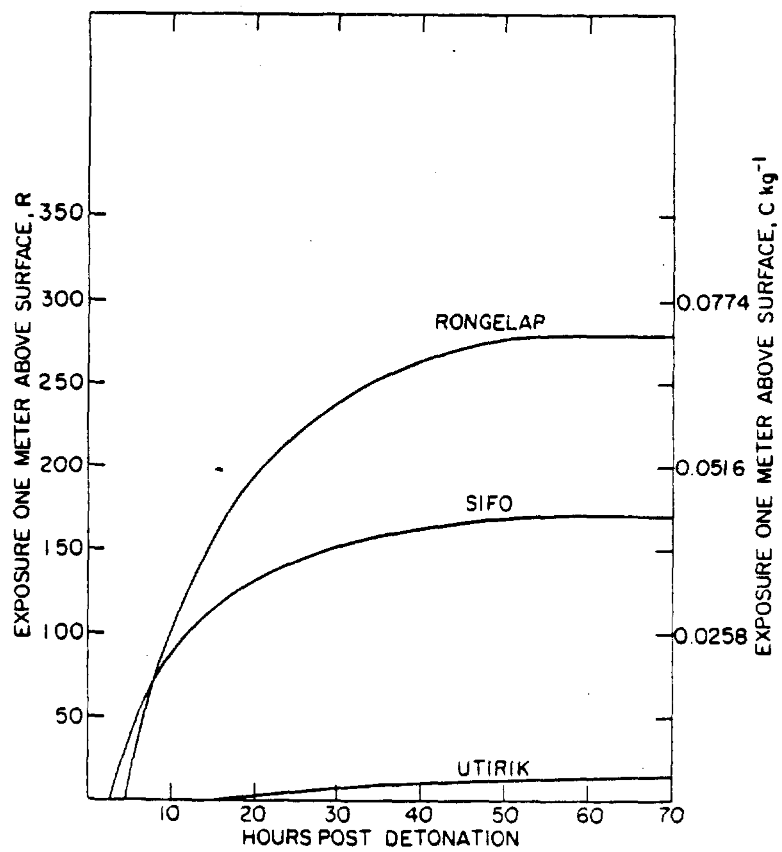


SLIDE 34

Integrated expousre and whole body absorbed dose. The total integrated exposure from the onset of fallout to evacuation was 7.2×10^{-2} C kg^{-1} (280 R) one meter above the surface of Rongelap Island. This estimate accounted for the build-up of fallout on the ground which was previously described by us and photons from 142 nuclides. A plot of the integrated exposure versus time is given here. The total integrated exposure at one meter above the surface of Sifo Island was 4.4×10^{-2} C kg^{-1} (170 R) and at Utirik Island 4.1×10^{-3} C kg^{-1} (16 R). These exposures were for the period of time from the onset of fallout up to evacuation, March 1 to 3, 1954.

These air exposure estimates lead us to agree with whole body and external thyroid absorbed dose estimates made by Cronkite et.al. (Cr56). After the multiplicative factor was applied to correct for living pattern, etc. we obtained a whole body dose estimate of 1.9 gray (190 rad) at Rongelap. This compared to 1.75 gray (175 rad) estimated by Cronkite.

INTEGRATED EXPOSURE



Internal thyroid absorbed dose. The product of age specific intake and age specific thyroid absorbed dose per unit intake was compiled for different hypothetical ages. These results were applied to the age and location of persons exposed during the acute phase and doses to population groups are listed here. The thyroid absorbed dose from all iodine and tellurium nuclides as 7.7 times the dose due to ^{131}I at Rongelap Island for adults. It was 10 times the dose due to ^{131}I at Sifo Island and 4. 7 times the dose due to ^{131}I at Utirik Island. The most probable ingestion dose evaluation by James (Ja64) for a 3.5 year old Rongelap girl was given as 14.45 gray (1,445 rad). James assumed the total thyroid absorbed dose from ingestion of all iodine isotopes in fallout was 2.6 times the thyroid dose due to ^{131}I. This factor is dependent upon the age of the fallout and the age of the individual and differs from ratios given here by us. Since James based the total thyroid dose on ^{131}I measurements in urine and this factor of 2.6, a significant difference in thyroid dose derived from the Bikini Ash method versus the James method occurs.

Several methods were used to estimate a range of fallout material ingested. One was to ingest known quantities of drug grade $CaCO_3$ with meals 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 of $CaCO_3$ when mixed with food, could not be sensed by taste at all. About 70 mg per meal were assumed to be ingested for the mean dose estimate. Another method to estimate a range of dose 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 intake of about 5 times the mean value. Another method was to examine the rage of ^{137}Cs daily activity intake from 1957 to 1983 for Rongelap and Utirik people. The intake rate was estimated from whole-body counting results. The range of ^{137}Cs intake rate was about 5 times the mean value (Le84). Another method was to examine the range of ^{137}Cs body burdens exhibited by the population inhabiting Bikini Island from 1974 to 1978 (Mi83). The range was 3.2 times the mean value. Based on the above range considerations, a value of 4 times the intake and thus 4 times the mean thyroid absorbed dose was assumed by us for estimates of maximum thyroid dose.

Age at Exposure	Total Number	External Whole Body Dose Gray	Internal Emitter Thyroid Dose Gray	Internal Emitter Dose / ^{131}I Dose
RONGELAP				
In Utero	3	1.9	4.5	8.1
<10	21	1.9	38	8.3
10-18	12	1.9	15	7.7
>18	31	1.9	11	7.7
SIFO				
In Utero	1	1.1	5.0	11
<10	7	1.1	9.9	11
>18	11	1.1	3.0	10
UTIRIK				
In Utero	8	0.11	1.2	4.9
<10	56	0.11	4.8	4.9
10-18	19	0.11	2.1	4.8
>18	84	0.11	1.5	4.7

SLIDE 36
PROTRACTED PHASE
INTRODUCTION

Subsequent to World War II, persons from the United States carried out several series of atmospheric tests of nuclear weapons in the Northern Marshall Islands between the years 1946 and 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 the inhabited atolls, Rongelap and Utirik.

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 three-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 returned to their atoll to occupy new homes, community structures and other facilities which had been constructed during their three-year stay at Majuro and Kwajalein Atolls.

During the first few weeks after the accident and at least once every year from 1957 to the present, a Brookhaven National Laboratory (BNL) 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 radiobiologial status of persons affected by tropospheric fallout from the BRAVO nuclear test.

Reports of their findings, including whole-body counting data and urine activty concentration data, are available in Cr56, Du56, Du57, Wo59, Co56, Co58, Co59, Co60, Co62, Co63, Co65, Co67, Co70, Co75 and Co80a. These reports may be consulted in order to follow the information presented here. Estimates of the intial body burdens of internal emitters were presented in Co55, Coh56 and Coh60. Since April 1978, the bioassay program and whole-body counting studies have been performed by members of the Safety and Environmental Protection Divison of BNL. Reports of their findings may be found in Gr77a, Gr77b, Le80a, Le80b, Le84, Mi80, Mi81 and Na80.

In addition to accidental contamination of people, certain groups of people were moved off their lands to prevent potential contamination which would result from the testing Program. Bikini Atoll was one area used to test nuclear weapons from 1946 to 1958. Prior to commencement of the testing program, all Bikini Atoll inhabitants were moved first to Rongerik Atoll and then finally to Kili Island.

Cleanup efforts at Bikini Atoll began in 1969 and persons decided to reside on Bikini Island at that time. By April 1978, the population numbered 138 people and consisted of caretakers and agriculturalists plus other Bikini families who found their way back via trade ships. This population remained on Bikini Island until they were relocated in August 1978 to Kili Island in the southern Marshalls and to Ejit Island, Majuro Atoll.

During the rehabilitation and repopulation years, the medical services provided by R.A. Conard and the Brookhaven Medical Team at Rongelap and Utirik were expanded to include sick call and body burden measurements at Bikini. Body burden measurements were made in 1974 (Co75) and in 1977 (Co77). In August 1977, the responsibility for providing body burden measurements was transferred from the Medical Department to the Safety and Environmental Protection Division of BNL. The 1978 and 1979 body burden measurements of the Bikini population were conducted by the latter organization.

In August 1978, the Bikini people were relocated to Kili Island and Majuro Atoll following increasing body burdens of ^{137}Cs. Removal of the Bikini population from Bikini Atoll eliminated the ^{137}Cs source term from the diet and limited the dose equivalent received by this population.

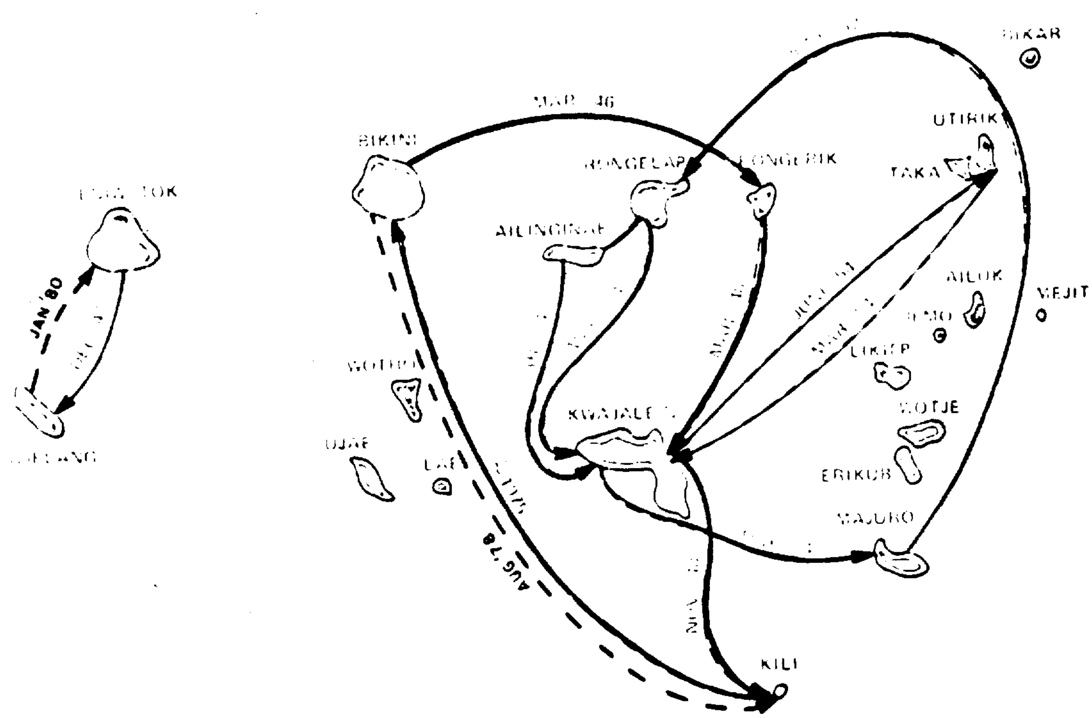
The scheduling of the first Enewetak nuclear test necessitated the removal of the people in 1947. On December 3, 1947 the Governor of the Marshalls flew to Enewetak and proposed to the chiefs that they move to Ujelang Atoll, which was then being prepared as a relocation site for the Bikini people. The two chiefs, Johannes and Abraham, were flown to Ujelang on December 4th and later returned to Enewetak after selecting sites for dwellings and community buildings. Temporary living quarters were ready for the people of Enewetak when they went to Ujeland on December 21, 1947. Permanent facilities on Ujelang were constructed in the spring of 1948.

On May 28, 1948 resettlement was completed. The first three nuclear test, the Sandstone series, were completed by May 14, 1948 and no additional tests were conducted at Enewetak until 1951. The last test was completed in July 1958.

In September 1974, the people of Enewetak and their advisors returned to Enewetak for a meeting with representatives from the Defense Nucler Agency, the Department of the Interior, and the Atomic Energy Commission. The purpose of the meeting was to present the draft environmental statement regarding the proposed project to rehabilitate the atoll, and to return the former residents there.

In February 1980, members of the BNL Marshall Islands Radiolocial Safety Program conducted a field trip to Japtan and Enewetak Islands, Enewetak Atoll and Ujelang Island, Ujelang Atoll. The purpose of this trip was to obtain baseline radionuclide body burden data on the Enewetak population prior to the repatriation in April 1980. The people of Enewetak repatriated the islands on the southern part of the atoll. Certain northern locations of the atoll have been off limits except for short visits. Most of the food is imported at this time. Monitoring of inhabitants has occurred on an annual basis since the people's return.

MOVEMENT OF PEOPLE PACIFIC TESTING



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Protracted exposure. The protracted exposure of the Marshallese occurred after people returned to the contaminated areas. The people of Utirik and Rongelap returned to a post accident environment involving radioactivity from one detonation. The people of Bikini and Enewetak Atolls returned to a post testing environment involving radioactivity from many tests occurring from 1946 to 1958. In order to assure the people that radiation exposure guidelines were being followed, routine bioassay missions have been undertaken since these people returned to their homes. Additionally, diet and living pattern studies, where scientists lived with the people for extended periods of time were undertaken to understand the internal and external exposure patterns. Information from the bioassay missions and other studies have been reviewed and estimates of radioactivity intake and corresponding dose equivalent have been made (Le84).

PROTRACTED EXPOSURE

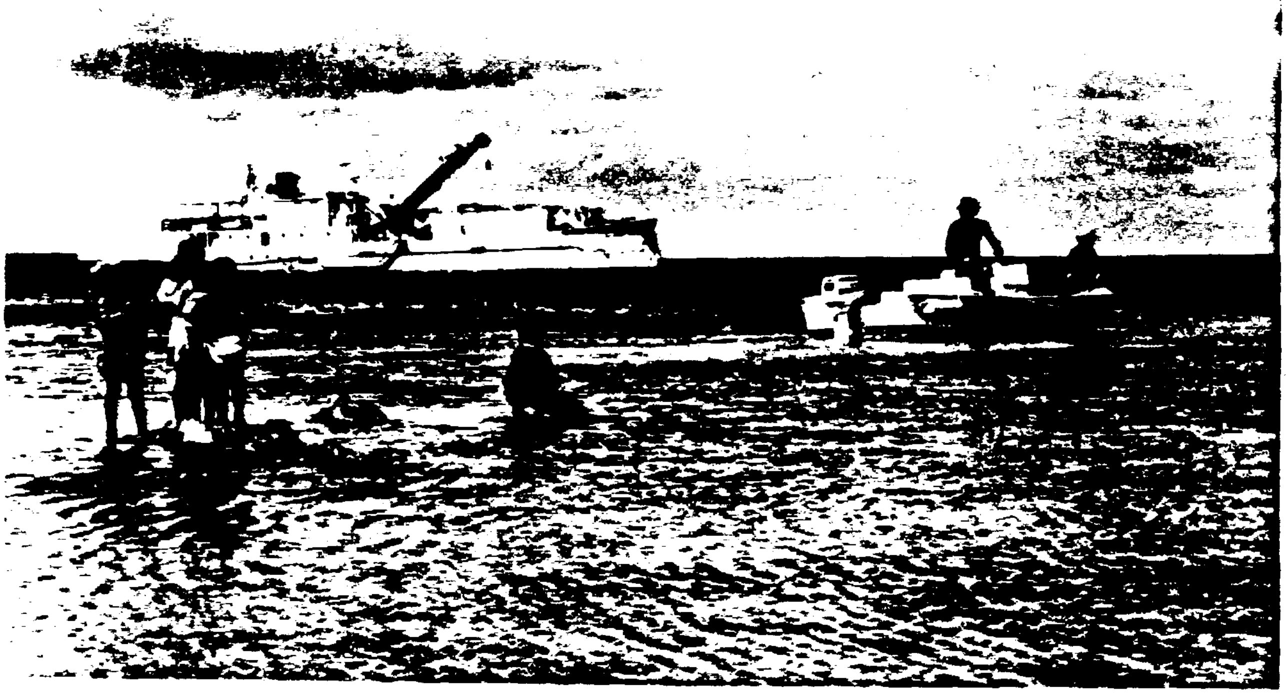
Field Measurements
Diet and Living Patterns
Body Burden Histories
Intake Estimates
Committed Effective Dose Equivalent

SLIDE 38

Field surveys. 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 as part of the Brookhaven medical examination program. A ship-borne portable whole-body counter with a standard chair geometry in a shielded steel room was employed (Co63). 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).

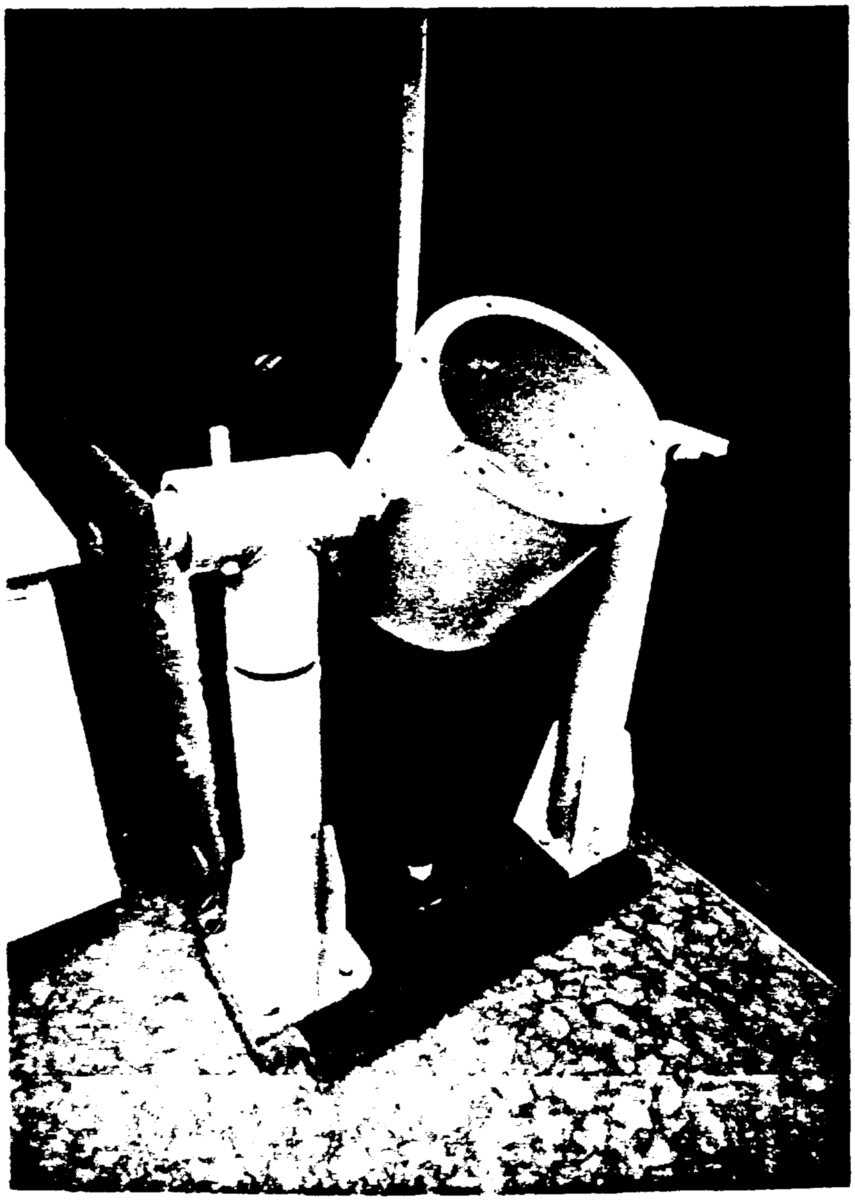
From 1978 to the present time, whole-body counting measurements were performed with the bed-type shadow shield whole-body counter (Co67). In 1980, a standard chair geometry was once again used. All three counting systems were intercalibrated and also calibrated against the large 54-detector whole-body counter at BNL.

Three body burden measurements of the Bikini Island population were conducted from 1974 to 1978 at Bikini Island. In 1980, 1981, 1982, and 1983, whole-body counting of the Enewetak population occurred. Whole-body counting in the field was done from a ship located in the lagoon of the atoll and people were taken to and from shore by small boat.



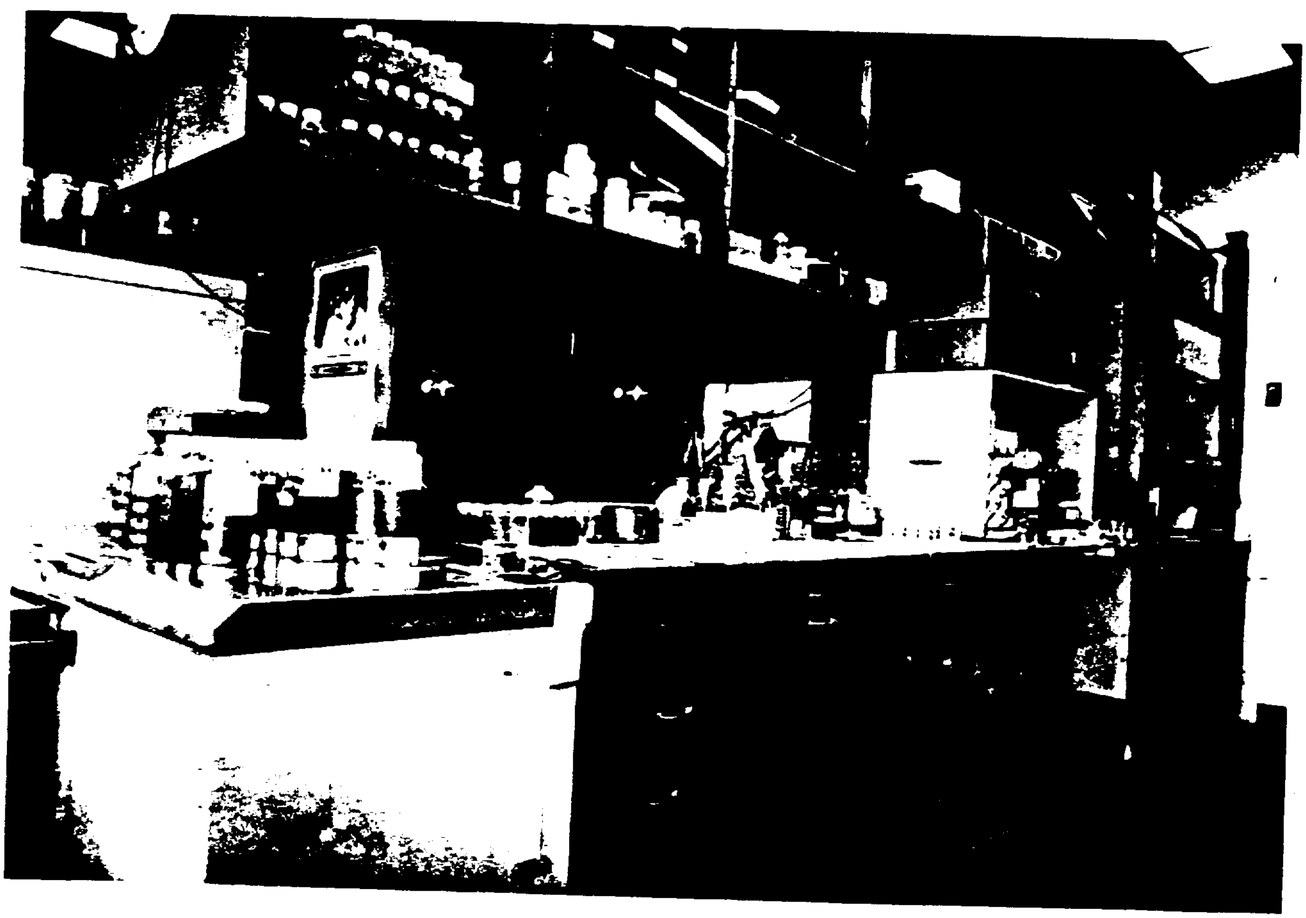
Whole-body counter. The detector chosen for field use by Brookhaven personnel was a 28 cm diameter, 10 cm thick, sodium iodide thallium activated scintillation crystal NaI(Tl). It is optically coupled to three low background magnetically shielded photomultiplier tubes connected in parallel through a summing box with the combined output routed to an amplifier and then to a microprocessor-based computer and pulse height analyzer (PHA). The PHA data is stored on a magnetic discette, and results are analyzed in the field and at BNL using a matrix reduction, minimization of the sum of squares techniques.

The gamma emitting nuclides observed have been ^{65}Zn, ^{137}Cs, ^{60}Co and ^{207}Bi. Additionally, naturally occurring ^{40}K is present in normal amounts. A typical counting time is 15 minutes and a typical minimum detection limit is 100 Bq (3 nCi). The whole-body counting system is currently standarized against a human like phantom.



SLIDE 40

Urine bioassay. Urine samples were collected during bioassay field surveys and during medical surveys. The samples were analyzed during the 1950's and 1960's by both USNRDL and the NYO-AEC Laboratories. During later years the samples were analyzed by BNL for gamma emitters and ^{90}Sr. During the 1970's and 1980's some samples were analyzed by Battelle Northwest Laboratories, Oak Ridge National Laboratory and by Los Alamos National Laboratory for ^{239}Pu. In 1983, ^{239}Pu analysis was initiated at BNL and samples collected in 1978 are being analyzed now. About 2000 urine samples and 200 fecal samples await analysis for ^{239}Pu.



SLIDE 41

External exposure measurements. In April 1975, BNL personnel initiated an external survey of Bikini Atoll in order to obtain information concerning the ambient external radiation levels resulting from the mid 1950's weapons testing program and to make dose equivalent determinations for the individuals living in the surveyed area. From 1975 to 1977, measurements were made to provide sufficient information on the external exposure received by the Marshallese people.

The equipment used were a Reuter Stokes environmental radiation monitor, model RSS-111, and a Baird-Atomic scintillation detector consisting of a sodium iodide detector (2.5 cm in diameter by 3.9 cm in length) connected to a ratemeter readout. Portable survey meters were used to help locate gross changes in the external exposure rate. Lithium fluoride thermoluminescent dosimeters were left on Bikini Island for several months and retrieved in December 1975.

Environmental exposure levels were assessed via the RSS-111. The NaI gamma spectrometer was used by us to determine the photon energy distribution and to compensate for the nonlinearity in the RSS-111 instrument response.

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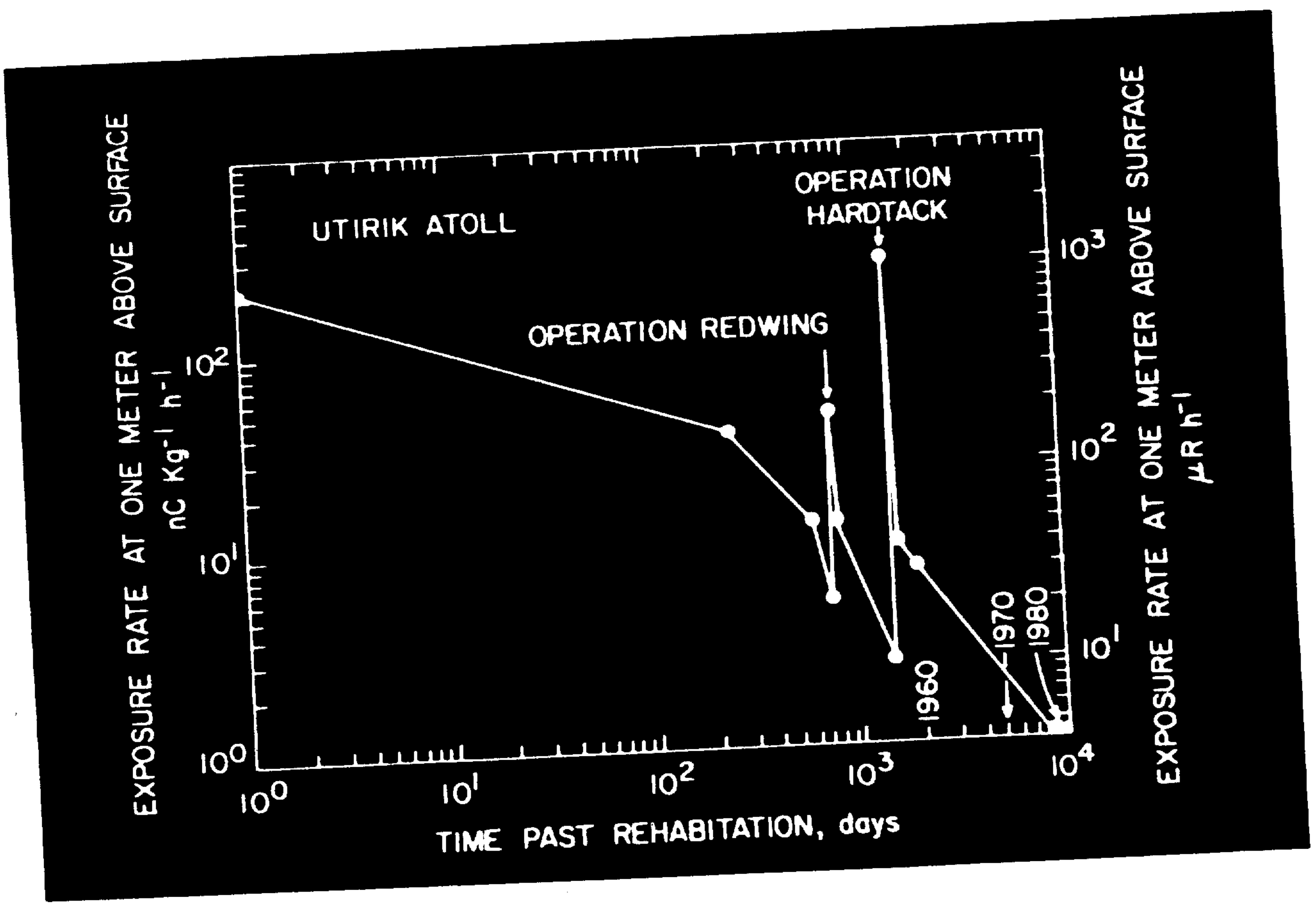
Diet and living pattern studies. During the 1970's diet and living patterns for the Marshallese were studied. The data was derived from literature, answers to questionnaires, direct observation by us while living with the Marshallese for periods extending from months to years, and from direct participation in their activities. Complex interactions, such as, the gathering of local foods, the receipt of food aid through programs, like school-lunch, and typoon-relief, and in recent times, the availability of cash for the purchase of imported foods were observed. The data provided us with necessary information for input into models that were used to assess the radiological impacts attributable to fallout.

SLIDE 43

Environmental levels of external exposure. Exposure rates were observed to decline following each test. At Rongelap and Utirik the residual levels from BRAVO fallout overshadowed the residual radiation from other tests. Occational elevations due to fresh fallout were evident, however, the exposure rate would return to the BRAVO baseline within several weeks. The levels at Bikini Island during the early 70's were about 5 times the levels at Rongelap. The levels on the southern islands of Enewetak are very close to natural background; 10^{-9} C kg^{-1} h^{-1} (3.7 μR h^{-1}). This low-level was due to the extensive clean-up at Enewetak prior to rehabitation.



Environmental levels of radioactivity. BNL personnel commenced limited environmental monitoring of the Marshall Islands for radioactivity in April 1974. Since then, members of the staff have made a number of field trips to the Marshall Islands to collect a representative cross-section of vegetation, animals, fruits, soil and water found on the inhabited islands for the purpose of assessing the activity intake by people.

The surveys covered Kwajalein, Wotho, Bikini, Rongelap and Utirik Atolls. In general, all samples were analyzed for ^{90}Sr, ^{238}Pu, ^{239}Pu and any gamma emitters which may have been present at the time of analysis.

The specifc activity per unit dry weight of foods, brush and soil are given here. The predominant activities were ^{90}Sr and ^{137}Cs. The activity ratios between islands were based on thousands of measurements and apply to all nuclides.

ENVIRONMENTAL LEVELS OF RADIOACTIVITY MID 1970's

	Bq g^{-1} Dry Weight				
Description	^{90}Sr	^{239}Pu	^{137}Cs	^{60}Co	^{241}Am
Bikini					
Pandanus Fruit	8.7	0.019	15	0.61	—
Scaveola Leaves	3.4	0.0093	14	—	—
Soil	2.0	0.052	2.9	0.048	0.27
Coconut Meat	—	—	3.5	—	—

Activity Ratio

Bikini / Rongelap	4
Bikini / Utirik	20

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Mode of intake. Ingestion of fish and locally grown food items were assumed to be predominant intake pathways. This hypothesis was based on direct observation of diet habits, the correspondance of increasing or decreasing body burdens with availability of locally grown food products, and the results of airborne activity measurements.

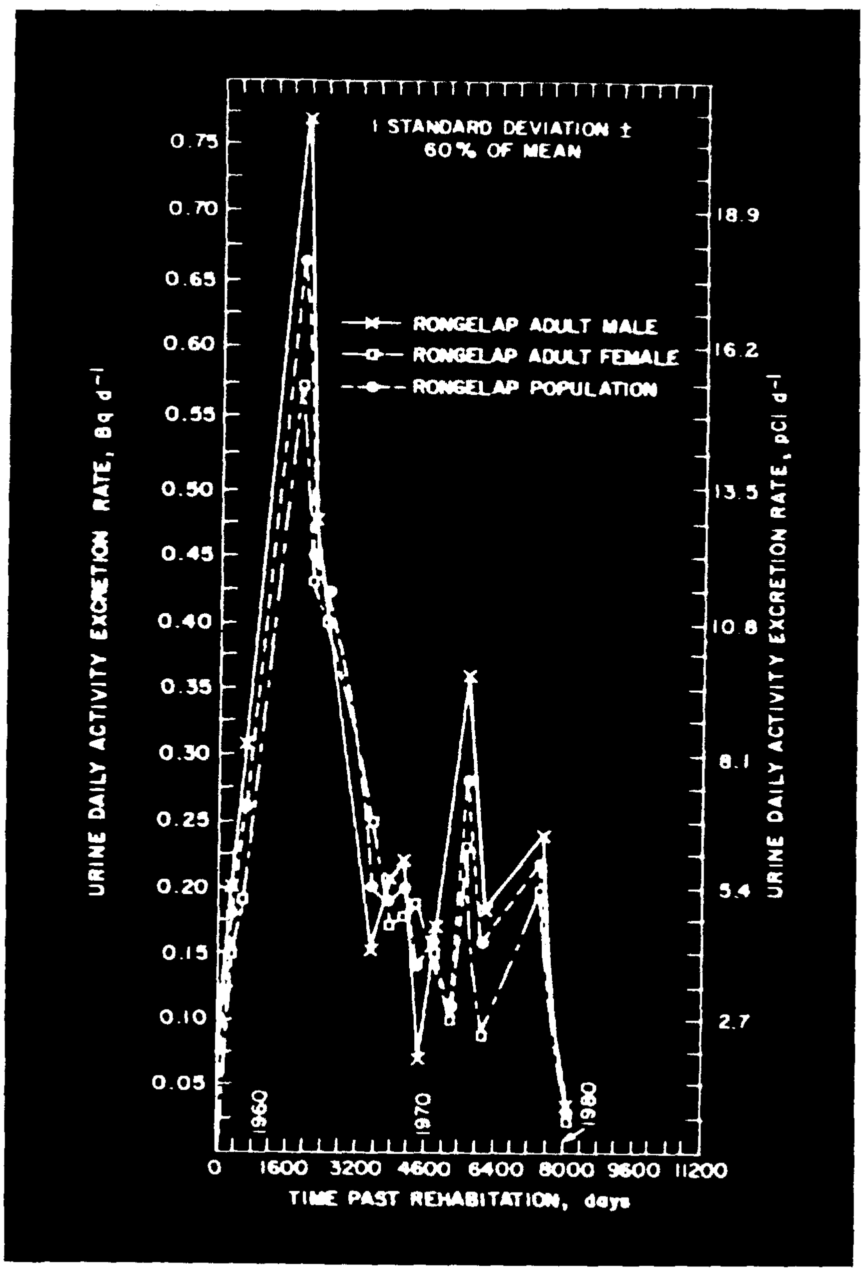
The dietary intake of ^{137}Cs was a major component contributing to the committed effective dose equivalent for the years after the initial contamination of the atolls. For persons whose diet included fish, ^{65}Zn was a major component of committed effective dose equivalent for the initial years post return to Utirik.

Diet habits varied from atoll to atoll and depended on the quantity and quality of imported foods. At Bikini during the 1970's and when body burdens rose rapidly, imported foods were described as bland and tasteless. Differences in diet were observed directly by us and may be related to the fact that atoll to atoll body-burden ratios were not similar to ratios for levels of activity in plants or animals.

Impact of living pattern on external whole-body dose. 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 factor of 2.8 x 10^{-8} Gy in tissue of interest per nC kg^{-1} (0.73 rad/R) measured in air at 1 m above the surface was used by us 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 by us 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 or organ; however, the difference in 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 were combined by us 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).

SLIDE 51 and 52

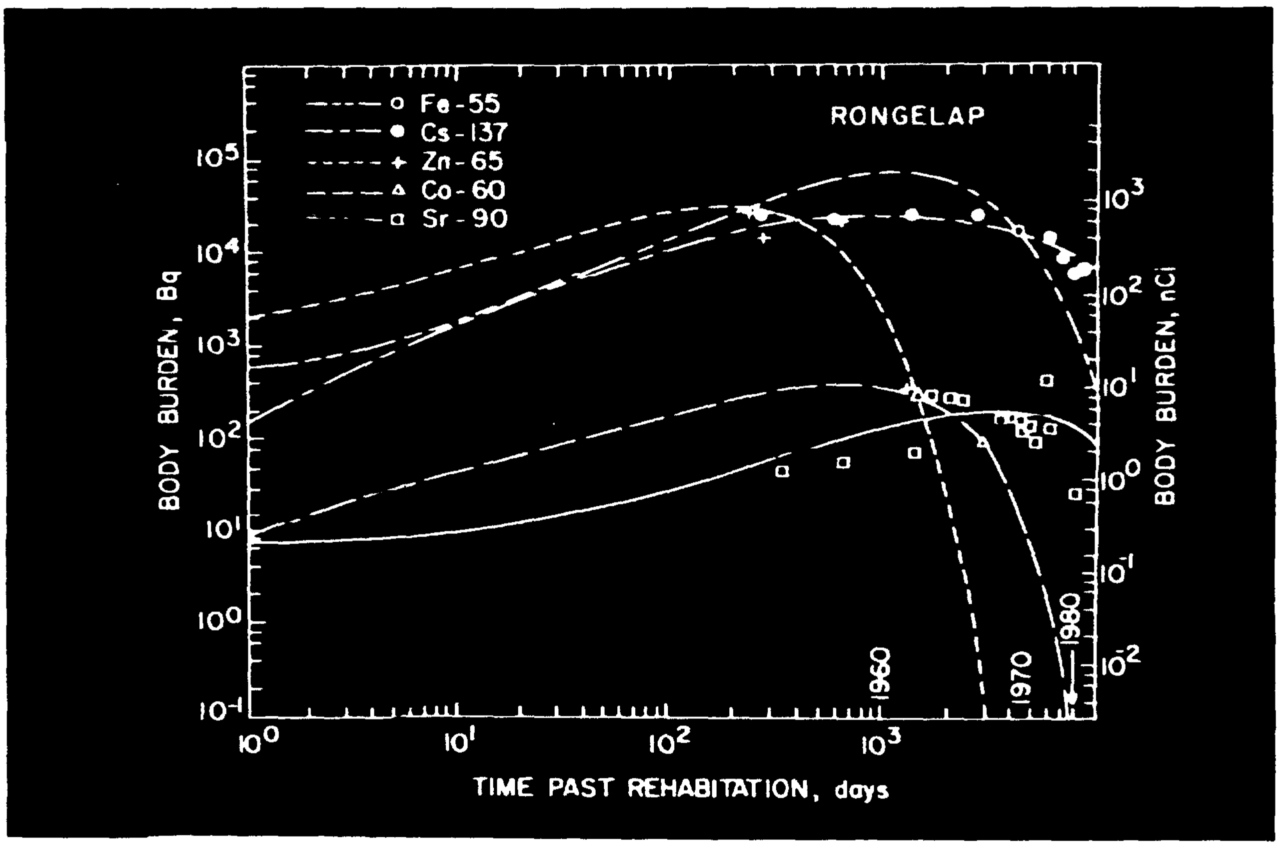
Body burden and excreta measurements. The body burdens which were measured directly had a standard deviation of ± 30% of the mean value for adults. The maximum body burden of ^{137}Cs was observed to be 3 times the mean value. Indirect measure of body burden by urine analyses resulted in greater variation. The standard deviation for ^{90}Sr was ± 60% of the mean value for adults. The standard error for the adult mean body burden was 5 times less than the standard deviation because many adults participated during each mission.

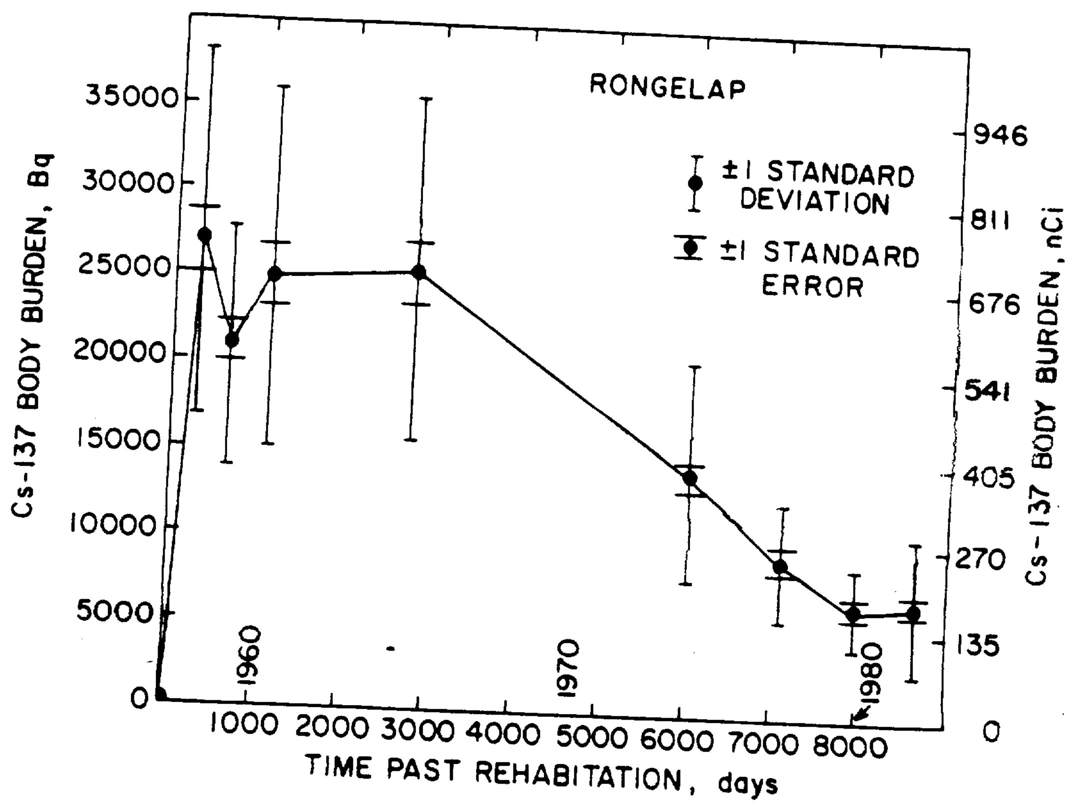


Body burden history at Rongelap and Utirik. Adult average body-burden data and urine-activity concentration data were used as input quantities to equations which related them to activity intake rates. These input data were obtained from Conard's medical report (Co56, Co58, Co59, Co60, Co62, Co63, Co67, Co70, Co75, Wo59) and from recent surveys performed by members of the BNL Safety and Environmental Protection Division.

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. To select an appropriate model for this relationship, we examined the body-burden history and the history of activity in vegetation and soil. Activity concentrations of ^{137}Cs, ^{129}I and ^{90}Sr in surface soil on Rongelap and Utirik Atolls were observed by us 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.

The lines fitting the declining continuous intake model at Rongelap are presented here. Measured results are plotted. The body burdens at Utirik were a factor of 2.6 times less than those at Rongelap for the period 1958 to 1984.



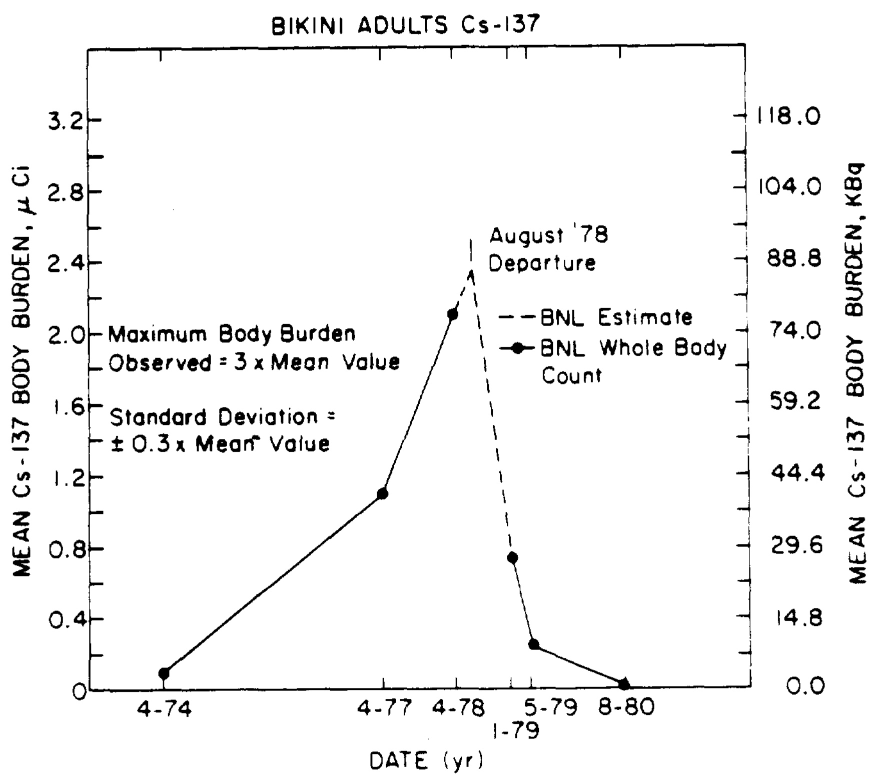


RONGELAP
±1 STANDARD DEVIATION
±1 STANDARD ERROR
Cs-137 BODY BURDEN, Bq
35000
30000
25000
20000
15000
10000
5000
0
Cs-137 BODY BURDEN, nCi
946
811
676
541
405
270
135
0
1960
1970
1980
1000 2000 3000 4000 5000 6000 7000 8000
TIME PAST REHABILITATION, days

SLIDE 54

<u>Body-burden history at Bikini.</u> Three body burden measurements of the Bikini Island population were conducted from 1974 to 1978 at Bikini Island. During this time, the mean ^{137}Cs body burden of the adult Bikini population increased by a factor of 20. This dramatic elevation of body burden appears to be solely attributable to increased availability of locally grown food products, specifically coconuts and coconut plant products.

An ingestion intake model for stepwise increasing intake was used to estimate total ^{137}Cs radioactivity ingested at Bikini. A constant continuous intake model was used by us to estimate total ^{90}Sr intake.



SLIDE 55

Status of plutonium measurements. The validity of the ^{239}Pu data used to estimate the body burden at Rongelap Atoll in 1973 had been considered by an Energy Research and Development Agency ad hoc committee. The committee concluded that because of the possibility of urine-sample contamination these data were uncertain. This indeed may 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 results.

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

The estimates for ^{239}Pu adult body burden were not used to derive values of intake and committed effective dose equivalent since they may have been the result of an erroneous urine collection technique and not the result of internal deposition. The potential for contamination 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 study of the sampling and analysis procedures which indicated to us that some ^{239}Pu in urine may not have been chemically recovered along with the tracer (Ry82). 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. This method is being developed to be used in conjunction with a photon-electron rejecting liquid scintillation spectrometer developed by McDowell and duplicated by us for low-level alpha spectroscopy (Mc72). The question following additional analysis of urine collected in 1979 and 1980 from former Bikini Atoll residents. The urines were collected in a contamination free environment and indicate higher than expected levels of ^{239}Pu. Further analysis using fission track-etch techniques will be done to confirm these results. Additionally, a comparison population has been chosen and samples collected from them. The await analysis.

^{239}Pu MEASUREMENTS

Date	Male Adult Population	^{239}Pu Excretion Rate mBq d^{-1}
1974	Bikini Males	0.9
1975	Bikini Males	0.7
1976	Bikini Males	0.5
1976	Bikini Males	0.4
1979	Bikini Males	2
1973	Rongelap Males, Females	9
1976	Rongelap Males	2

SLIDE 56

Intake estimates and dose equivalent. Adult average values for activity ingestion rate on day of return were calculated for all nuclides at Rongelap, Utirik, or Bikini. This information was used to estimate adult body-burden histories based on the assumption of declining continuous intake or increasing intake.

The declining continuous intake equation provided us with 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.

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 result in indirect ^{90}Sr measurements of body burden deviating widely from the hypothetical curve. In contrast the ^{137}Cs results fit the curve closely.

The method use to fit the data was not chosen to minimize the weighted sum of squares of deviations of the body-burden estimates. Instead average values of initial intake rate were selected to represent all the body-burden data. For Rongelap, the ^{137}Cs body burdens varied from the fitted intake function by a maximum factor of 1.7 and an average factor of 1.4; the ^{90}Sr body burdens varied from the fitted intake 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 the fitted intake function for each population. The 50-yr interval chosen for internal intake represented the years 1957-2007 for Rongelap residents. For Utirik residents, the 50-yr interval represented the years 1954-2004. The committed effective dose equivalent was based on this cumulated intake. At Bikini the integral intake was for a 4.5 year period, 1974-1978.

For the nuclide ^{137}Cs, an age dependent retention function was incorporated into the fitted intake function. In the estimate of adult committed effective dose equivalent a body mass of 60 kg was used based on 28 years of adult body mass measurements.

INTAKE ESTIMATES

Declining Continuous Intake
Increasing Intake

COMMITTED EFFECTIVE
DOSE EQUIVALENT

Retention vs Age
Body Mass

Declining continuous intake. The intake removal rate constant calculated for each nuclide in the Rongelap and Utirik adult populations is given here. In the cases of the Rongelap and Utirik people for who sequential body-burden data were available, the constant 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. The value of the constant 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 was not possible. For the estimate of cumulated ^{55}Fe intake, the constant was assumed equal to zero. Thus, for ^{55}Fe, radioactive decay was assumed by us to be the only cause of reduced daily activity intake during the residence interval.

Where data were available for comparison, the values of the constant 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 percent decrease in the atom ingestion rate was computed. A 9% reduction in dietary ^{137}Cs was computed for each year at Rongelap and Utirik. For dietary ^{90}Sr, an 8% reduction was estimated. The ^{60}Co and ^{65}Zn intakes were reduced rapidly during the first 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.

DECLINING CONTINOUS INTAKE

Nuclide	Intake Removal Rate Constant
^{60}Co	2.0×10^{-3} d^{-1}
^{137}Cs	2.0×10^{-4} d^{-1}
^{65}Zn	1.3×10^{-3} d^{-1}
^{90}Sr	1.7×10^{-4} d^{-1}

SLIDE 58

Rongelap summary. The nuclide giving the greatest internal committed effective dose equivalent at Rongelap was ^{137}Cs. Diet items containing ^{137}Cs and ^{90}Sr were those which were locally grown. Land animals also contained ^{137}Cs and ^{90}Sr. Diet items containing ^{65}Zn, ^{60}Co and ^{55}Fe were those which were taken from the lagoon.

1957-2007 RONGELAP
PROTRACTED EXPOSURE
SUMMARY

Nuclide	Bq 50 Year Intake	Sv Adult Mean Committed Effective Dose Equivalent
^{60}Co	40,000	0.00034
^{137}Cs	1,500,000	0.022
^{65}Zn	310,000	0.0019
^{90}Sr	9,000	0.00053
^{55}Fe	2,400,000	0.00048
External	Natural Background Subtracted	0.017
Total	—	0.042

Utirik summary. Use of the body-burden extrapolation equation leads us to the conclusion that ^{65}Zn could have been the major contributor to the ingested activity during the first years post-rehabitation of Utirik Atoll. This was supported to some extent by a Japanese report (JCCRRER56) which indicated to us 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 (100-10,000 cpm). Fish with count rates greater than 100 cpm at the surface were discarded by the fishermen. Radiochemical techniques indicated the prominence of ^{65}Zn in the tuna's edible flesh.

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.

1954-2004 UTIRIK
PROTRACTED EXPOSURE
SUMMARY

Nuclide	Bq 50 Year Intake	Sv Adult Mean Committed Effective Dose Equivalent
^{60}Co	54,000	0.00044
^{137}Cs	860,000	0.013
^{65}Zn	5,200,000	0.030
^{90}Sr	1,700	0.00010
^{55}Fe	1,900,000	0.00036
External	Natural Background Subtracted	0.041
Total	—	0.085

SLIDE 60

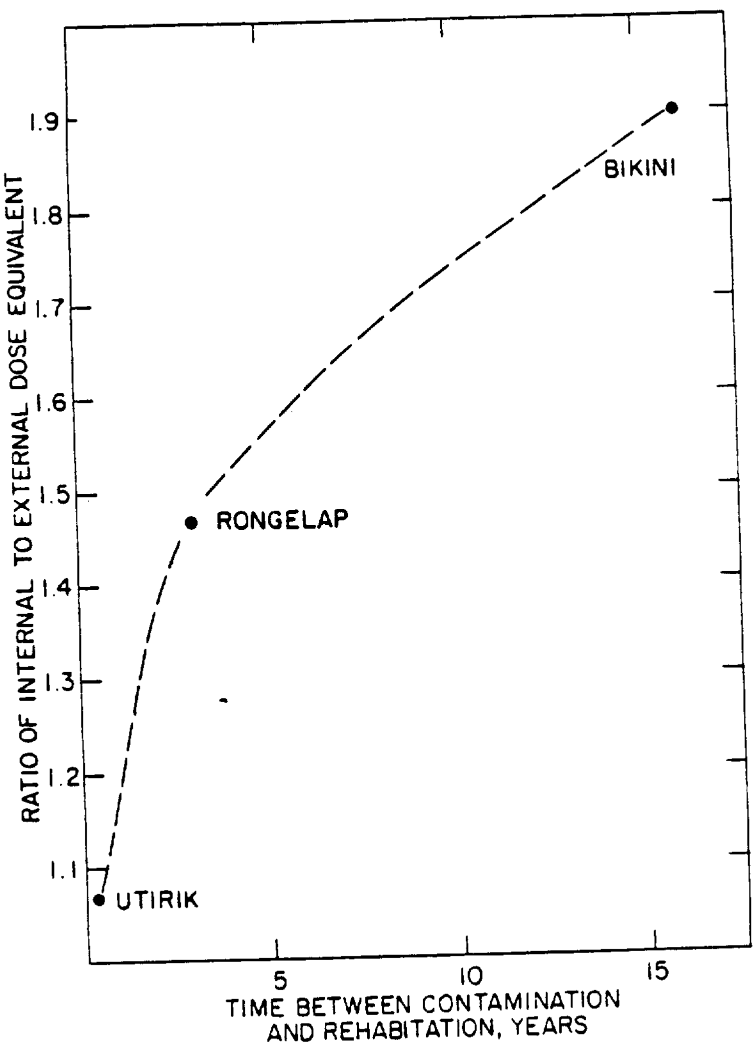
Bikini summary. The nuclide ^{65}Zn was not included in the dose equivalent at Bikini because it was not present at the onset of exposure. Blood bioassay was not done on Bikinians and no estimate of ^{55}Fe dose equivalent was made by us. The predominant nuclide ^{137}Cs was taken into the body at an ever increasing rate during the exposure interval and direct comparison with declining continuous intake at Rongelap or Utirik may be inappropriate. It is clear that ^{137}Cs, dose equivalent relative to external dose equivalent was greater at Bikini than at the other atolls.

1974-1978 BIKINI
PROTRACTED EXPOSURE
SUMMARY

Nuclide	Bq 4.5 Year Intake	Sv Adult Mean Committed Effective Dose Equivalent
^{60}Co	3,900	0.000032
^{137}Cs	530,000	0.0084
^{90}Sr	4,200	0.0020
External	Natural Background Subtracted	0.0055
Total	—	0.016

SLIDE 61

Return to Bikini. The ratio of total internal committed effective dose equivalent to external dose equivalent was plotted by us versus time of return relative to the BRAVO detonation. It is apparent to us that the ratio increases with increasing time post return. In general, the ratio at Bikini Island would be about 2.5 if return in 2020 is hypothesized. From 2020 to 2050, we estimate an external whole body dose equivalent if 0.015 Sv (1.5 rem). The total estimate of internal plus external dose equivalent would be about 0.05 Sv (5 rem) for this 30 year period. Therefore, an unrestricted rehabitation of Bikini Atoll might begin in 2020 if their enviroment is not cleaned-up. This dose equivalent estimate is exclusive of ^{239}Pu dose equivalent.



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