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EXTERNAL RADIATION LEVELS ON BIKINI ATOLL, MAY 1967

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HASL-190
HEALTH AND SAFETY (TID-4500)

EXTERNAL RADIATION LEVELS ON BIKINI ATOLL - MAY, 1967

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December, 1967

ABSTRACT

An intensive radiological survey of the islands of Bikini Atoll was conducted in April-May 1967 for the purpose of determining the levels and components of the external gamma radiation fields in this former weapons testing area. Fourteen islands and the two island complexes of the atoll were surveyed with instrumentation which included a field gamma spectrometer system, a high pressure ionization chamber, scintillation and G.M. survey meters, and thermoluminescent dosimeters. A large number of soil samples were taken for laboratory NaI(Tl) and Ge(Li) gamma spectral analysis. Total exposure rates were found to vary considerably from site to site and island to island. Levels measured over soil ranged from less than 10 μr/hr to over 500 μr/hr. Major contributors to the radiation fields usually included ^{137}Cs, ^{60}Co, ^{125}Sb, and ^{102m}Rh with a large number of other isotopes present. The large amount and consistency of the data indicate that a reliable and comprehensive picture has been obtained of the external gamma radiation environment of the atoll.

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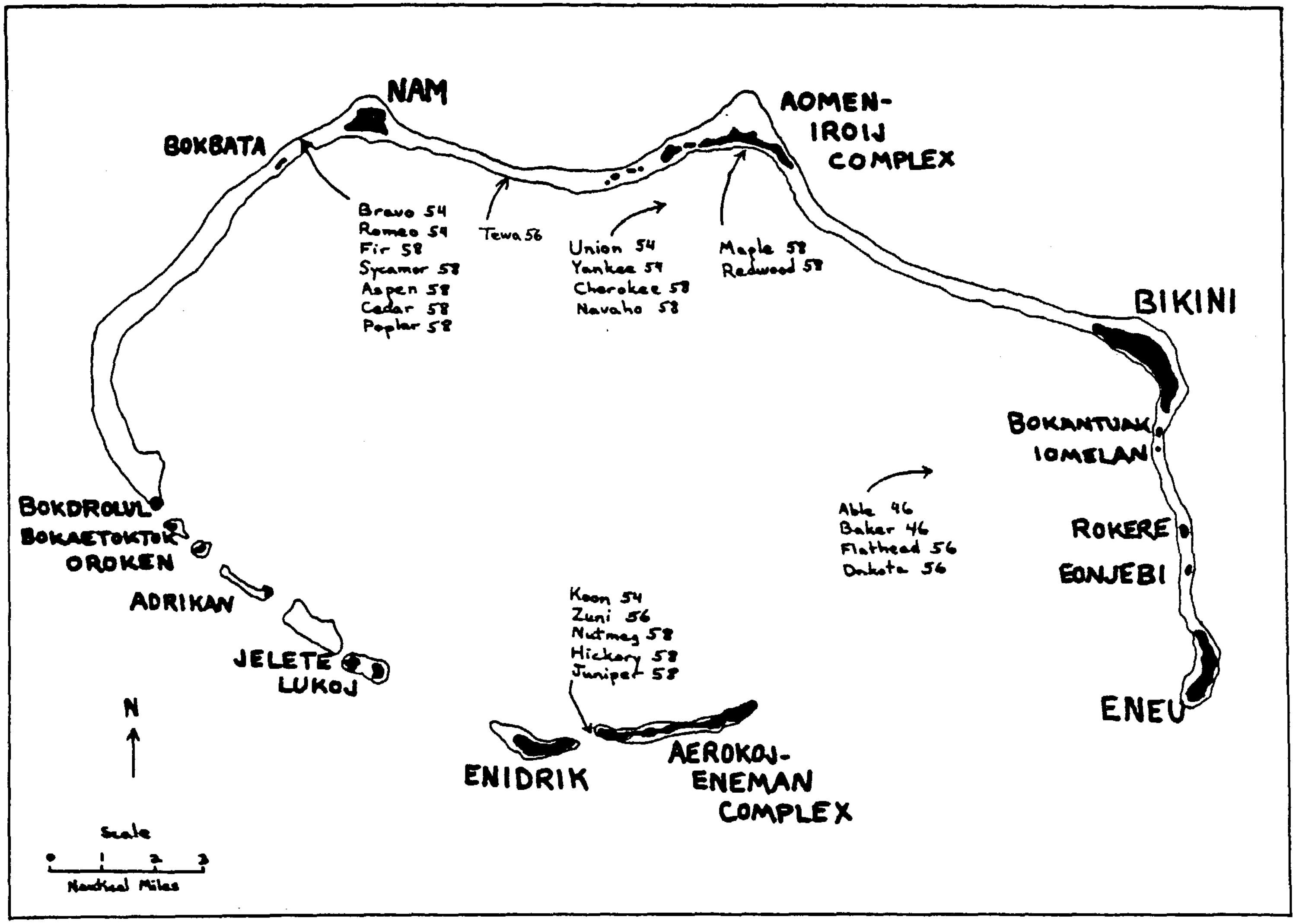

Figure 1. Bikini Atoll

I. INTRODUCTION

A radiological survey of the islands of Bikini Atoll in the mid-Pacific was conducted in late April and early May of 1967, nine years after cessation of extensive testing of nuclear devices in the area. The survey, sponsored by the Division of Biology and Medicine of the U. S. Atomic Energy Commission, included general observations of the prevailing environmental conditions and a detailed investigation of external environmental radiation levels. Exposure rates due primarily to penetrating gamma radiation were measured, and the principal radioisotopes contributing to the total exposure rate on each of the major islands of the atoll were determined.

Bikini Atoll is located in the northern Marshall Islands. The atoll consists of a number of small coral islands surrounding a lagoon 22 miles long and 13 miles wide. Total land area of the atoll is 2.32 square miles, of which 1.25 square miles comprises the three largest islands, Bikini, Eneu, and Nam. Figure 1 is a map of the atoll. The names of the islands differ on the various hydrographic charts, being usually variations of Japanese renditions of the original Marshallese names. On the map in Figure 1 and throughout this report we have used the Marshallese names of the islands.

The testing of nuclear devices at Bikini Atoll occurred during 1946, 1954, 1956, and 1958 and included the detonation of some 23 devices of both fission and thermonuclear types. The locations of the tests and the code name and year of each event are indicated on the map in Figure 1. Most of the shots were detonated on barges anchored in the lagoon or on the atoll reef. Two shots were air drops, Able and Cherokee, two were underwater, Baker and Maple, and three were surface bursts, Bravo, Zuni, and Koon. All of the islands received in varying degrees the resultant radioactive fission and activation products which were spread about the area. Although prevailing winds generally carried the local fallout westward, there were exceptions - notably shot Bravo, when unexpected winds carried the fallout toward the east.

An extensive survey of the atoll was last carried out in 1964, when the emphasis was on examining the radioactivity of flora and fauna and obtaining large numbers of samples of rats, birds, soils, and marine life for laboratory analysis. Thus, the gathering of additional samples of these types on this survey was not a primary requirement. However, a fairly large number of soil samples were taken and brought back for analysis so that the in situ measurements could be supplemented by calculations based on the isotopic concentrations determined by laboratory gamma ray spectroscopy, radiochemistry, and lithium drifted germanium spectroscopy.

The external radiation survey techniques utilized were largely those developed and used by the Health and Safety Laboratory for the past several years in conducting detailed investigations of the properties of the external radiation environment in the United States[1,2,3].

In addition to the survey measurements an experiment of the radiological effects of clearing a particularly heavily vegetated area was carried out on Bikini Island near the beginning of the survey trip.

Besides the authors, who were primarily responsible for the external radiation measurements, the survey team included Edward Held, University of Washington Marine Radiobiologist, the survey leader; his assistant, Robert Erickson; Arnold Joseph of the Division of Biology and Medicine; James Hiyane, Trust Territory District Agriculturist; Jack Tobin, former Trust Territory District Anthropologist; and Francis Tomnovek and Edward Jones of the U. S. Naval Radiological Defense Laboratory (USNRDL) who conducted most of the TLD studies and supplied and serviced the G-M detectors.

The survey team spent a total of 16 working days on the atoll using a U. S. Trust Territory ship, the M. S. Militobi, as a base of operations. Fourteen islands and the two island complexes were surveyed. Only the very small island of Adrikan in the southwest corner of the atoll was by-passed. About ten days were spent on the three large islands, particularly Bikini Island (seven days). All of the members of the team participated in conducting the experiments and gathering the data on external radiation. The data on the marine, plant, rat samples, and agricultural and anthropological observations will be published elsewhere.

In the following sections of this report we discuss in detail the radiation instrumentation, data collection and analysis, and present environmental radiation results for each island. Tables containing data pertinent to external radiation levels on Bikini Atoll conclude the report.

II. INSTRUMENTATION, DATA COLLECTION AND ANALYSIS

A high pressure ionization chamber and a γ-ray spectrometer system were used to obtain in situ exposure rates and spectra. The spectra were then analyzed to determine the individual exposure rates contributed by each major γ-ray emitting isotope in the soil. Because of the bulk and weight of the analyzer system, ionization chamber, and related power supplies, and the resultant difficulty in transporting the equipment from the ship via small boats to the shore and thence in many cases through heavy brush to a survey site, these types of measurements were limited to 16 sites on the three major islands. In all some 29 field spectra were obtained.

A small scintillation counter survey meter and a number of rugged G-M counter survey meters were used to extend the total exposure rate measurements over these islands and to survey the smaller islands. Although the data obtained with these instruments is less accurate for a particular location, their use enabled us to extend our measurements over a fairly large area conveniently and consequently obtain a more complete picture of the variation of radiation levels across the major islands and from island to island.

In addition to these measurements, thermoluminescent dosimeters were placed at a large number of locations on Bikini and Eneu Islands at the beginning of the survey and collected about ten days later and returned to the United States for readout. These passive dosimeters were employed to provide an independent check on the data obtained with the other instrumentation.

Soil samples were also taken at various locations exhibiting unusually high or low activity. All of these samples were returned to the United States for laboratory analysis, however, several were also spectrally analyzed on our 4 in. x 4 in. NaI(Tl) detector aboard ship to obtain identification of the major γ-ray emitters in the sample. At several locations a complete depth profile set of soil samples was taken so that the variation of isotopic concentrations with depth might later be investigated.

A. Instrumentation

Spectrometer System - The HASL spectrometer system consists of a 4 in. x 4 in. NaI detector with preamplifier and high voltage battery pack, a 400 channel multichannel analyzer and parallel printer, a DC-AC converter and a 12 volt storage battery. The calibration of the detector is described in detail in previous HASL reports[2,3]. In brief, the exposure rate due to a particular isotope in the ground is inferred from the number of counts under a spectrum total absorption peak characteristic of that isotope using calibration factors determined from a combination of laboratory experiments and theoretical calculations.

The prominent total absorption peaks observed in all the field spectra (see Figure 2 for a typical field spectrum) were at 1.17 and 1.33 MeV (^{60}Co), .10 MeV (^{155}Eu), .44 MeV (^{125}Sb), and .662 MeV (^{137}Cs). These isotopes appeared to be responsible for almost all of the total exposure rate at the spectrometer locations. Individual exposure rates for ^{137}Cs, ^{60}Co and ^{125}Sb were inferred for each field location. The ^{155}Eu exposure rate was assumed to be of minor importance due to its very low source energy. For those locations where the ionization chamber was not used or the other total exposure data were inconsistent, the spectrometric data were analyzed to obtain total exposure directly[3].

Except for the two Eneu locations, all spectra were taken in ten minute runs. During this time there was no appreciable gain shift due to temperature changes. In almost all cases we were able to obtain excellent field spectra with only minor equipment malfunctions even though the equipment had to be carried by hand through heavy brush, loaded and unloaded into small boats in fairly rough surf, and operated and stored in ambient temperatures of approximately 85 - 95°F and relative humidities of 70 - 80%.

Ionization Chamber - Our high pressure ionization chamber has a 5.6 liter sensitive volume and is filled to a pressure of about 700 psi with pure argon gas[3]. The chamber wall is

0.135 in. stainless steel and effectively discriminates against all beta radiation. The ionization current is read out on a Victoreen Model #475A Dynamic Capacitor Electrometer. This chamber has been shown to have a flat energy response over all γ-ray energies of importance in environmental radiation studies and to allow determination of total γ-ray exposure rates from about 1 μr/hr to 200 μr/hr with a precision usually better than 2% and an accuracy of better than 5%[3]. A careful calibration was done in the laboratory with standard NBS calibrated ^{226}Ra and ^{60}Co sources both before and after the survey and periodic checks for consistency were made in the field with a small ^{226}Ra check source. A correction for the contribution to the ionization current from cosmic rays was determined by measuring the cosmic ray component alone on top of the bridge deck of the ship in the middle of the Lagoon. The value obtained (3.4 μr/hr) was consistent with the value of the cosmic ray exposure rate for this latitude inferred from our previous extensive cosmic ray measurements[3].

Total exposure rates were measured with the ionization chamber at almost all the field spectrometer locations, as well as at several other sites. These total exposure rates were later compared with the sum of the individual component exposure rates inferred from the field spectrometer data.

Portable Scintillation Detector - The HASL portable scintillation detector consists of a 1.5 in. x 1 in. NaI(Tl) crystal and 1 in. photomultiplier tube attached to a very stable count rate circuit. This instrument is relatively insensitive to beta and cosmic radiation. It is calibrated for particular field conditions by comparing readings with γ-ray exposure rates determined from the ionization chamber at a number of locations. The "field calibration" was done both on Bikini and Nam with identical results.

This type of calibration allowed us to use the instrument to extend the results of a few very accurate and precise ionization chamber and spectrometer measurements over a wide area. We thus quickly obtained a large amount of data which,

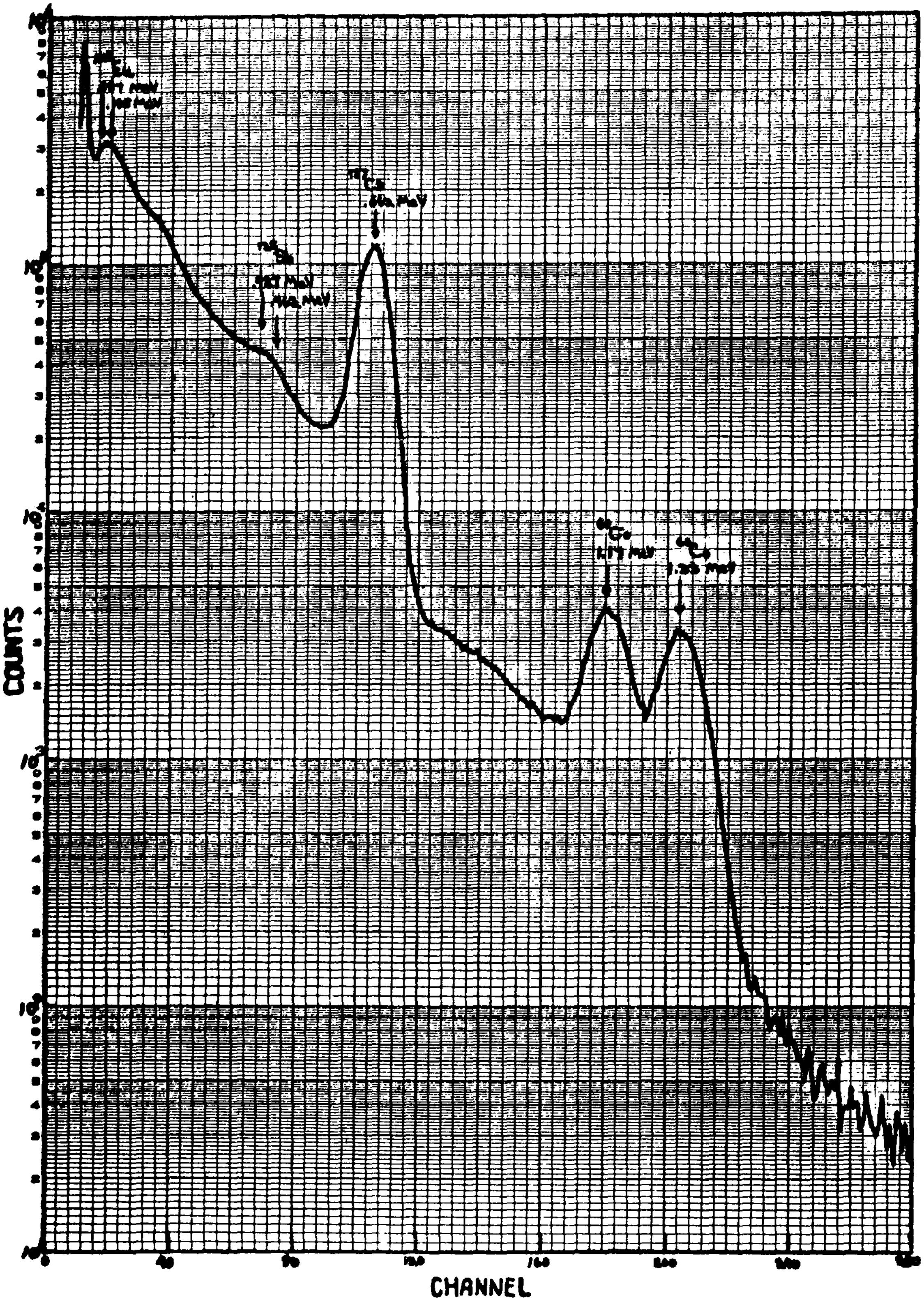

Figure 2. Typical NaI(Tl) field spectrum. Bikini Island, O Transect, Location 7, 10 minute counting interval.

although not of comparable precision and accuracy to the primary data, were useful in determining the range and variation of the radiation field.

G.M. Survey Meters - A number of G-M type Radiac Meters (IM-85/PDR-27F), supplied by NRDL, were used to obtain a wide coverage of total exposure rate data. These particular instruments were chosen for their ruggedness and dependability under severe environmental conditions. Although these survey meters were calibrated in the laboratory it was found that the calibration factor was unsuited to environmental radiation half-space geometry. The instruments exhibited a considerable energy and angular response when exposed to different energy sources in the laboratory, as well as a slight β-ray response even with the β-ray shield closed. For these reasons it was felt that the laboratory calibration should be discarded in favor of a "field calibration" against the ionization chamber and spectrometer. Because of the lack of sensitivity of G-M tubes to gamma radiation at the relatively low levels usually encountered, an individual reading taken with one of these instruments was imprecise. However, the mass of data taken when corrected using the "field calibration" satisfied the primary purpose of the instrument which was to delineate the range of exposure rates over a given island and the variation from island to island.

Survey meter readings were made on paths which were cut through the thick brush on many of the islands (particularly on Bikini Island) along lines which ran lengthwise along the island, across the island or around the perimeter, 50 to 100 ft. inland. The thickness of the brush dictated where transects could be located and the transects frequently deviated substantially from straight lines. The meters were generally monitored constantly along the transects with readings recorded about every 50 ft. (estimated). Readings were taken at about the three foot level, although as expected for γ radiation, there was no significant variation with height. Readings were also made next to any unusual artifacts, scrap metal, bunkers, or building remains.

All the corrected G-M tube gamma radiation readings obtained by the survey team are given in Table 1 for each measurement site along with all other total exposure rate data obtained at that site. Although some beta plus gamma radiation readings were taken these data were inconsistent and are not reported.

Thermoluminescent Dosimeters - A large number of thermoluminescent dosimeters (TLD) were used during the survey. NRDL contributed the majority of these detectors. The predominant type used was a plastic capsule filled with LiF powder and enclosed in styrofoam inside a small plastic box. This type of dosimeter was placed every 100 ft. (measured) along each of the major transects on Bikini and Eneu Islands. Total exposure rate measurements were also made at each site. The dosimeters were left in place approximately ten days. Controls remained aboard ship. Both sets were returned to NRDL for readout after the trip. The results are given in Table I in terms of the net average exposure rate over the time of exposure.

There is some question as to whether these dosimeters were shielded adequately from beta radiation. This lack of adequate shielding might partially explain the slightly higher average exposure rates obtained from these dosimeters at survey sites relative to the other instrumentation at the same sites.

NRDL also exposed several low background CaF_2:Mn dosimeters at various locations on Bikini and Eneu. These dosimeters and controls were returned to the Naval Research Laboratory in Washington, D. C. for readout. Although the metal case surrounding the dosimeter, which is used to flatten the energy response, should eliminate most of the β-ray response, these results also appeared to be slightly higher than results from the other instrumentation. However, the total doses to which these dosimeters were exposed were relatively small and the time between exposure and readout was quite long. This resulted in the necessity of subtracting sizeable background readings. In addition, there was usually only one dosimeter per monitored location and thus only one readout available per site.

Twenty HASL TLD dosimeter units, each consisting of a carefully selected individually calibrated low background CaF_2:Mn dosimeter and a LiF extruded rod in a shielded container were placed at several different sites on Bikini and Eneu Islands, including many of the spectrometer sites and a few of the NRDL TLD sites. Another 30 of these units were used as controls. Some of these controls were left in Honolulu and Kwajalein on the trip to the atoll and the rest were kept aboard ship. Four were worn by two of us at all times when ashore. The large number of controls allowed us to make very accurate measurements of the average background exposure of the detectors for various stages of the trip. A correction was also made for the background exposure rate to the controls kept aboard ship during the survey. A careful experiment in the laboratory enabled us to account for the self-activation of the CaF_2:Mn dosimeters due to ^{40}K in the glass envelopes of the units. The resulting control dosimeter exposures were consistent with the expected exposure for the time the dosimeters spent on each stage of the trip and their location during that time. The net exposure rates determined from these data for the various field sites are also given in Table 1. Overall, the agreement is quite good considering the small number of measurements, and the results substantiate the overall consistency of the various measurements.

It must be kept in mind in interpreting all the TLD results that the results of a single dosimeter placed at a particular location may not be representative of the average exposure rate over a larger area surrounding the dosimeter. The dosimeter may not "see" the same radiation field as an ionization chamber or scintillation detector placed a few feet away. This is especially true of many areas on Bikini Atoll where local hot spots are quite prevalent. Also we are comparing a single measurement at a particular time with an average exposure per hour determined from a 7 - 10 day exposure. In general, all the TLD results tend to substantiate the ranges and general trends predicted by the data from the active instrumentation.

B. Soil Sampling

Soil samples were taken from almost all of the islands of the atoll. On Bikini Island complete and careful depth profiles were obtained. All the samples were returned to the United States for quantitative gamma-ray spectrometric analysis by the University of Washington Laboratory of Radiation Ecology and by HASL. Selected samples were analyzed by HASL contractors for ^{90}Sr. Qualitative lithium drifted germanium Ge(Li) spectrometry of many of the samples was carried out under contract for HASL to determine all the gamma emitting isotopes in the soils.

The results of the gamma spectrometric analyses of the depth profiles were used to determine the approximate average relaxation length of the assumed exponential isotopic concentration in the soil[2,3]. A relaxation length of 2 cm was found to be consistent with these data and this number was used in determining the field spectrometer calibration factors[2,3].

Gamma-ray exposure rates for various isotopes were calculated from the laboratory gamma spectrometric soil analysis data only for the locations where the soil samples were taken from a known depth and area. For these calculations the relaxation length varied from 1 to 3 cm (i.e. about 67% of the activity was in the first 1 to 3 cm of soil). The results of these calculations turned out to be relatively poor (see Section III) due to the difficulty in obtaining a soil sample representative of the area as a whole. Although we could not always calculate accurate absolute exposure rates from the soil data, by making the following plausible assumptions about the distribution of radioisotopes in a given soil sample, we were able to obtain useful quantitative estimates of the relative contributions of each emitter to the total exposure rate. The first assumption is that the percentage of the total gamma-ray activity per gram of soil due to a given isotope does not vary significantly within an area of approximately a 30 ft. radius about the soil sampling site. The second is that there is no significant fractionation in penetration into the ground; i.e. all the isotopes have roughly the same local depth distribution. If these two assumptions hold, one can calculate the percentage of the total exposure rate due to each emitter in the vicinity of the soil sample site since the ratios of exposure rates per unit concentration for the various isotopes in question vary hardly at all with assumed depth distribution in the soil for relaxation lengths of 1 to 4 cm[3,5]. Thus, to determine the percentage of the total exposure rate due to a given isotope one need not know the average isotopic depth distribution over the area as a whole, from what depth the soil sample was taken, or whether the total activity of the sample is representative.

The first assumption is probably quite reasonable. We tested the second assumption by using the gamma spectrometric analyses of the soils taken at the three sites where profiles were obtained on Bikini Island. We give below the percentage of the total sample activity due to each isotope as a function of depth for these sites. The actual concentration data is given in Table 2.

PERCENTAGE OF TOTAL γ-RAY ACTIVITY*

Depth	^{137}Cs	^{60}Co	^{125}Sb	Other**
		Location 7 - Bikini		
0-1"	84%	3%	8%	5%
1-2"	82%	2%	12%	4%
2-3"	71%	1%	23%	5%
		Location 5 - Bikini		
0-1"	65%	12%	16%	7%
1-2"	66%	12%	18%	4%
2-6%	71%	5%	14%	10%

Clearing Experiment - Bikini

0-1"	89%	1%	6%	4%
1-2"	81%	-	9%	10%
2-3"	88%	1%	6%	5%
3-4"	85%	2%	8%	6%
4-5"	81%	5%	9%	5%
5-6"	74%	5%	15%	6%

*Very low energy γ-ray emitters such as ^{155}Eu and ^{241}Am are not included in the total activity.

**Includes contributions from ^{106}Rh, ^{102m}Rh, and ^{207}Bi when present.

The percentages for each isotope are relatively unchanging with depth. Since the standard deviation in the concentration measurements is sometimes quite large (see Table 2), this suggests our second assumption is also reasonable.

The percentage of the total exposure rate due to each of these isotopes was calculated for each of these sites using the average percentage concentration over all depths and compared with the field spectrometer data with excellent agreement. These results are given in Section III in the discussion of the Bikini Island data. The data from the analyses of all the soil samples obtained on the other islands of the atoll were then used in a similar manner to estimate the percentage of the average total exposure rate around the site due to each isotope in the soil.

During the 1964 Bikini Atoll survey a number of soil samples had also been obtained and analyzed by the University of Washington. None of these samples were from exactly the same locations as the 1967 samples; however, this calculation of percentage of total exposure rate due to each emitter was also done for these data. The results in general were consistent with the 1967 results. On islands where ^{137}Cs was the primary contributor in 1964, it still is in 1967. On islands where ^{60}Co and ^{125}Sb are now the primary contributors, the 1964 soil data usually indicate that these two isotopes contributed even a larger percentage of the total exposure in 1964; often even larger than would be estimated from half life alone, suggesting that weathering may play an important role on these islands.

The concentrations of various radioisotopes in the soil varied considerably from island to island with the islands further from detonation sites exhibiting mostly fission product activity, while islands close-in to detonation sites exhibited a variety of both fission and activation products. The particular γ-ray emitters found on each island and their relative concentrations are discussed further in Section III which treats in detail the environmental radiation fields on each individual island.

C. Error Estimates and Data Evaluation

Error in Total Gamma-Ray Exposure Rates - Based on our past experience with these instruments, the consistency of the field data, and the laboratory calibrations, total exposure rates at specific sites surveyed with the ionization chamber and/or the spectrometer system are estimated to be accurate to within 1 μr/hr. Total exposure rates obtained with the portable scintillation detector are probably about ± 10% S.D. and those with the G-M survey meters about ± 20% S.D. The overall accuracy in the range of the measurements for the sites surveyed is probably better than 10%.

Error in Partial Exposure Rates for Major Emitters - The partial exposure rates obtained from the field spectrometric measurements for ^{137}Cs, ^{60}Co, and ^{125}Sb are estimated to be accurate to ± 10% S.D. for the first two emitters and ± 20% S.D. for the latter. The ^{125}Sb estimate sometimes includes a small contribution from ^{102m}Rh. This estimate is based on the calibration accuracy as well as the amount by which the sum of the individual exposure rates differs from the independently measured total exposure rate. In most cases this difference was less than 10% and is probably due to errors in the assumed depth distribution relaxation length, non-uniformity of the radiation field, ground roughness effects, and neglect of very low energy emitters. As discussed in references 2 and 3, the field spectrometric exposure rate estimates are very insensitive to local inhomogeneities in isotope concentration, small errors in relaxation length, or slight ground roughness effects as opposed to the large errors which would be obtained by calculating the exposure rates using concentration data from an atypical soil sample. This is due primarily to the fact that the spectrometer "sees" a large area of soil and averages out most of these inhomogeneities.

The estimates of the percentage of the total exposure rate due to each emitter obtained from both the soil concentration data and the field spectrometric data agree quite well and these estimates, whenever given, are probably fairly reliable keeping in mind that on many of the islands they are based on just one soil sample from a single location.

Error in TLD Results - The accuracy of the exposures obtained from the TLD data (see Table 1) is best indicated by comparison with the ionization chamber results at mutual sites. The HASL TLD data seem to agree fairly well on the average, although a few individual values appear to be quite far off. The NRDL TLD data appear to be about 20% higher on the average with larger variations.

Overall Consistency of Data - The overall consistency of the ionization chamber and spectrometric measurements, TLD results, and calculations from the soil analysis indicates that the range of exposure rates on each island and the major contributors to these exposure rates have been determined quite accurately. This consistency is verified by the data in Table 1 and the data discussed in the next section.

III. EXTERNAL ENVIRONMENTAL RADIATION ON BIKINI ATOLL

External gamma radiation levels were found to vary considerably from island to island around the atoll. Typically, the levels on a given island ranged from very low near the lagoon and ocean shores to much higher near the center of the island. Hardly any natural radioactivity was detected at any of the field spectrometry measurement sites or in any of the soil samples. This lack of natural radioisotope content was not unexpected since the soil of coral atolls consists primarily of $CaCO_3$.

The isotopes contributing to the gamma radiation field varied considerably from island to island. On islands close to blast sites such as Eneman and Aomen-Iroij ^{60}Co, ^{125}Sb, and ^{155}Eu were predominant while on Bikini and Eneu islands the major emitters were ^{137}Cs, ^{60}Co, ^{125}Sb, and ^{155}Eu. ^{60}Co was present in fair amounts everywhere, probably as a result of the many tests on steel barges in the lagoon. On several islands close to blast sites considerable quantities of rhodium isotopes were detected. Other isotopes such as ^{144}Ce, ^{152}Eu, ^{65}Zn, and ^{207}Bi were also occasionally detected (by Ge(Li) spectrometry) in some of the soil samples. ^{241}Am was detected in all the soil samples in varying quantities indicating the expected presence of plutonium isotopes.

In addition to the gamma-ray exposure rates discussed in this report, the free air ionization and also the exposure to any potential residents would be increased by the contribution from β-ray emitters. Because of the fairly large ^{137}Cs concentrations found on many islands, one would expect correspondingly high ^{90}Sr concentrations, and ^{90}Sr would be by far the most important β-ray emitter present. Based on the measured ^{137}Cs concentrations and radiochemical determinations of ^{90}Sr concentrations (see Table 2) in a few of the sampled soils, ^{90}Sr concentrations appear to range from about 100 to 2000 dpm/gm for the first inch of soil as compared to corresponding concentrations on the order of 1 dpm/gm in the United States. These concentrations might increase the free air exposure by as much as several hundred

μr/hr. This would result in a fairly sizable increase in skin dose but a fairly negligible increase in dose to the reproduction organs because of the low penetrating ability of ^{90}Sr β-rays. We estimate that the maximum bone marrow and gonadal doses to a person sitting on the surface of the ground would be at most 10% of the corresponding ^{137}Cs γ-ray dose, while at 1 meter above the ground this ratio would probably be even less than 0.05. Since ^{90}Sr can be taken up by plants and enter the food chain, the high levels of ^{90}Sr in the soils of Bikini Atoll should be considered more an internal radiation hazard rather than an external radiation hazard and, therefore, will not be considered further in this report.

In this section, the external radiation environment on each of the islands surveyed is discussed in detail beginning with the largest island, Bikini. All of the terrestrial gamma total exposure rate data discussed in this section are given in Table 1. The available soil concentration data at the time of publication are given in Table 2. Examples of the Ge(Li) spectra of several of the soil samples from various islands are shown in Figures 8 through 12.

A. Bikini Island

Bikini Island, the largest island of the atoll, is approximately 1/2 mile wide and 2 1/2 miles long (see Figure 3). The island is quite heavily overgrown with brush, primarily scaevola, making passage across the island very difficult. Coconut palms and pandanas trees are significantly few in number. Most of these disappeared during the testing period as roads were laid across the island and land was cleared for housing and work areas.

The radiation survey of Bikini concentrated on the former native village area on the lagoon side near the center of the island. Two paths were cut across the island near the northern and southern ends of the village area. A survey between these paths was conducted along the overgrown village road which runs along the lagoon shore about 100 ft. inland. Measurements were also made on paths cut across the northern and southern tips of the island. A heavily vegetated

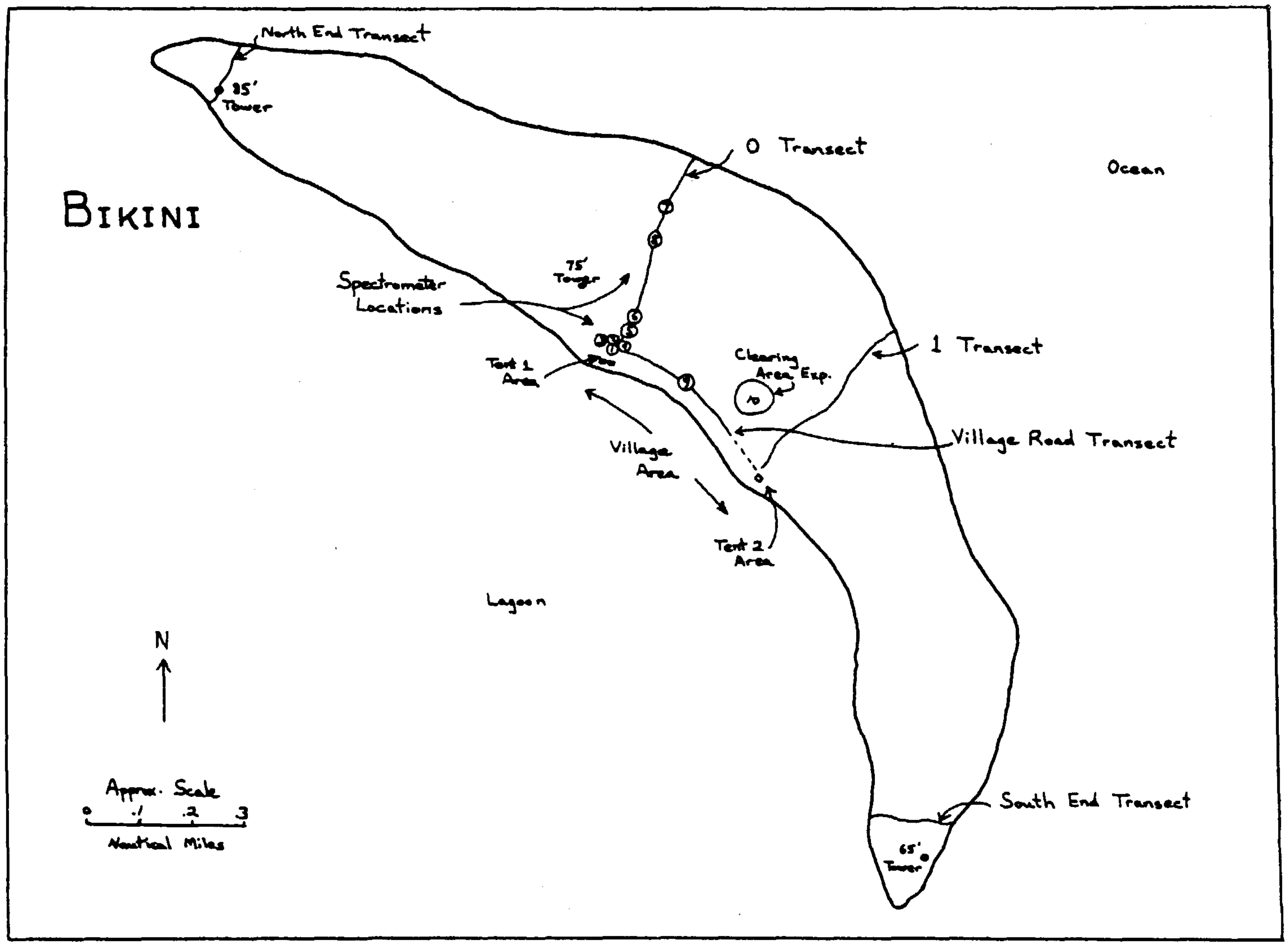

Figure 3. Bikini Island. Approximate locations of survey transects are indicated. Numbered circles are locations of field spectrometric measurements.

area near the old village site was chosen for a more detailed clearing experiment. The choice of locations and number of survey transects was limited by the location of good boat landing areas, the available time, and the small size of the survey party.

The map of Bikini Island (Figure 3) shows the approximate routes of the survey and the spectrometer and ion chamber measurement locations. A number of spectrometer measurements were made in the vicinity of Tent 1 at the beginning of the 0 Transect (near the lagoon shore) while work progressed on clearing the transect. The transect was then surveyed with the portable meters, and spectrometer measurements made at some of the areas exhibiting significantly higher or lower radiation levels. The Village Road required a minimum of clearing to be made passable. The 1 Transect again required considerable work with machetes and chain saws to allow passage for a portable meter survey. Field spectrometric measurements were also made at the midpoint of the Village Road and at the area chosen for the clearing experiment. For the North and South End Transects, no clearing was necessary.

<u>Total and Individual Isotope Exposure Rates Along the 0 Transect</u> - Readings of the portable scintillation counter were made every 50 ft. along the 2850 ft. 0 Transect. Geiger counter readings were recorded every 150 ft. These readings along with the ionization chamber results provide a profile of the radiation levels across the island as shown in Figure 4. Most of these data fall within a band of exposure rates ranging from 20 to 30 μr/hr near the lagoon shore, from 50 to 80 μr/hr in the center of the island, and from 10 to 20 μr/hr near the ocean beach. Several areas exhibited much higher exposure rates than these average values. There were also some locations which exhibited significantly lower than average radiation levels.

The increase in radiation near the center of the island appeared to correlate with the density of the vegetation. Near the shores the vegetation is sparse and the soil is very sandy, conducive to weathering and deeper penetration of fallout. Vegetation is much more dense over the central part of the island. The soil contains much organic matter, and moisture is continually being drawn into the roots of the plants. These factors probably influence the retention of fallout near the surface of the ground as well as cause large local variations in soil activity. Slight depressions in the ground surface can also become areas where fallout might accumulate. The spectrometer and ionization chamber (A_3) results for locations along the 0 Transect are given below. The percentage of the total exposure is given in parenthesis for each emitter.

SPECTROMETER AND IONIZATION CHAMBER EXPOSURE RATES
(μr/hr)

Location	^{137}Cs	^{60}Co	^{125}Sb	Total	A_3
#1 0'	19.0 (77%)	3.0 (12%)	2.8 (11%)	24.8	24.0
#2 50'	17.8 (78%)	2.4 (10%)	2.7 (12%)	22.9	22.8
#3 50' (in brush)	18.9 (78%)	2.1 (9%)	3.3 (14%)	24.3	25.0
#5 300'	22.8 (61%)	11.3 (30%)	3.5 (9%)	37.6	41.2
#6 400'	27.2 (62%)	12.5 (29%)	4.0 (9%)	43.7	47.5
#7 1800'	83.6 (74%)	19.5 (17%)	10.3 (9%)	113.4	103.2
#8 1410'	28.1 (76%)	4.9 (13%)	3.8 (10%)	36.8	36.1

Locations 1 and 2 were close to the lagoon shore at the beginning of the transect (0 ft. and 50 ft., respectively). These were in small clearings. The brush became quite dense only beyond about 200 ft. on the transect. The exposure rates at Locations 1 and 2 were very low, characteristic of locations near the shore. Location 3 was also near the 50 ft. point but with the instruments placed well in among some vegetation. A slightly higher exposure rate than at Locations 1 and 2 was recorded here. Locations 5 and 6 were 300 ft. and 400 ft. along the transect. Location 7 was a slightly depressed area near the 1800 ft. point. This location was characterized by quite heavy vegetation, scaevola and a stand

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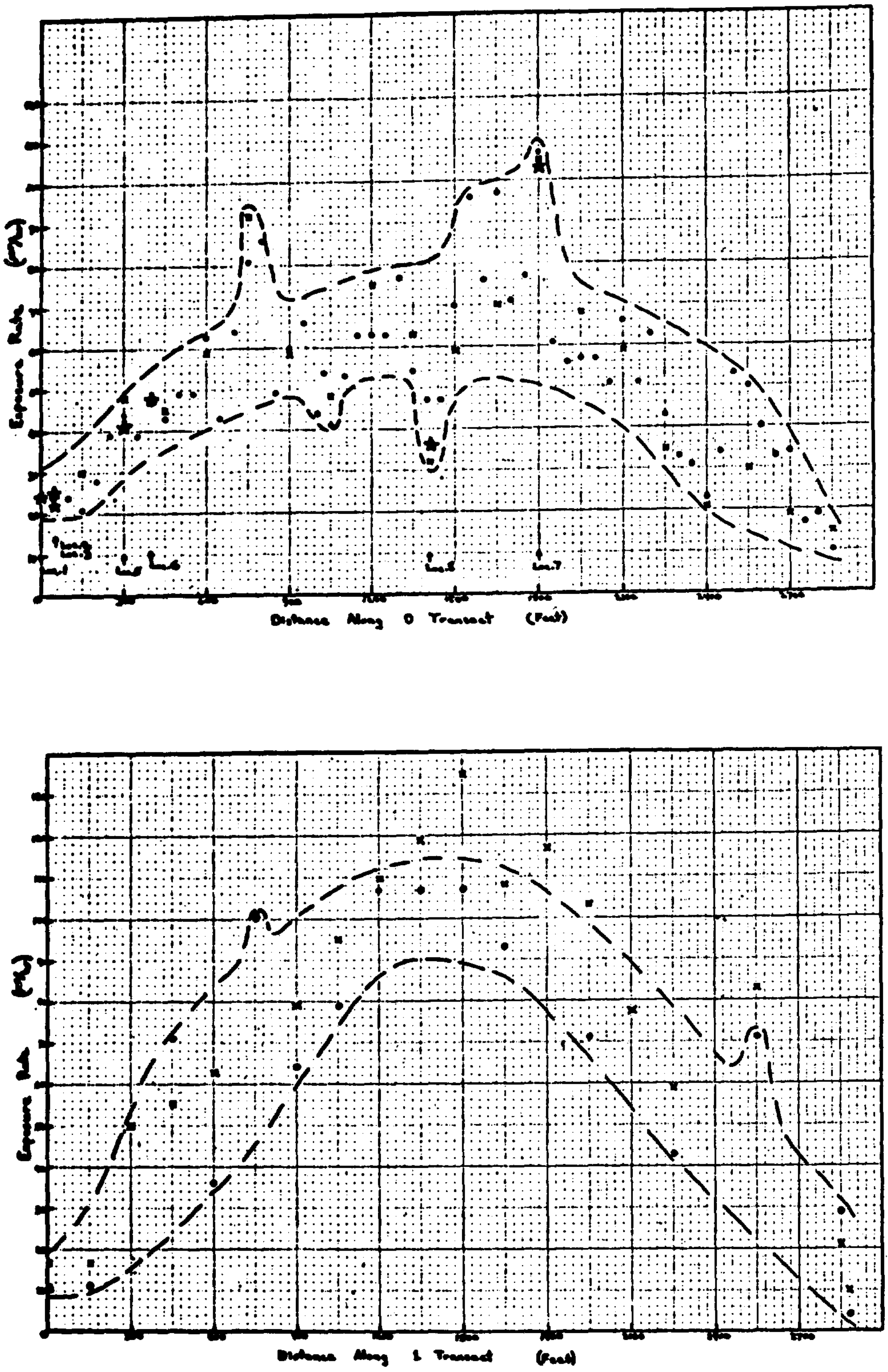

Figures 4 and 5. Exposure rate profiles of 0 and 1 Transects. Points are scintillation detector measurements, small x's gieger counter measurements, and stars are spectrometer locations.

of young cordia trees, and exhibited the highest levels encountered on the 0 Transect. Much lower levels were recorded at Location 8 at 1400 ft.

The spectrometric results indicate that the predominant radionuclide present in the soil on Bikini was ^{137}Cs with lesser amounts of ^{60}Co and ^{125}Sb. These were the main contributors to the total exposure rate. Of these three isotopes, ^{137}Cs contributed 76 to 78% of the total exposure rate and ^{60}Co and ^{125}Sb were each responsible for about 10 to 12%. Objects of scrap steel such as abandoned steel cable reels often showed high ^{60}Co contamination and this produced a higher local total exposure rate.

In the analysis of the spectrometer data it has been assumed that the radionuclides are distributed exponentially in the soil with a 2 cm relaxation length. This is consistent with the laboratory analysis of soil samples taken at Locations 5 and 7 and from the area of the clearing experiment. Non-uniform distribution of the gamma emitters and neglect of minor contributors is reflected in the small discrepancies between the ionization chamber and spectrometer total exposure rates given in the above table. Considering the general non-uniformity in fallout distribution throughout this area, agreement between the two measurements is quite good. For all the locations, the values agree to within 10%.

Exposure rates were also calculated from the results of the laboratory analysis of the soil samples taken at Locations 5 and 7. These values are given below together with the percentage of the total exposure due to each isotope.

EXPOSURE RATES CALCULATED FROM SOIL SAMPLE DATA

	^{137}Cs	^{60}Co	^{125}Sb
Location 5			
Total activity per cm^2	368 pc	42 pc	32 pc
Calculated from concentration in soil sample	19 μr/hr	9 μr/hr	1 μr/hr
Inferred from field spectrum	23 μr/hr	11 μr/hr	4 μr/hr
Percentage of total exposure rate based on soil analysis (see p. 11)	57%	32%	9%
Percentage of total exposure rate from field spectrometer and ionization chamber data	61%	30%	9%
Location 7			
Total activity per cm^2	2240 pc	79 pc	242 pc
Calculated from concentration in soil sample	157 μr/hr	25 μr/hr	10 μr/h
Inferred from field spectrum	84 μr/hr	20 μr/hr	10 μr/h
Percentage of total exposure rate based on soil analysis (see p. 11)	82%	7%	9%
Percentage of total exposure rate from field spectrometer and ionization chamber data	74%	17%	9%

The discrepancy between the soil sample and the spectrometer exposure rate results indicates the problems involved in obtaining a representative soil sample. The agreement in the values of the percentage exposure rates is quite good verifying the two assumptions discussed in Section II.

Both the field spectra and the laboratory spectra indicated that isotopes other than ^{137}Cs, ^{60}Co, and ^{125}Sb were also present in the soil. The energies and/or concentration of these isotopes, however, were too small to contribute significantly to the total exposure rate. In order to more accurately determine the identities of these isotopes, samples of the soil at Locations 5 and 7 were also analyzed by Ge(Li) spectrometry. These spectra indicated the presence of ^{155}Eu, ^{152}Eu, ^{241}Am, and possibly ^{106}Rh in addition to the isotopes already mentioned. An unidentified weak 238 keV emitter was also detected (see Figure 8).

NRDL LiF TLD dosimeters were placed every 150 ft. along this transect. HASL TLD dosimeters were placed near spectrometer Locations 1, 2, 3, 4, and 5, although in the case of Location 2 the TLD dosimeter was not exactly in the center of the measurement site. In most cases the TLD's were taped to branches along the transect. In general, the TLD results show the same trend as the other total exposure rate data (see Table 1), although the NRDL results are slightly higher on the average.

In order to determine if there was any significant difference in exposure due to the proximity of dosimeters to vegetation, a dosimeter of each type (NRDL and HASL) was placed on a stake in the middle of the open trail at Location 5 for comparison with the two taped to the vegetation. For this location, at least, there was no significant difference in the readings of the two sets of dosimeters. The high readings of the HASL dosimeter at Location 2 are probably due to the highly variable nature of the radiation field. This dosimeter was taped to a branch of a bush in a general area where the radiation field appeared to be lower than average as evidenced by the area survey results. However, it is quite possible the vegetation in this generally sandy soil of minimum organic content could have concentrated more ^{137}Cs in its immediate vicinity. The TLD results at the other locations along this transect are in excellent agreement with the other data.

Total and Individual Isotope Exposure Rates Along the Village Road Transect - Twenty-one hundred feet of the Village Road between 0 and 1 Transects (see Figure 3) were surveyed. Scintillation and Geiger counter readings were made every 150 ft. as determined with a marked 150 ft. length of rope. These measurement points coincided with the placement of NRDL TLD dosimeter packages. Spectrometer and ionization chamber measurements were made at the beginning of the transect, Location 4, and at the midpoint, Location 9.

The road was generally clear of brush, particularly past the 1200 ft. point toward the Tent 2 area. The soil was rather sandy and weathered, and the radiation levels were relatively low and uniform, from 20 to 40 μr/hr from 0 ft. to 1040 ft., and from 8 to 18 μr/hr from 1350 ft. to 2100 ft. Only the 1200 ft. point was located in the midst of somewhat denser vegetation. The exposure rate measurements at this location were correspondingly higher; about 57 μr/hr. The spectrometer and ion chamber measurements are summarized below.

SPECTROMETER AND IONIZATION CHAMBER EXPOSURE RATES
(μr/hr)

Location	^{137}Cs	^{60}Co	^{125}Sb	Total	A_3
#4 0'	17.7 (80%)	1.7 (8%)	2.8 (13%)	22.2	24.6
#9 1050'	26.7 (77%)	3.9 (11%)	4.0 (12%)	34.6	37.5

The dominant emitter again is ^{137}Cs, contributing 77 to 80% of the total exposure rate. No soil samples were taken. The TLD results (Table 1) also show the same pattern as the portable meter readings, although the HASL results at Locations 4 and 9 are quite high, possibly for the same reasons as discussed in reference to the Location 2 result.

The exposure rate measurements along the Village Road and at Locations 1, 2, and 3 on the 0 Transect may be assumed to be fairly typical for the area along the lagoon shore, not too far inland. The total exposure rates averaged 20 to 40 μr/hr. More weathered areas such as sections of open roadway and the large cleared area around the 1500 ft. point on the Village Road (reportedly a former recreation area) had exposure rates of 10 to 20 μr/hr. Around more protected areas within the lagoon shore region characterized by denser vegetation in more organic soil, exposure rates of 60 μr/hr and more were measured.

<u>Total Exposure Rates Along the 1 Transect</u> - The vegetation along the 1 Transect was much more dense than that encountered along the 0 Transect. The area along the 1 Transect appeared less disturbed by previous clearing or construction activity. A number of pandanas trees and a few coconut palms were seen in this region.

Survey meter measurements were made every 150 ft. along this 2850 ft. transect coinciding with the placement of TLD's. The exposure rate profile is shown in Figure 5. Exposure rates rose to uniformly high values near the center of the transect where they were 90 to 110 μr/hr or greater. The geiger counter with the probe window open indicated a fair amount of β-ray contribution in the area near the 1350 ft. point and beyond the transect center. This probably explains the higher G-M counter gamma exposure rates obtained in this area, since the geiger counter was found to overestimate gamma exposure rates in the laboratory in the presence of a large β-ray field. Exposure rates ranged between 10 and 20 μr/hr very near the lagoon and ocean beaches. No localized areas of significantly higher or lower radiation levels were encountered although they may well exist. The dashed lines drawn in Figure 5 enclose most of the measurements made along the 1 Transect, except for the geiger counter readings in the higher β-active region.

No field spectrometer measurements were made along this transect due to the extreme difficulty in traversing the path even when not carrying equipment. Neither were any soil samples obtained.

Again the TLD results (Table 1) show the same pattern as the survey meter results with the 4 HASL TLD results agreeing very well with the corresponding HASL scintillation counter readings.

Total Exposure Rates Along the South and North End Transects

Short transects were made of the north and south tips of the island. The vegetation was not thick in these areas. Along the North End Transect and around an 85 ft. observation tower, the exposure rates were typical of close-to-shore values; 20 to 40 μr/hr.

The South End Transect was through a former construction camp housing area. Exposure rates were low in the open areas 5 to 25 μr/hr. In a small cordia grove on the lagoon side of the island a value of 60 μr/hr was obtained. Other high readings, 50 to 60 μr/hr, were noted when the survey meter was placed near the concrete housing foundations in the area. This activity can possibly be explained as due to retention of fallout which accumulated on the rough concrete surfaces.

No soil sample or field spectrometric data were obtained although a few TLD units were exposed (see Table 1).

Total and Individual Isotope Exposure Rates at the Clearing Experiment Site - The question whether uptake of radioactive materials by plants contributes significantly to the external radiation field was carefully investigated. If such uptake were significant, clearing the brush might reduce the radiation levels to some extent. The area chosen for the experiment was of quite dense vegetation, mainly scaevola 8 ft. to 10 ft. high, about 400 ft. inland from the 1800 ft. station on the Village Road. Initial survey meter readings about the center of the area indicated fairly uniform exposure rates of about 60 μr/hr. A full set of spectrometer and ionization chamber measurements were made before any clearing began and were repeated as the area was progressively cleared to a 10 ft., 20 ft., and 30 ft. radius. These measurements showed no significant effect on exposure rate or changes in the spectrum. These results are summarized below.

CLEARING EXPERIMENT EXPOSURE RATES
(μr/hr)

Radius of Cleared Area	^{137}Cs	^{60}Co	^{125}Sb	Total	A_3
0'	47.2	5.2	9.1	61.5	59.0
10'	48.6	5.2	8.6	62.4	59.0
20'	50.8	5.5	8.0	64.3	59.9
30'	52.2	5.7	8.5	66.4	60.5

The slight increase in the total of the ^{137}Cs, ^{60}Co, and ^{125}Sb exposure rates indicates that there is possibly some increase in the unscattered gamma radiation affecting our partial exposure rate estimates, but there is a corresponding reduction in the scattered radiation and thus little effect on the total exposure rate. The more important effect of the vegetation seems to be to enhance scattering of the radiation from emitters in the soil thereby producing a slightly softer energy spectrum. This effect more than compensates for the increase in exposure rate at the detector due to radiation originating in the vegetation itself.

The quantity of vegetation removed was staggering. As the brush was removed from the area, it was identified and weighed. These statistics are given below.

VEGETATION REMOVED IN CLEARING EXPERIMENT

Area	Scaevola	Dodonea	Litter
Pounds of Aerial Portions			
10 ft. radius	593	33	59
10 - 20 ft. radius	1717	112	364
20 - 30 ft. radius	2902	67	386
Total	5212	212	809

	Pounds Per Square Foot		
10 ft. radius	1.89	0.10	0.188
10 - 20 ft. radius	1.82	0.12	0.386
20 - 30 ft. radius	1.85	0.04	0.246
Total	1.84	0.08	0.286

Samples of the vegetation were analyzed for radionuclide content at the University of Washington. These data were not available at the publication time of this report and will be included in a later report.

While clearing of vegetation has no significant immediate effect, it is possible that certain long range effects could lead eventually to somewhat lower radiation levels. Since water is no longer taken up by the plants, the flow of ground water is disrupted. This factor and the subsequent weathering of the cleared area could cause less retention of fallout products near the surface of the ground. Thus, lower radiation levels in such an area might result.

A careful soil depth profile (Table 2) was obtained from an area 25 feet west of the center of the cleared area. Also, several 6" diameter x 6" deep cores were taken along a radius to the north from the center at 10 foot intervals. The soil appeared to be of high organic content and had an average moisture content of about 10% and a bulk density of about 1.2 gm/cm^3. The isotopes were found to be distributed with depth in a roughly exponential manner for the first 3 inches with an approximate relaxation length of 3 cm. However, the activity from 3 - 5" was much higher than allowed for by this exponential model. The exposure rates calculated for the total measured concentrations, assuming a 3 cm relaxation length is typical for the area as a whole, are given below along with the percentage of the total exposure rate due to each isotope.

EXPOSURE RATES CALCULATED FROM SOIL SAMPLE DATA

	^{137}Cs	^{60}Co	^{125}Sb
Clearing Experiment Area			
Total activity per cm^2	4200 pc	90 pc	600 pc
Calculated from concentration in soil sample	240 µr/hr	19 µr/hr	24 µr/hr
Inferred from field spectrum	52 µr/hr	6 µr/hr	9 µr/hr
Percentage of total exposure rate based on soil analysis (see p. 11)	84%	8%	6%
Percentage of total exposure rate from field spectrometer and ionization chamber data	77%	9%	14%
Core activity (pc/gm)			
10 feet north of center	74	<.6	74
30 feet north of center	251	3.4	26

The percentages of the total exposure rate due to each isotope were calculated as discussed in Section II (p. 11) and agree reasonably well with the field spectrometric data in contrast to the calculated exposure rates which are quite high, much higher than could be explained by the excess activity from 3 - 5 inches. The core data also given in the table illustrate the large local variation in the total activity which is probably the main reason for the high values for the calculated exposure rates.

This cleared area was resurveyed two weeks later upon return to Bikini Island. The exposure rate measured at the center of the area was essentially the same as before (59.6 µr/hr). Additional measurements were made around the edges of the area to determine the degree of uniformity of the exposure rate. The exposure rates obtained were: South side 59.9 μr/hr, East side 68.7 μr/hr, North side 76.8 μr/hr, and West side 83.0 μr/hr. The corresponding field spectra indicated the differences in exposure rates were due to differences in ^{137}Cs, ^{60}Co, and ^{125}Sb contributions, rather than to any new contributors, with the percentage contributions of each isotope remaining fairly constant. These local variations in the isotope distribution pattern seemed to be typical of many areas on Bikini and again indicate the difficulty in obtaining a soil sample representative of the area as a whole. However, the excellent agreement of the sum of the field spectrometric exposure rate estimates with the ion chamber measurements and the agreement of the two independent calculations of the percentage of total exposure rate due to each isotope verifies that the field spectrometer averages out most of these variations.

Four HASL TLD dosimeters were exposed at this site for about 8 days duration. The average exposure rates were 56 μr/hr for two placed in the center, 78 μr/hr for one placed on the northeast side of the clearing, and 65 μr/hr for the fourth which was situated on the southwest side of the clearing. These data agree quite well with the ionization chamber and spectrometer total exposure rate estimates, tabulated above.

A study of the Ge(Li) spectrum of the soil obtained from this site indicated, as was the case for the soils obtained on the 0 Transect, the presence in small amounts of ^{152}Eu, ^{155}Eu, and ^{241}Am in addition to ^{137}Cs, ^{125}Sb, and ^{60}Co.

<u>Summary of Exposure Rates on Bikini Island</u> - The total gamma-ray exposure rates on Bikini Island ranged from 10 - 120 μr/hr. In general, the areas close to shore were 20 - 40 μr/hr and the island center was 50 - 80 μr/hr while scattered hot spots exhibited levels up to 120 μr/hr. Cosmic rays result in an additional exposure rate of ~3.4 μr/hr at all locations. The primary contributor to these gamma-ray exposu rates was ^{137}Cs, with ^{60}Co and ^{125}Sb the only other significant contributors.

B. Eneu

Eneu, the second largest island, is located along the southeastern rim of the Atoll near the main channel opening into the lagoon (Figure 1). The island was the logistics center for the atoll during the testing period. A major aircraft runway is located on the southern part of the island. Several piers are on the lagoon side. Towers are located at both ends and near the island center. Buildings are numerous - a large assembly building near the south tower, the terminal building and hangar near a large concrete parking area adjacent to the runway, and personnel housing along the Village Road and along the northeastern ocean beach. Only a few parts of the island seemed to have escaped the construction activity, notably the central region in the northern half, where there were a number of coconut-bearing palms. In general, the island was less overgrown with wild brush than was Bikini.

Radiation levels on Eneu were quite low - among the lowest measured on the atoll. This island was the farthest away from the main testing locations along the north and northeast reef and was also favorably located to avoid fallout, including that carried eastward from shot Bravo.

Measurements were made primarily near the road which runs along the lagoon side of the island. This is the area of most probable past or future native settlement. Survey readings were recorded every 300 ft. beginning at the aircraft hangar and ending near the north tower (see Figure 6). TLD's were also placed along the road and left for approximately two weeks. Gamma spectral measurements were made in front of the aircraft hangar and about 1200 ft. north of the hangar in a clearing adjacent to the road. Survey meter measurements were also made around the south tower, along two transects north of the parking area and near the northern end, and along the ocean side of the island about 50 ft. inland from the northern perimeter.

The survey meters indicated radiation levels of from 2 μr/hr to a maximum of 10 μr/hr. The highest levels were found in the northeast, slightly inland. The lowest levels were near the runway on Cross Transect 1. For such small

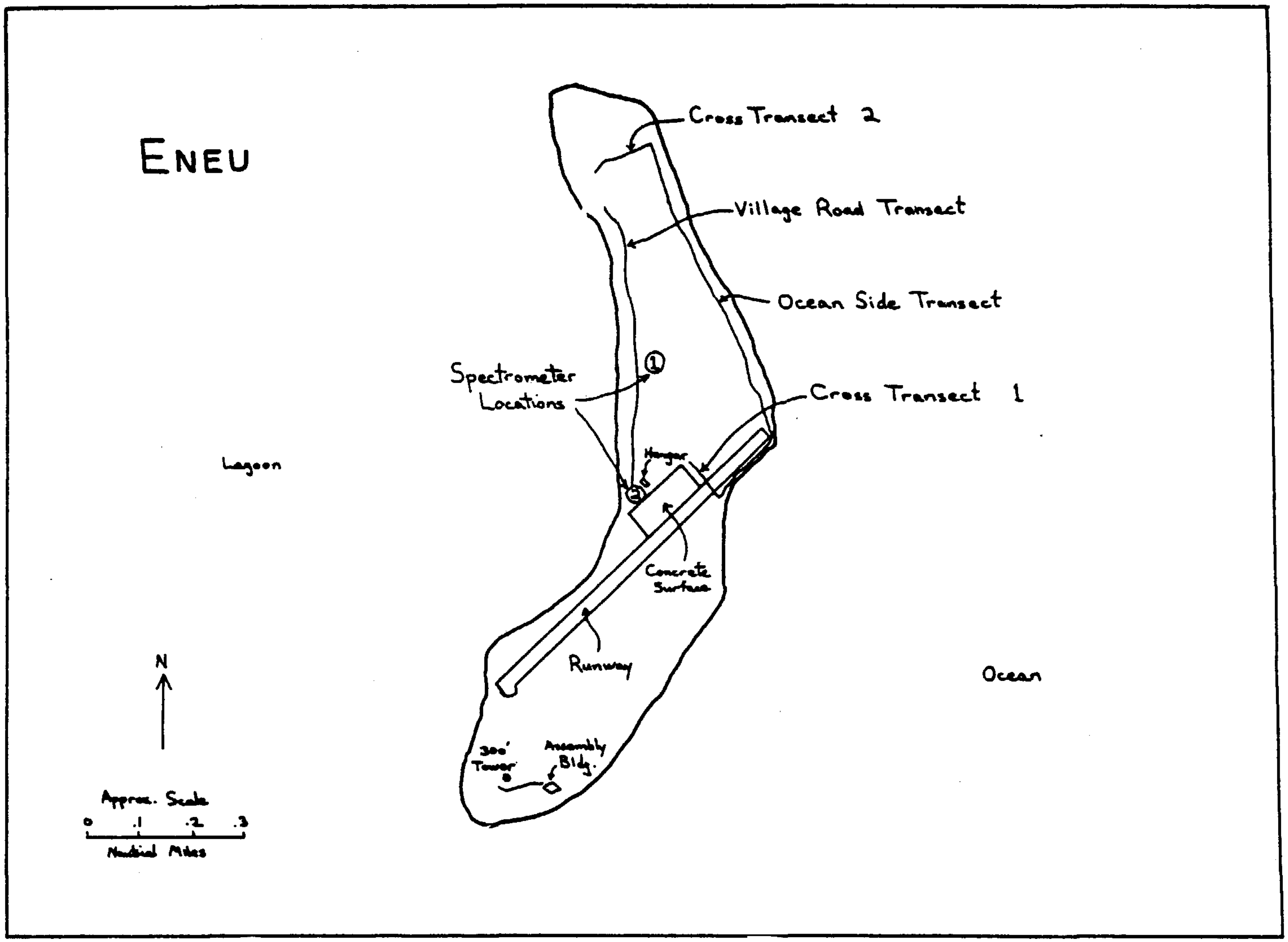

Figure 6. Eneu Island

variations in radiation levels, little can be said about the characteristics of areas where high or low levels might be found.

Field gamma spectral measurements, at two locations (see Figure 6) are summarized below.

SPECTROMETER AND IONIZATION CHAMBER EXPOSURE RATES
(μr/hr)

Location	^{137}Cs	^{60}Co	^{125}Sb	Total	Total exposure rate
Aircraft hangar	3.1(78%)	.5(12%)	.4(10%)	4.0	4.1
1200 ft. north	3.0(63%)	1.5(31%)	.3(6%)	4.8	5.1

The exposure rates at these two locations were representative of the average levels of radiation for the island. The radioisotopes, which were present, were in proportions similar to locations on Bikini, though in much less quantity with the major contributor to the total dose rate still ^{137}Cs (60 to 80%).

With the HASL TLD units placed on Eneu, we obtained exposure rate estimates consistent with the other measurements. At four locations along the lagoon road, the TLD results were 6.7 μr/hr, 4.6 μr/hr, 13.2 μr/hr, and 5.7 μr/hr. The NRDL TLD measurements did not show non-zero readings due probably to the larger uncertainty in the background subtraction.

No soil samples were taken on Eneu in 1967 due to the very low gamma radiation levels which are in the range of the natural exposure rates commonly found in the Continental U. S.[1,3]. However, the 1964 soil data confirm that ^{137}Cs is the major contributor to the total exposure rate.

C. Bokantuak, Iomelen, Rojkere, Eonjebi

The islands between Bikini and Eneu are quite small. Unusually high tides are capable of washing across these low islands, and consequently only scrub brush survives in the sand and coral soil.

The four islands were surveyed with G-M counters only. Several transects were made across each island. The radiation levels were quite low and uniform. Most recorded readings were ~10 μr/hr. The range of radiation levels on the four islands was 3μr/hr to 10 μr/hr (Table 1).

D. Aerokoj-Eneman Complex

The Aerokoj-Eneman Complex, nine miles west of Eneu, is a two-mile chain of five islands connected by partly eroded causeways. Only the western-most island, Eneman, exhibited significant radiation levels.

The two eastern islands, Aerokoj and Aerokojlol are connected and almost indistinguishable as separate islands. These two islands were almost completely cleared of vegetation during the testing period. An aircraft runway ran the length of the islands. A water distillation plant and a personnel housing area were located on the southern side of Aerokoj. Some coconut seedlings were found growing quite well around the former campsite. The islands had isolated stands of brush, but not nearly the density of vegetation on Bikini. The ground was grass covered and was used by a considerable number of nesting sea birds. Survey measurements with the scintillation counter and the G-M counter were made along the center of these islands with spot measurements nearer the ocean and lagoon shores. Readings were quite low and uniform, similar to Eneu. The range of G-M counter readings was 3 to 10 μr/hr. The terrestrial gamma exposure rates measured with the scintillation counter ranged from only 1 to 3 μr/hr. Because the radiation levels were so low on these two islands, no soil samples were taken.

The longest causeway of the complex connects western Aerokojlol with Bikdrin. This island and the next one quite near to the west, Lele, are so small as to be little more than wide spots on the causeway. There were some tidal pools in low depressions on these islands which contained mullet and milkfish. The vegetation was primarily scaevola. Radiation levels along the causeway and on these small islands were low and uniform - 6 to 8 μr/hr measured with the scintillation counter and 10 μr/hr with the G-M counter. Some pieces of metal scrap found along the long causeway gave higher readings. Samples analyzed with the spectrometer on the ship showed the contamination to be mostly ^{60}Co.

The western-most island of the complex, Eneman, is largest in extent. The vegetation was quite thick around the tower on the eastern end, becoming less dense near the center and western end. The western end was, in fact, quite desolate, with low depressions of moist sandy soil covered with black algae. Concrete blocks off the end of the island mark the ground zero for the testing of several devices. Extreme variations in radiation levels were found on Eneman. The eastern end was similar to the rest of the complex - 1 to 10 μr/hr. Beyond the center part of the island toward the western end, however, levels ranged from 20 to 60 μr/hr. The areas surrounding the sand craters on the western end were also within this range. The craters themselves (the algae covered sand depressions very near the blast area) were quite hot - from 100 to over 500 μr/hr. The highest level measured on the whole atoll was in this area on western Eneman - 570 μr/hr measured with the scintillation counter.

Soil samples were taken from two locations on Eneman where these high radiation levels were recorded. Analysis of these samples indicated primarily ^{60}Co activity with considerable ^{125}Sb, ^{155}Eu, and ^{102m}Rh activity. ^{152}Eu, ^{106}Rh, and ^{241}Am activity was also seen in the Ge(Li) spectra. There was relatively little ^{137}Cs activity. The table below gives the percentage of the total exposure rate due to each isotope at the two locations.

ENEMAN SOIL ANALYSIS RESULTS

	^{137}Cs	^{60}Co	^{125}Sb	^{102m}Rh
Percentage of total	3%	87%	8%	2%
exposure rate	6%	83%	7%	4%

Pieces of metal scrap with varying amounts of ^{60}Co contamination were found scattered about the western part of Eneman. These were mostly steel cables and pieces of steel reinforcing rods in concrete fragments.

E. Enidrik

Enidrik is the largest island of the southern group and is fourth largest of the atoll. It is less than one mile west of Eneman. The vegetation is quite thick, particularly in the island interior. There are stands of cordia and pisonia trees and several pandanas trees with the usual ground cover of scaevola, messerschmidia, and guettarda. Several survey transects were made from lagoon to ocean side on the eastern part of the island. Survey of the larger western part was less systematic due to the density of vegetation.

Readings with the G-M counter on the eastern part of the island generally ranged from 3 to 10 µr/hr. In one area near the eastern end, a reading of 30 µr/hr was obtained. Some metal scrap in this region exhibited significant contamination.

The western part of the island showed variations in the radiation levels similar to Bikini - low levels near the ocean and lagoon shore with higher levels inland, indicative of greater retention of radioactive products by the organic soil. Measurements with the scintillation counter ranged from 3 to 19 µr/hr on a transect near the center of Enidrik. The range was 9 to 235 µr/hr on a transect farther to the west. The low level was near the ocean high tide line. Mid-island on this transect the levels were around 30 to 90 µr/hr. The highest levels on the island were measured aroun a concrete instrument bunker near the lagoon shore. Other regions where high levels were found were located near the western end over a desert-like plain and near depressions with black algae cover. Readings with the G-M counter in these regions ranged from 110 to 217 µr/hr.

Soil samples were taken from two areas on the western end where the highest levels were measured. The analyses of the samples indicated that the major contributors to the exposure rate were ^{60}Co, ^{102m}Rh, and ^{125}Sb. These three emitters probably account for about 85% of the total exposur rate, with the remainder due mostly to ^{137}Cs (12%). ^{155}Eu, ^{101}Rh, ^{102}Rh, ^{106}Rh, and ^{65}Zn, were also detected (see Figure 9).

F. Lukoj - Jelete

These two islands in the southwest part of the atoll are quite similar to one another. They are small, more or less round with black coral rock overgrown with ipomea vines along the shore areas. Inland the islands had very dense vegetation. The soil was very damp with considerable thickness of decaying organic matter. These islands also had large bird populations.

Survey of these islands was generally done by circling each island about 100 ft. inland. Spot measurements were made in the interior with at least one transect across the island through the dense vegetation.

The radiation levels on Lukoj were quite high. On one short transect the range was 61 to 104 µr/hr with the scintillation counter and 63 to 130 µr/hr with the G-M counter. On another transect which cut more nearly across the center of the island the ranges were 100 to 171 µr/hr and 83 to 197 µr/hr. A soil sample was taken near the center of the island where the higher levels were measured. This soil sample was analyzed on both NaI(Tl) and Ge(Li) spectrometers. The spectra indicated that the major γ-ray emitters present were ^{60}Co, ^{125}Sb, ^{102m}Rh, ^{155}Eu, and ^{137}Cs with traces of ^{101}Rh, ^{144}Ce, ^{106}Rh, ^{241}Am, and ^{65}Zn (see Figure 10). We estimate from this sample that approximately 60% of the exposure rate at this site was due to ^{60}Co, 30% to ^{125}Sb and ^{102m}Rh, and the rest primarily to ^{137}Cs.

Jelete is similar in almost all respects to Lukoj. The radiation survey was accomplished by encircling the island about 100 ft. inland. Readings with the G-M counter ranged from 63 to 130 μr/hr. No soil samples were obtained.

G. <u>Oroken - Bokaetoktok - Bokdrolul</u>

These small islands, the most westerly of the southwest group, exhibited similar general characteristics - black coral rock shores, dense vegetation, moist, highly organic soil, and quite large bird populations. The islands were essentially undisturbed by construction and other similar activities connected with the testing operations.

Radiation levels on these islands were somewhat lower than on Lukoj and Jelete. On Oroken the measurements around the island about 50 ft. inland ranged from 17 to 30 μr/hr. Closer to the center of the island the levels were around 40 μr/hr. The highest level measured with the G-M counter was 43 μr/hr.

On Bokaetoktok the levels were only slightly lower, ranging from 10 to 23 μr/hr with a maximum of 30 μr/hr near the center.

On Bokdrolul fairly uniform readings of from 24 to 36 μr/hr were recorded with the scintillation counter. A similar range was found with the G-M counter with one measurement of 50 μr/hr. Lower levels of about 10 μr/hr were typical near the ocean or lagoon shores. No soil samples were obtained from these islands.

H. <u>Bokbata</u>

A sand bar is all that remains of the island of Bokbata in the northwest part of the atoll. There is no vegetation whatever on the small narrow island. Just to the north is the Bravo crater. Off the southern tip is an isolated concret instrument bunker.

The radiation levels on the island were about 15 μr/hr. High tides must frequently wash across the island. Consequent there is little retention of radioactive materials, but traces are still found due to the close proximity of the tests.

Samples of sand from the island and some bottom sediments from the Bravo crater were taken for gamma spectral analysis. The sand exhibited mostly ^{60}Co, ^{137}Cs, and ^{125}Sb activity. ^{60}Co appeared to be responsible for about 60% of the exposure rate, ^{137}Cs about 30% of the exposure rate, and ^{125}Sb and other elements the remainder. The bottom sediment sample, while containing all of the above isotopes, also contained considerable ^{207}Bi activity. The major contributor was again ^{60}Co.

I. Nam

Nam, the third largest island, is also located in the northwest part of the atoll. This island exhibited yet another variation of the atoll topography, which caused each island to seem markedly different in appearance. Nam has large open areas covered with fimbrisytlis and ipomea vines. Messerschmidia trees, unsurrounded by thick underbrush, were able to spread out and achieve large sizes. A great number of birds were nesting on the island.

Radiation levels were found to vary widely on Nam. In addition, special problems were presented by pieces of highly active scrap metal scattered about the island. One piece of metal found half-buried near the center of the island approached the activity of a typical laboratory ^{60}Co calibration source - ~500 μr/hr at 1 meter. It is possible that a large number of these metal artifacts are in the soil of this island due to its close proximity to testing areas.

A full set of radiation measurements was performed on Nam. Ionization chamber measurements were made at four widely separated locations with spectrometer measurements at three of them. A number of transects of the island and routes around the island were made to obtain measurements with the portable counters. The approximate locations of these measurements are shown in Figure 7.

The portable survey instruments indicated exposure rates from 10 to 60 µr/hr around the edge of the island and from 15 to 160 µr/hr near the center (see Table 1). Isolated areas had much higher radiation levels, particularly the northeastern section where exposure rates of over 200 µr/hr were measured.

The spectrometer measurements indicated that the major contributor to the radiation field was ^{60}Co. This was the contamination on the buried metal scrap, but the radioisotope was also found in a soil sample taken from the island. The other major contributor was ^{137}Cs. Only small amounts of ^{125}Sb were present. The exposure rates due to each isotope and its percentage of the total is shown below for each location, along with the total exposure rates measured with the ionization chamber.

SPECTROMETER AND IONIZATION CHAMBER EXPOSURE RATES
(µr/hr)

Location	^{137}Cs	^{60}Co	^{125}Sb	Total	A_3
1 (Center near bunker)	25.8(39%)	39.4(59%)	1.1(2%)	66.3	75.5
2 (Northeast corner)	60.6(33%)	119.5(66%)	2.0(1%)	182.1	204.0
3 (Near lagoon shore)	18.1(50%)	17.2(48%)	.6(2%)	35.9	34.1
4 (Center on western side)					55.3

The agreement between spectrometric and ionization chamber total exposure rates is least satisfactory for Locations 1 and 2 on this island than for other locations surveyed on Bikini and Eneu. This is probably due to the non-uniformity of distribution of radioactive materials on Nam. Near both Locations 1 and 2, highly active pieces of metal scrap were located in the soil within a few hundred feet of the measurement sites. Such deviations from uniform distribution change the spectrometer calibration slightly, though the exposure rate estimates from the total absorption peaks of the spectrum still represent close to average values for a large area about the detection point. Measurements with the ionization chamber over a larger area would probably have resulted in a better average total exposure rate estimate.

A soil sample was taken at Location 2. It is quite probable that this sample is not representative of the area as a whole, but the ratios of the concentrations of various major emitters present help verify the percentage exposure rates obtained from the field spectra. The laboratory NaI(Tl gamma spectral analyses indicate that ^{60}Co does contribute about 50% of the exposure rate at this site with almost all of the remainder due to ^{137}Cs. The Ge(Li) spectrum (Figure 11) indicates the presence of ^{125}Sb and ^{155}Eu and very slight traces of ^{152}Eu, ^{106}Rh, and also ^{241}Am, and thus ^{241}Pu Two soil samples obtained in 1964 (not at the same identical locations) indicate that at that time ^{60}Co was responsible for ~70% of the total exposure rate. This may indicate that on islands such as Nam, where there is little organic material in the soil and sparse vegetation, weathering may be important and could have caused the total exposure rate to decrease much more rapidly than half-life analyses would predict. Unfortunately, due to the sparsity of the data and the observed non-uniformity of the radiation field, this hypothesis cannot be verified at this time.

J. Aomen-Iroij Complex

The Aomen-Iroij Complex consists of the causeway connecte islands of Aomen, Lomilik, Odrik, and Iroij from east to west respectively. These islands are centrally located along the northern atoll reef. The island chain is quite long and narrow and has only sparse vegetation.

Several tests of nuclear devices were conducted in the near vicinity of this island complex, and thus the extremes in radiation levels typical of blast areas were found here. A survey using the portable meters was made along a route down the middle of the complex. These measurements ranged from 5 to 20 μr/hr on Aomen, 20 to 330 μr/hr on Lomilik, 10 to 40 μr/hr on Iroij, and 3 to 7 μr/hr on the causeways. Except for the higher values on Lomilik, these exposure rates were typical of weathered, sandy soils capable of only low retention of radioactive materials. The hot spots on Lomilik were depressed areas with clay-like soil.

A soil sample was taken from the area of greatest activity. The soil analysis indicated that ^{60}Co was responsible for more than 3/4 of the total exposure rate, with ^{125}Sb and lesser amounts of ^{102m}Rh and ^{137}Cs contributing almost all the remainder. Traces of ^{106}Rh, ^{101}Rh, ^{144}Ce, ^{155}Eu, and ^{241}Am, and thus ^{241}Pu were also detected (see Figure 12). A 1964 sample from Iroij indicated that at that time ^{60}Co contributed about 75% of the total exposure rate, ^{125}Sb about 8%, ^{137}Cs about 9%, and ^{102m}Rh the remainder, in substantial agreement with the 1967 data for Lomilik.

Many pieces of fairly radioactive metal scrap were found throughout this area. Although most of the time this contamination was due to ^{60}Co, several samples exhibited only unidentified 240 keV gamma-ray activity.

IV. SUMMARY AND CONCLUSIONS

An intensive external radiation survey of Bikini Atoll was carried out during April and May of 1967. Total exposure rates were found to vary considerably from island to island and from site to site on a given island. Levels measured over soil ranged from less than 10 µr/hr to over 500 µr/hr. (External gamma radiation levels in the United States due to naturally occurring emitters in the soil range from 0 to about 20 µr/hr.) On Bikini and Eneu Islands the major contributor by far to the total exposure rate was found to be ^{137}Cs with minor but significant contributions from ^{60}Co and ^{125}Sb. On Nam and other islands closer to blast sites ^{60}Co was the main contributor with important contributions from ^{125}Sb, ^{102m}Rh, and sometimes ^{137}Cs. Other isotopes, including ^{207}Bi, ^{155}Eu, ^{152}Eu, ^{65}Zn, ^{106}Rh, ^{101}Rh, ^{144}Ce, and ^{241}Am, were also detected occasionally.
The range of radiation levels on each island are summarized below.

SUMMARY OF RADIATION LEVELS - GAMMA EXPOSURE RATES
(µr/hr)

Island	Exposure Rate Range	Major Contributors
Bikini	10-120	^{137}Cs
Weathered Areas	10-30	
Close-to-Shore	20-40	
Island Center	50-80	
Hot Spots	80-120+	
Eneu	2-10	^{137}Cs
Nam	10-330	^{60}Co, ^{137}Cs
Outer Edge	10-30	
Island Center	15-150	
N.E. Corner	110-330	
Bokantuak, Iomelan, Rojkere, Eonjebi	3-10	*

Aerokoj-Eneman Complex:		
Aerokoj, Aerokojlol	1-10	*
Bikdrin, Lele	6-10	*
Eneman	1-570	^{60}Co, ^{125}Sb, ^{102m}Rh
East Eneman	1-10	
West Eneman	20-570	
Enidrik	3-235	^{60}Co, ^{125}Sb, ^{102m}Rh
East Enidrik	3-30	
West Enidrik	10-235	
Lukoj	60-200	^{60}Co, ^{125}Sb, ^{102m}Rh
Jelete	60-130	*
Oroken	15-45	*
Bokaetoktok	10-35	*
Bokdrolul	20-50	
Bokbata	10-30	^{60}Co, ^{137}Cs
Aomen-Iroij Complex:		
Aomen	5-20	*
Lomilik	20-330	^{60}Co, ^{125}Sb
Odrik, Iroij	10-40	*

*No soil sample or field spectra measurements.

It should be noted that these are the ranges of our measurements. It is quite likely that there are locations where the local exposure rates are higher than the upper limits given in the table.

Since ^{137}Cs has a half life of 30.5 years as compared to half lives of 2.7 and 5.2 years for ^{125}Sb and ^{60}Co, respectively, the exposure rate levels on islands where ^{137}Cs was the major contributor, most importantly Bikini, can be expected to persist at almost the current levels for some time to come with only slight reductions due to decay and weathering. Studies of ^{137}Cs penetration into soils usually have indicated that in undisturbed soils with high organic content very little penetration of ^{137}Cs takes place after the first 1 or 2 years after deposition[6,7]. Since in 1967 the soil samples indicate most of the activity is still in the first inch of soil we can probably discount weathering as an important factor in lowering the exposure rates on Bikini Island. The levels on Nam and on some of the other larger complexes, where ^{60}Co and other relatively short-lived isotopes are the major contributors, although at present in general higher on the average than Bikini Island, will decrease more rapidly and in a few ^{60}Co half-lives will probably exhibit levels generally much lower than Bikini Island. Since the soil on some of these islands contain very little organic material, weathering may result in an even more rapid decrease in exposure rates. Thus, the levels on Bikini Island itself are likely to be the limiting factor in assessing the long term hazards to any future population living on the atoll and centered on Bikini Island.

The consistency of the various portable detector, ionization chamber, TLD, and spectrometer results indicate we have obtained a reliable and comprehensive picture of the external gamma radiation environment on the atoll. The soil sample results, although not as consistent with the other data as could be desired due to the problems of obtaining representative samples in a very inhomogeneous distribution, do nevertheless substantiate the field spectrometric predictions as to the relative importance of various emitters in the soil. The importance of the field spectrometric measurements in expanding and increasing the information of the survey meter readings again illustrates the utility of such a system in undertaking an environmental radiation survey. Comparable data on the composition of the radiation field could only have been obtained by analyzing hundreds of carefully obtained soil samples, if at all.

The data in this report should form a solid basis for estimating external dose to a returning population as a function of time after return, assuming with the aid of the survey team's anthropologist various realistic models for their living conditions, areas of habitation, and daily habits.

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TABLE 1

TOTAL EXTERNAL EXPOSURE RATES (μr/hr)*
BIKINI ATOLL: APRIL-MAY, 1967

Location	Ion Chamber	Scintillation Counter	GM Counter	HASL LiF	TLD's CaF	NRDL LiF	TLD's CaF
BIKINI							
0 Transect							
0' (Loc. 1)	24.0	24	30			10	30
50' (Loc. 2)	22.8	24		55	46		
50' (Loc. 3)	25.0			27	31		
150'		21	30				
300' (Loc. 5)	41.2	44	48	47,46	45,40	70	53,57
400' (Loc. 6)	47.5	47					
450'		43	45				
600'		63	59			80	90
750'		81	92				
900'		60	59			70	90
1050'		41	48			60	50
1200'		63	75			100	80
1350'		54	63			70	70
1410' (Loc. 8)	36.1	36	32				
1500'		70	59			80	70
1650'		97	70			100	120
1800' (Loc. 7)	103.2	107	105			130	100
1950'		57	68			80	90
2100'		66	59			90	70
2250'		43	35				
2400'		23	21			30	7
2700'		34	19				
2850'		10	15			10	10
Village Road							
0' (Loc. 4)		22		44	42		
150'		23	25			30	30
300'		33	30			40	15

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*1 μr/hr = 7.6 mrad/year.

450'			33	37			40	3
600'			29	28			40	4
750'			34	35			40	3
900'			31	28			30	6
1050'	(Loc. 9)	37.5	36	37	71	85	40	5
1200'			63	45			70	60
1350'			16	15			20	15
1500'			12	12			20	20
1650'			13	12			20	15
1800'			11	10			10	80
1950'			9	10			20	40
2100'			11	12			20	8

Location	Scintillation Counter	GM Counter	HASL LiF	TLD's CaF	NRDL TLD's LiF
		1 Transect			
0'	11	17			
150'	11	17			
300'	50	50			80
450'	71	55	53	47	
600'	36	63	44	46	80
750'	100	101	96	98	
900'	64	79			80
1050'	79	95			
1200'	107	110			140
1350'	107	119	160	148	170
1500'	107	135			170
1650'	93	108			140
1800'		117			
1950'	71	103			110
2100'		77			
2250'	43	59			70
2400'		95			
2550'	71	83			90
2700'		72			
2850'	29	21			40
2880'	4	10			
		North End Transect			
Tower		23			
65'		30	53	49	40

30
40
30
60
50
60
15
20
15
80
40
8

300'	43	68	68	80

South End Transect

High Tide Line	5
50'	15
200'	21
300'	50
450'	25
600'	18
750'	19
900'	18
950'	11
1000'	6
Ocean Beach	1

BOKANTUAK

Location	GM Counter
Transect 1 Mid-Island	
Lagoon Shore	10
50'	10
100'	10
150'	3
200'-450'	10
Transect 2 800'N. of No. 1	
Across Island	10
Transect 3 600'S. of No. 1	
Across Island	10

ROJKERE

Location	GM Counter
Transect 1 N. End	
Across Island	10
Transect 2 900'N. of No. 1	
Ocean Shore	10
50'-200'	10
250'	3
Transect 3 2400'S. of No. 1	
Across Island	10

IOMELEN

Transect 1 N. End	
Across Island	10
Transect 2 800'S. of No. 1	
Across Island	10

EONJEBI

Transect 1 N. End	
Across Island	10
Transect 2 1050'S. of No. 1	
Ocean Shore	3
50'	3
100'-250'	10
Transect 3 Mid-Island-Between 1&2	
0'	3
50'-200'	10

ENEU

Location	Spectrometer	Scintillation Counter	GM Counter	HASL LiF	TLD's CaF	NRDL LiF	TL
		Village Road Lagoon Side of Island, Northern Half					
Aircraft Hangar (Loc. 2)	4.1	4	8			0	
300'		2	8			0	
600'			5			0	
900'		3	3			0	
1200' (Loc. 1)	5.1	4	3			0	
1500'		4	3			0	
1800'		4	10			0	
2100'		4	10	3.5	5.7	0	
2400'			3			0	

2700'	10			0
3000'	8	7.0	6.3	0
3300'	3	5.5	5.9	0
3600'	3	13.9	12.4	0
3900'	3			0
4200'	3			0
4500'	3			0

South End

300' Tower	3	0
Assembly Bldg.	8	10
1100' from S. End Runway	3	0

Cross Transect 1
N. of Hardened Runway

TLD's

Location	Scintillation Counter	GM Counter
NW Corner of Surface	3	3
150'	2	3
300'	2	3
450'	2	3
600'		3
E. Edge of Island	2	3

Ocean Side
N. Half ~50' Inland

Location	Scintillation Counter	GM Counter
300'	2	3
600'	2	3
900'	2	3
1200'	2	3
1500'	10	3
1800'	4	3
2100'	3	3
2400'	5	10
2700'	6	10
3000'	3	3

Cross Transect 2
N. End Ocean to Lagoon Side

Location	Scintillation Counter	GM Counter
150'	3	10
300'	7	3
450'	4	3

AEROKOJ - ENEMAN COMPLEX

Location	Scintillation Counter	GM Counter	Location	Scintillation Counter	GM Counte
Aerokoj - Aerokojlol			**Eneman**		
E. End Aerokoj	1	10	W. End	26	200
300'	1	10	300'	53	200
600'	2	10	500'	79	200
900'	2	10	600'	64	200
1200'	1	10	700'	570	200
1500'	1	10	800'	236	200
1800'	1	10	900'	170	200
2100'	1	10	1000'	67	200
2400'	2	10	1300'	36	30
2700'	2	10	1600'	24	23
3000'	3	10	1600' Lagoon Shore	28	23
3300'	2	3	1600' 300' Across	61	23
3600'	1	10	1600' 900' Across	26	17
3900'	1	10	2200'	4	10
4700'	2	10	2300'	7	10
5000'	3	10	2600'	7	10
5300'	1	10	2900'	3	10
5600'	1	10	Near Tower	3	10
5900'		10	At Tower	3	10
6200'		3	3200'	2	10
6500'		10	3500'	1	10
			3800'		10
Causeway - to Bikdrin			Causeway - to Lele		
6800'	1	3	0-600'	1	10
7100'	1	3			
7400'	1	3			

Bikdrin - Lele

E. End	6-8	10
300'	6-8	10
600'	6-8	10
900'	6-8	10
1200'	6-8	10
1500'	6-8	10
1800'	6-8	10
W. End	6-8	10

ENIDRIK

East Half

Location	GM Counter
Transect 1 ⅓ Way from E. End	
Lagoon Shore	10
150'	10
300'	10
600'	3
900'	3
1200'	3
Transect 2 1000' E. of No. 1	
Ocean Shore	3
150'	10
300'	3
900'	3
1200'	3

West Half

Location	Scintillation Counter	GM Counter
Transect 1		
300' from Mid-Island		10
Small Pond-Inshore		10
Lagoon Shore	3	17
150'	9	13
600'	19	
W. End-Algae Patch		110
W. End-Algae Patch		143
Desert-like Plain		217
Ocean Beach		63
Lapturis Clearing		23
Shore Line		10
Transect 2		
Lagoon Side - 150'	235	
300'	170	

Transect 3

2500' E. of No. 1

Lagoon Shore	3
150'	30
300'	10

Transects 4 and 5

50' and 100' E. of No. 3

Across Island	10

Transect 6

1000' W. of No. 1

Lagoon Shore	10
150'	10
300'	10
450'	10
600'	10
750'	10
900'	3

450'	86
600'	57
750'	30
900'	13
Ocean Beach	9

LUKOJ

Location	Scintillation Counter	GM Counter
N.W. End		
Shore Area	14	10
100' Inland	86	97
Transect 1 700' Inland from N.W. End		
Ocean Shore	61	97
150'	104	130
300'	86	110
450'	71	63

JELETE

Location	GM Counter
Around Island 100' Inland	
Mid-Island-Lagoon Shore	63
300'	97
600'	117
900'	97
1200'	130
1500'	97
1800'	63
2100'	130
2400'	97

Transect 2

2300' Inland from N.W. End

Lagoon Shore	100	83
150'	117	130
300'	141	163
450'	171	197
600'	129	163
750'	143	177
900'		110
1050'		97

S.E. End

Lagoon Shore		63
2700'		97
3000'		97
3300'		63
3600' Starting Pt.		63

Location	Scintillation Counter	GM Counter
OROKEN		
Around Lagoon Shore 50' Inland		
W. End	13	10
150'		17
Transect at 150'		
150'	19	37
300'		43
450'	39	43
600'		30
750'		23
Around Ocean Shore 50' Inland		
150'	26-30	17
300'	26-30	23
450'	26-30	23
600'	26-30	30
750'	26-30	17
900'	26-30	17

Location	Scintillation Counter	GM Counter
BOKAETOKTOK		
Around Lagoon Shore 50' Inland		
W. End	12	3
150'	21	10
300'	19	30
450'	16	17
600'		10
750'	10	3
900'	13	23
Transect at 900'		
150'	17	23
200'	20	
250'	21	
300'	21	23
400'	19	

BOKBATA

Mid-Island Transect

S. End	12	23
150'	12	23
300'	12	30
450'	12	23
600'	12	17
750'	12	17
900'	12	17
1050'	12	17
1200'	12	10
1350'	12	10
1500'	12	10
1650'	12	10
1800'	12	10
N. End	12	10

BOKDROLUL

Around Lagoon Shore
50' Inland

N.W. End	13	3
0'	24	37
150'		37
300'	36	37
450'		37
600'	34	50

Transect at 600'

150'	29	37
300'	32	37
350'	34	23
400'	32	
450'	27	
500'	33	
550'	30	

NAM

West Around Lagoon Shore
Begin Middle - 50' Inland

Location	Scintillation Counter	GM Counter
0'	13	17
150'		17
300'	13	30
450'		23
600'	17	37
750'		23
900'	29	30
1050'		30
1200' W. End		10

East Around Lagoon Shore
Begin Middle - 50' Inland

Location	GM Counter
150'	17
300'	17
450'	17
600'	10
750'	17
900'	17
1050'	17
1200'	17
1350' S.E. End	30

1350'		43
1500'		30
1650'		10
1800'		23
1950'		37
2100'		97
2250'		97

1500'	43
1650'	43
1800'	83
1950'	97
2100'	117

Transect 1
S. to N. Across Island

Lagoon Shore	17	17
150' Spec. 3	21	37
300'	57	37
450'	71	63
600'		63
750' Spec. 1	72	57
900'	100	97
1050'		163
1200'	79	97
1350'	15	
1500'	14	

Transect 3

150'		130
300'	214	330

West Around Ocean Shore
N.E. to N.W. Corner - 50' Inland

0'	37
150'	37
300'	43
450'	37
600'	43
750'	37
900'	43
1050'	30
N.E. Corner	57

Transect 2
E. Shore to N.N.W.

150'	197
300'	163
450'	117
600'	130
750'	110
900'	230
1050'	230
1200'	163
Ocean Shore	30

AOMEN - IROIJ COMPLEX

Location	Scintillation Counter	GM Counter
Aomen - Odrik		
Mid-Island from E. Tip		
0'	10	3

Location	GM Counter
Iroij	
W. End	10

500'	5	3
1000'	10	3
1500'	7	3
2000'	15	17
2500'	5	3
3000'	17	23
3500'	15	17
4000'	46	37
4100'	250	197
4500'	270	330
5000'	148	130
5500'	328	330
6000'	33	17
6500'	27	23
7000'	22	17
7500'	15	17
8000'	7	10
9000'	10	3
9500'	15	10
9600'	5	3

Bet. Lagoon and Ocean	10
W. of Bunker	23
Lagoon Side of Bunker Widest Part	23
Ocean Beach	3
150'	30
300'	30
450'	23
600'	37
800' Pond	30
850' Lagoon Beach	30
W. End Pond	37
E. End Pond	10
E. End Island	17

TABLE 2

HASL RADIOCHEMICAL AND GAMMA-SPECTROMETRIC ANALYSES OF BIKINI ATOLL SOILS (a,b) (pc/gm OF DRY SOIL)

Location	Depth	% Moisture	^{137}Cs	^{60}Co	^{125}Sb	^{106}Ru (c)	^{90}Sr
Bikini - Pit 1,	0-1 in.	6	456±5	<1.3	29±5	26±8	69
Clearing Experiment Site.	1-2 in.	8	245±6	<1.8	28±5	29±8	47
Approximate mean	2-3 in.	13	233±2	2.5±.5	16±3	14±4	-
bulk density =	3-4 in.	14	116±7	<4.0	50±9	<30	-
1.2 gm/cc.	4-5 in.	14	295±4	18±2	37±5	18±6	-
	5-6 in.	13	129±2	8±1	26±3	10±4	-
	6-7 in.	14	22.2±0.4	1.3±0.2	10±0.5	<2	-
	7-8 in.	14	14.1±0.5	.5±.2	14±0.7	<3±	-
	8-9 in.	15	8.2±.2	<.2	7.0±.3	1.8±.7	-
	6" Core - r=10 ft.	-	74±2	<.6	7.4±1.3	7.2±2.5	-
	6" Core - r=30 ft.	-	251±5	3.4±1.9	26.1±4.2	23.7±7.0	-
Bikini - Pit 5,	0-1 in.	36	1100±10	38±3	100±10	65±20	875
Field Location 7.	1-2 in.	35	177±2	4.6±.5	25±2	9±3	575
Approximate mean	2-3 in.	24	34±1	<.4	11±1	3±2	135
bulk density =	3-8½ in.	22	3.6±0.1	.14±.03	1.1±0.1	<.6	18.3
1.1 gm/cc.	8½-11½ in.	12	.88±.03	<.06	.24±.07	<.3	-
Bikini - Pit 6,	0-1 in.	25	40±2	7.7±.5	10±1	4±2	464
Field Location 5.	1-2 in.	10	33.5±0.4	7.8±0.2	8.9±.6	<2.1	-
Approximate mean	2-6 in.	10	11±2	.8±.1	2.2±.3	1.5±.6	-
bulk density = 1.1 gm/cc.	6-10 in.	18	11±2	<.2	2.2±.2	<.9	-

West End Eniman - Algae Crust	0-.6 cm.	13	15±3	95±3	53±4	29±8	-
	.6-1 in.	8	36±5	363±7	217±11	136±23	-
	1-2 in.	9	7±1	101±1	31±2	19±5	82.5
West End Eniman - Pit 3	0-5 mm.	27	148±28	402±31	235±55	430±125	-
	5 mm. - 1 in.	22	-	-	-	-	
	1 in. - 2 in.	22	109±22	512±27	204±46	266±100	-
	2 in. - 3 in.	15	23±5	132±7	43±12	70±26	-
Aomen - Iroij - Pit 4 - 1 mile from East Bunker. Approximate mean bulk density = 1.3 gm/cc.	0-¼ in.	38	-	-	-	-	2150
	¼-1¼ in.	32	-	-	-	-	-
	1¼-2¼ in.	13	6.6±1.2	126±2	152±3	47±6	-
Enidrik - West End	Mixed	17	39±7	44±5	177±16	<56	-
Bokbata (Boby)	Mixed	10	8.2±0.2	4.6±0.1	3.2±.3	4.2±.5	-
Nam - Pea Patch	0-2 in.	30	200±2	60±1	52±3	17±5	568
Bravo Crater - Bottom Sediment			14.8±1.5	49.7±1.9	13.9±2.7	46±7	26.1-^{207}Bi ±9.7

Lukoj - Pisonia Grove	Mixed	58	357±36	464±23	1070±80	<284

a. The ^{90}Sr analysis was by radiochemistry. All other analyses are by gamma spectroscopy.

b. Errors (S.D.) reflect counting errors and goodness of fit and do not reflect sampling errors. Average sample weight was ~50 grams. Counting samples from the same soil sample often exhibited activities differing by 10-20%.

c. Includes ^{102m}Rh, ^{101}Rh, and ^{106}Ru-Rh.

FIGURES 8a - 12d

Ge(Li) spectra of soils taken from Bikini Atoll. Each spectrum is presented in four 800 channel segments. The energies of the more prominent peaks and probable identification are given. The ^{40}K peak is due to background in the counting apparatus.

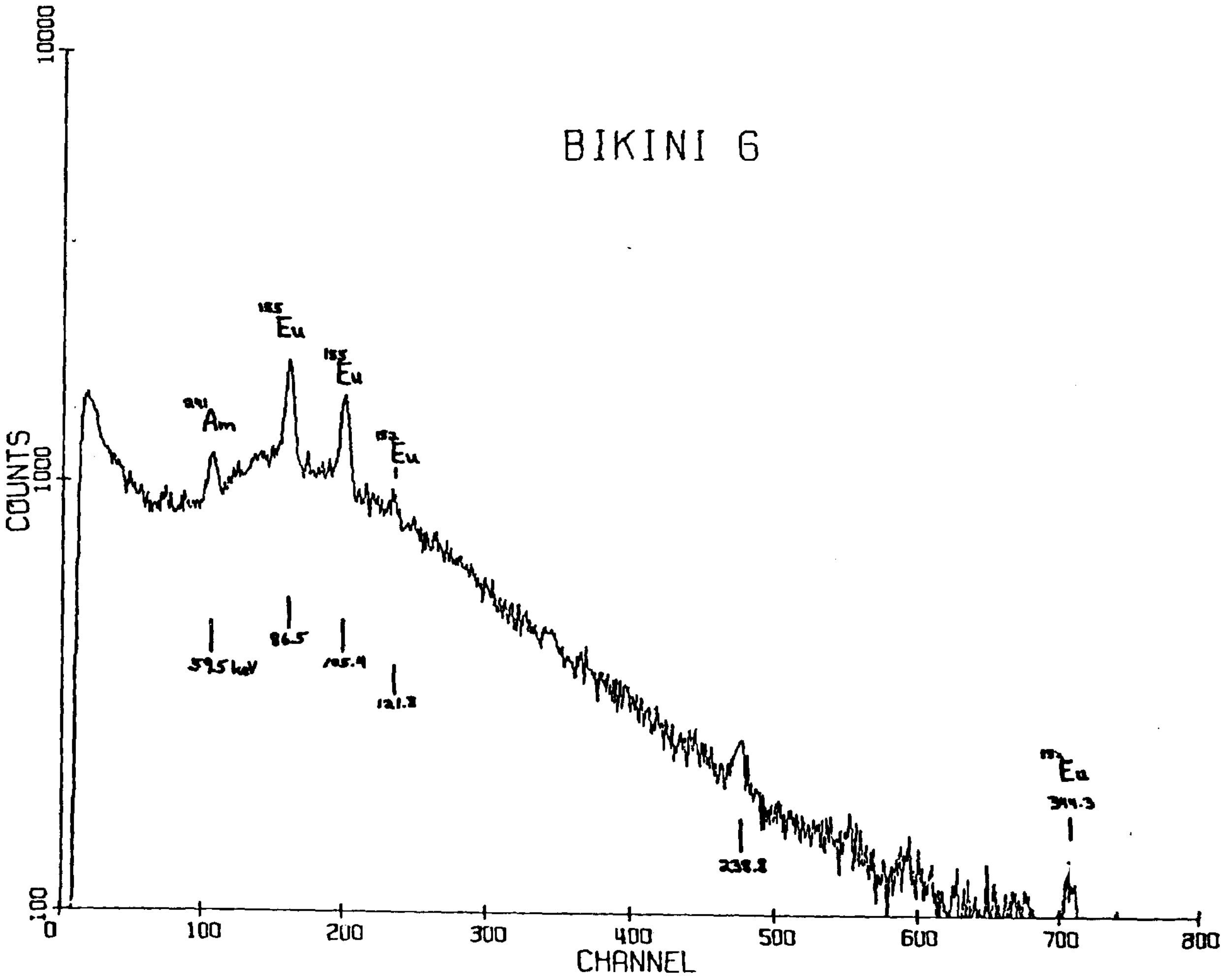

Figure 8a. Ge(Li) spectrum of soil sample taken from Bikini Island, Pit 6, 0 Transect, Location 5.

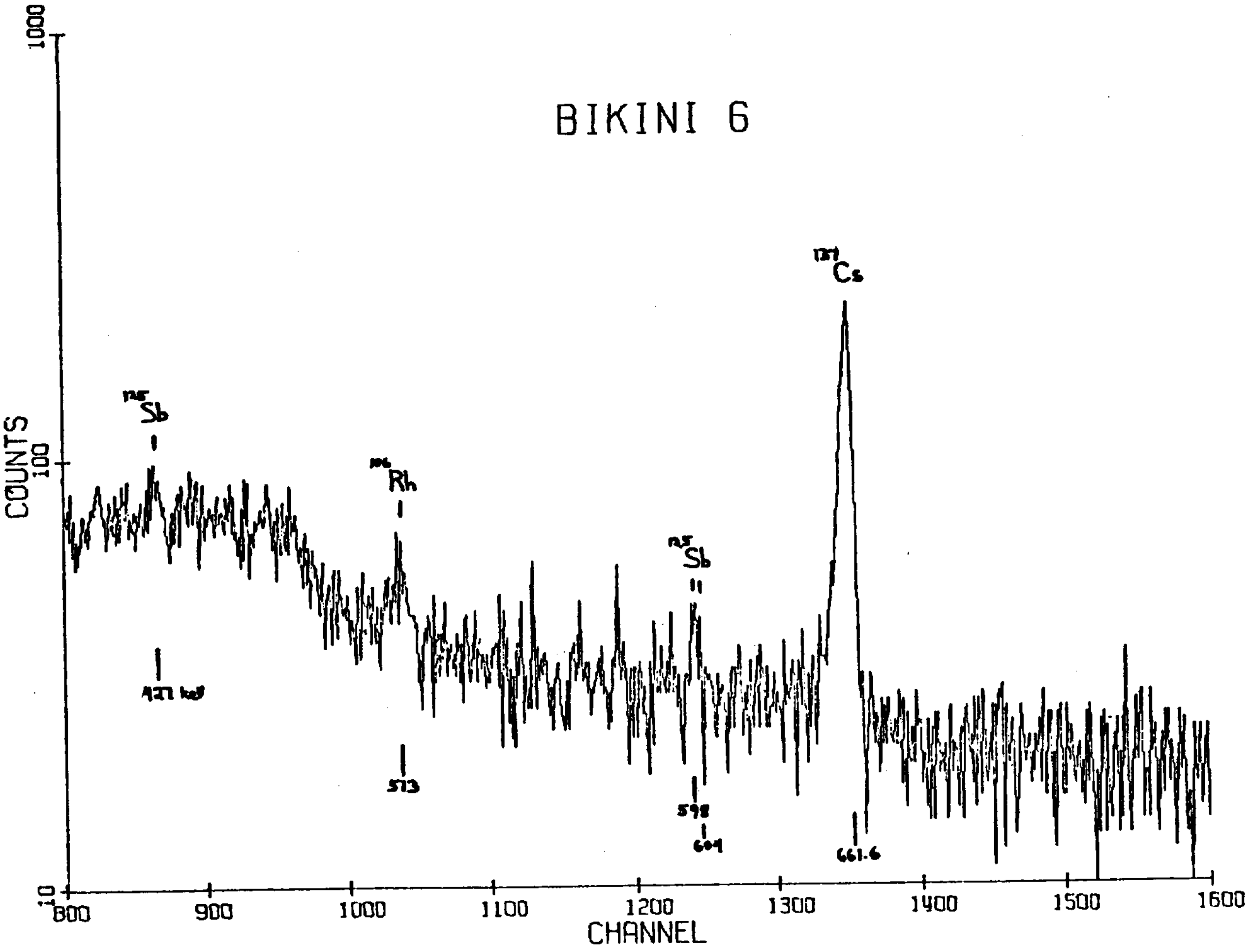

Figure 8b. Ge(Li) spectrum of soil sample taken from Bikini Island, Pit 6, 0 Transect, Location 5.

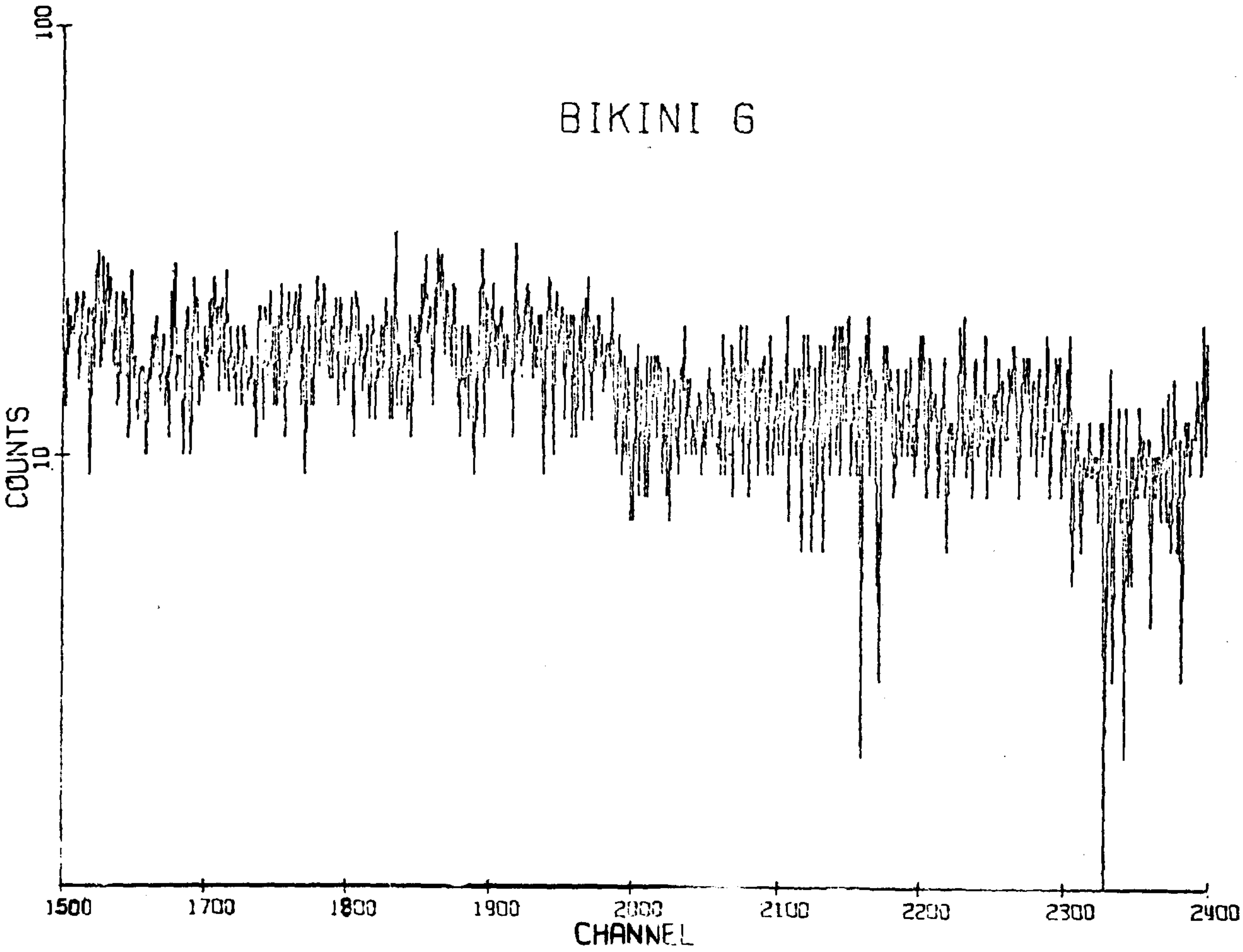

Figure 8c. Ge(Li) spectrum of soil sample taken from Bikini Island, Pit 6, 0 Transect, Location 5.

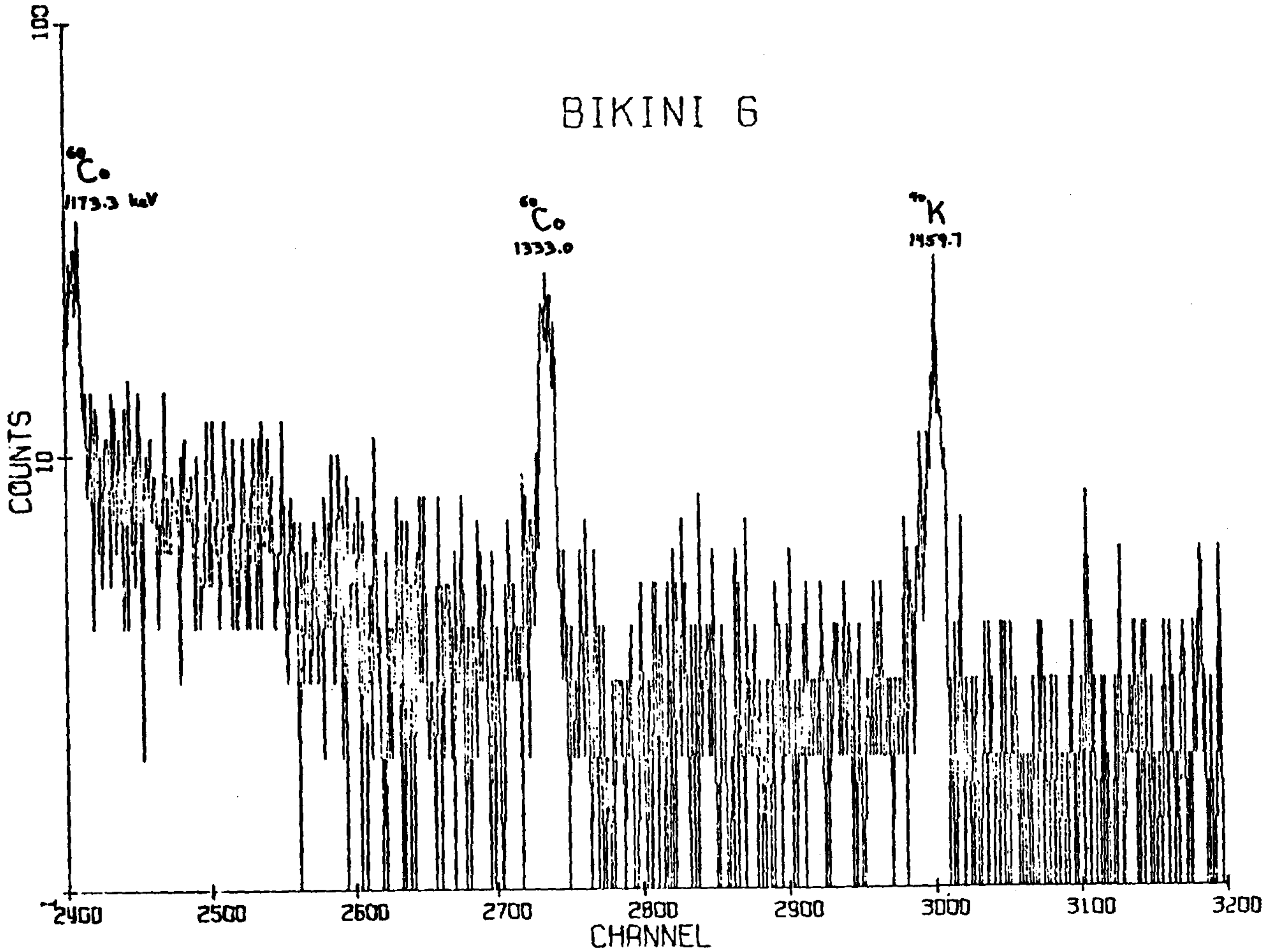

Figure 8d. Ge(Li) spectrum of soil sample taken from Bikini Island, Pit 6, O Transect, Location 5.

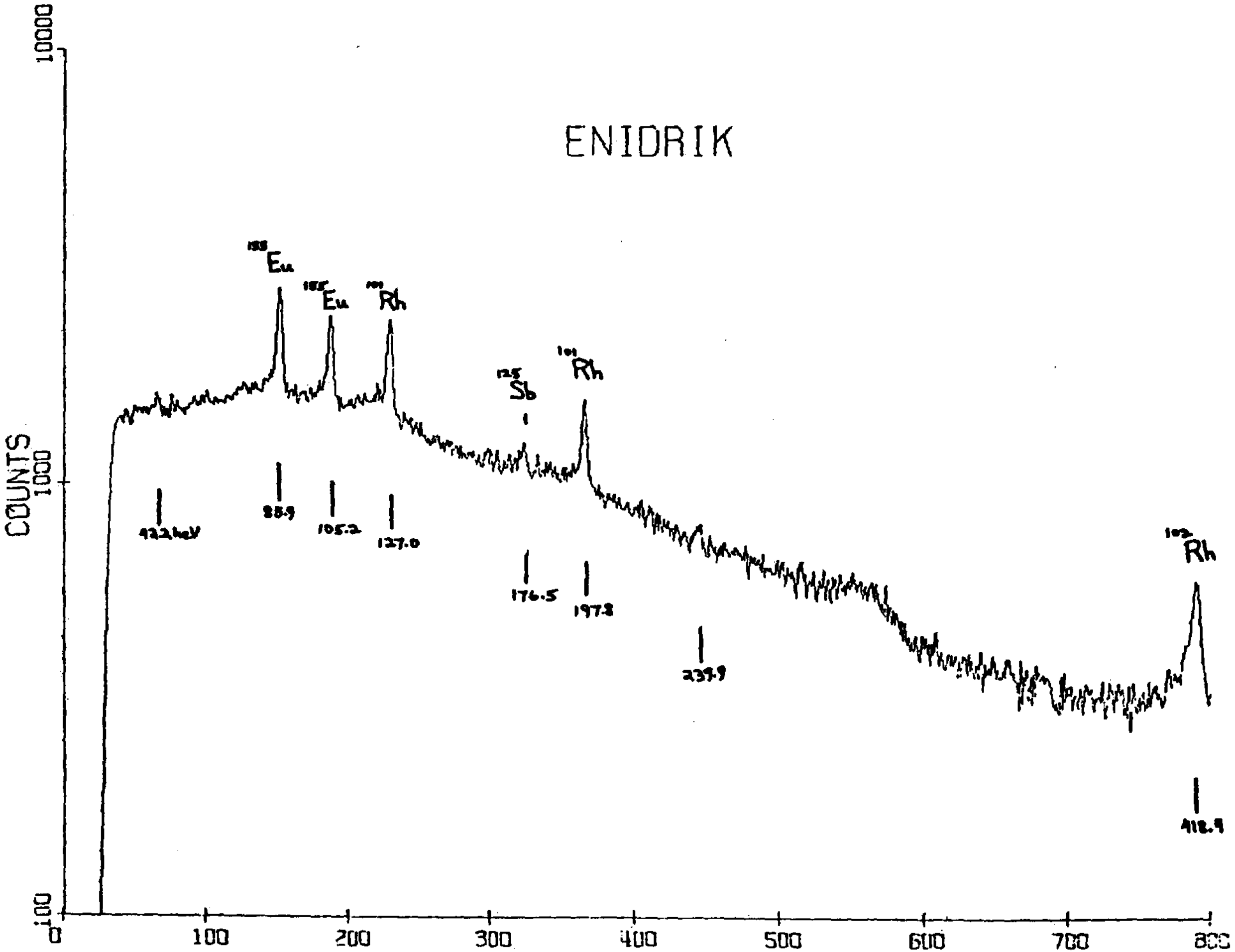

Figure 9a. Ge(Li) spectrum of soil sample taken from Enidrik Island.

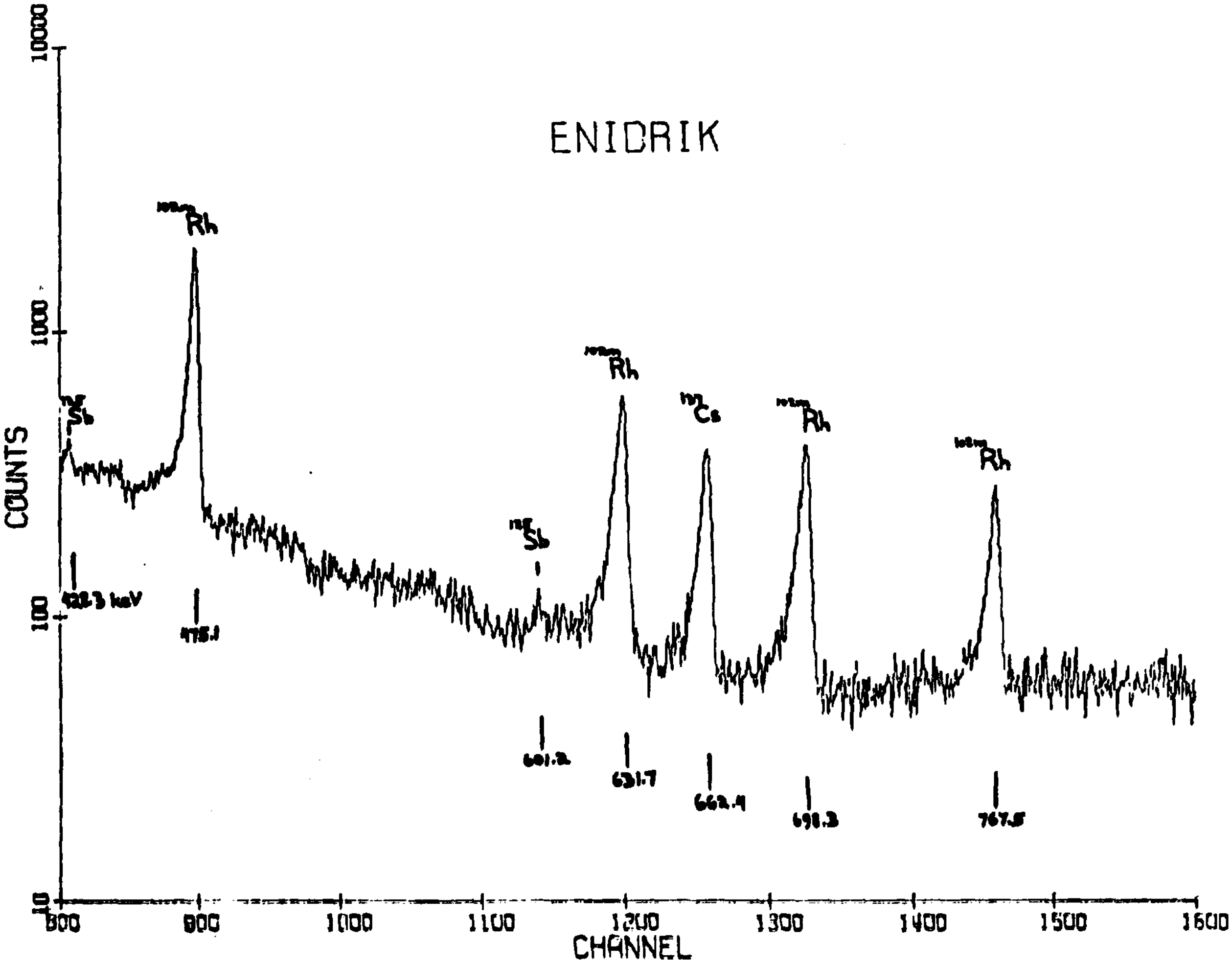

Figure 9b. Ge(Li) spectrum of soil sample taken from Enidrik Island.

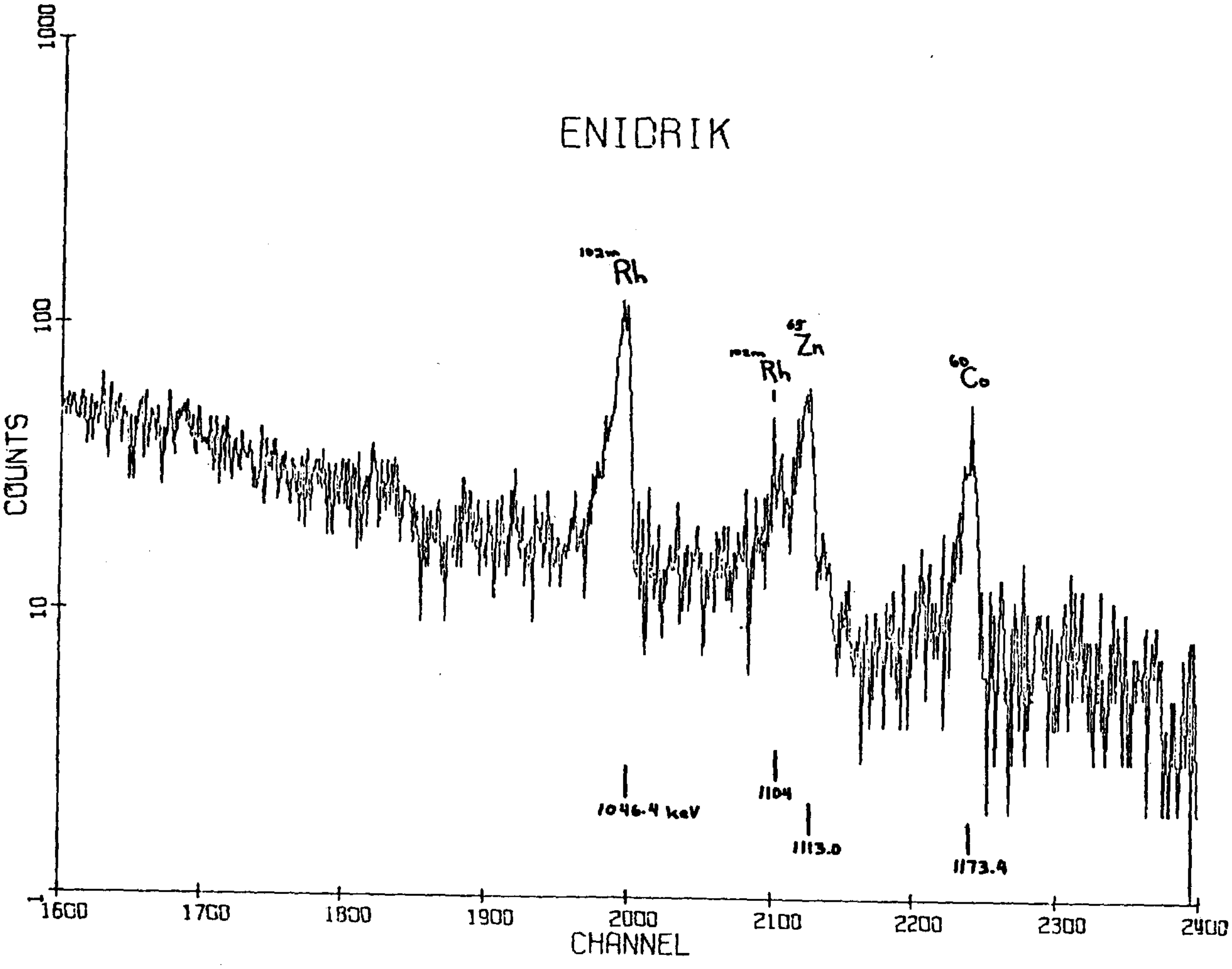

Figure 9c. Ge(Li) spectrum of soil sample taken from Enidrik Island.

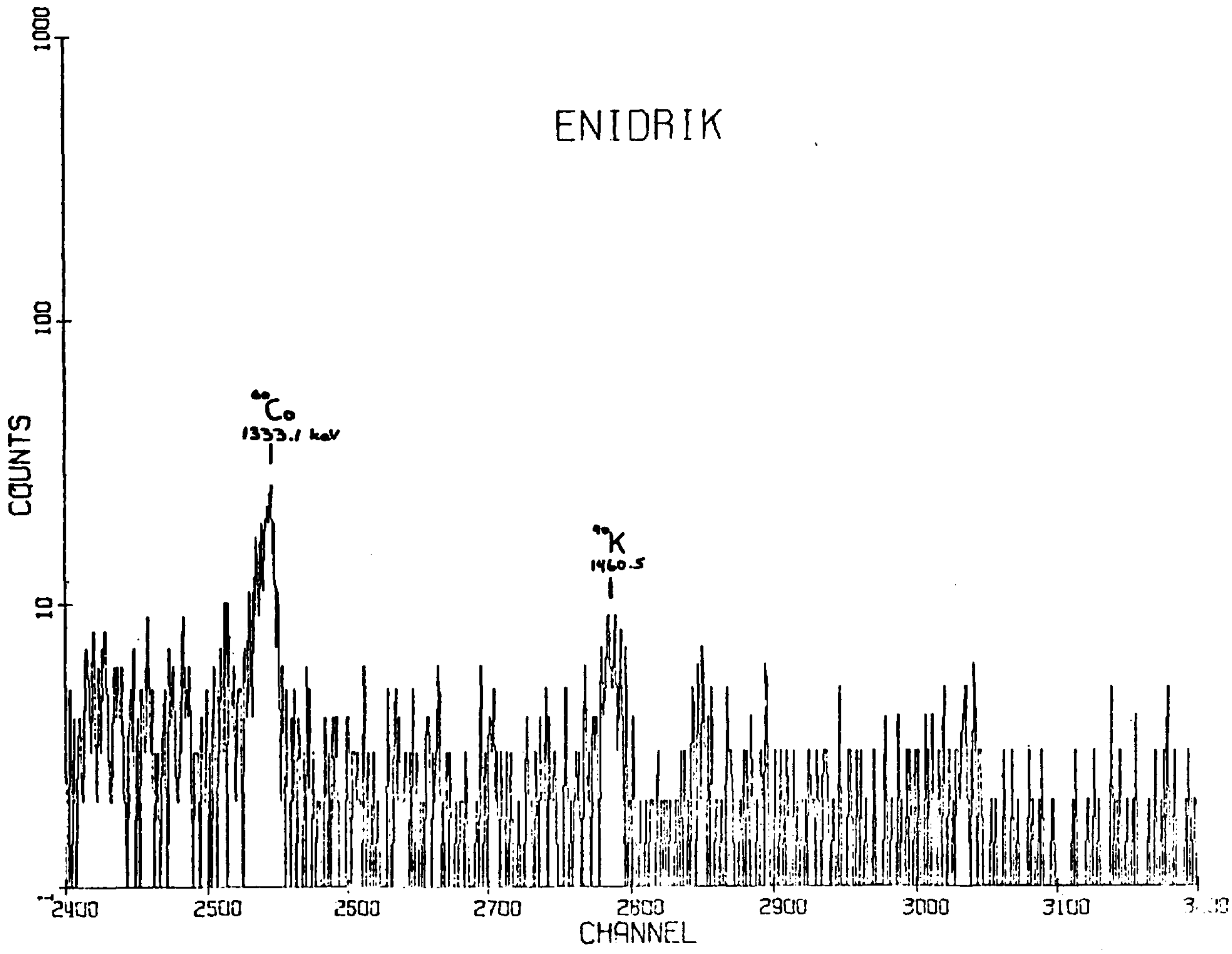

Figure 9d. Ge(Li) spectrum of soil sample taken from Enidrik Island.

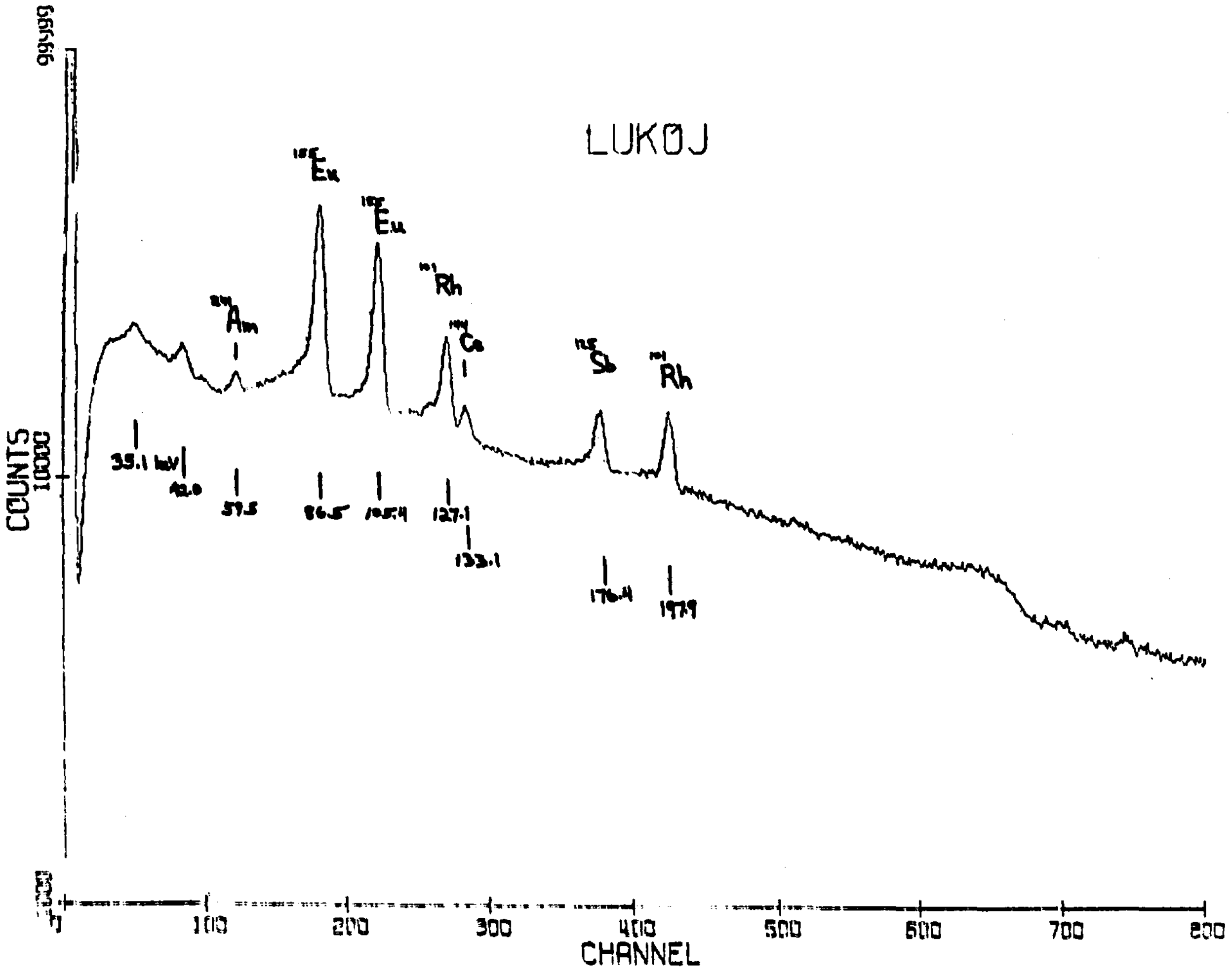

Figure 10a. Ge(Li) spectrum of soil sample taken from Lukoj Island.

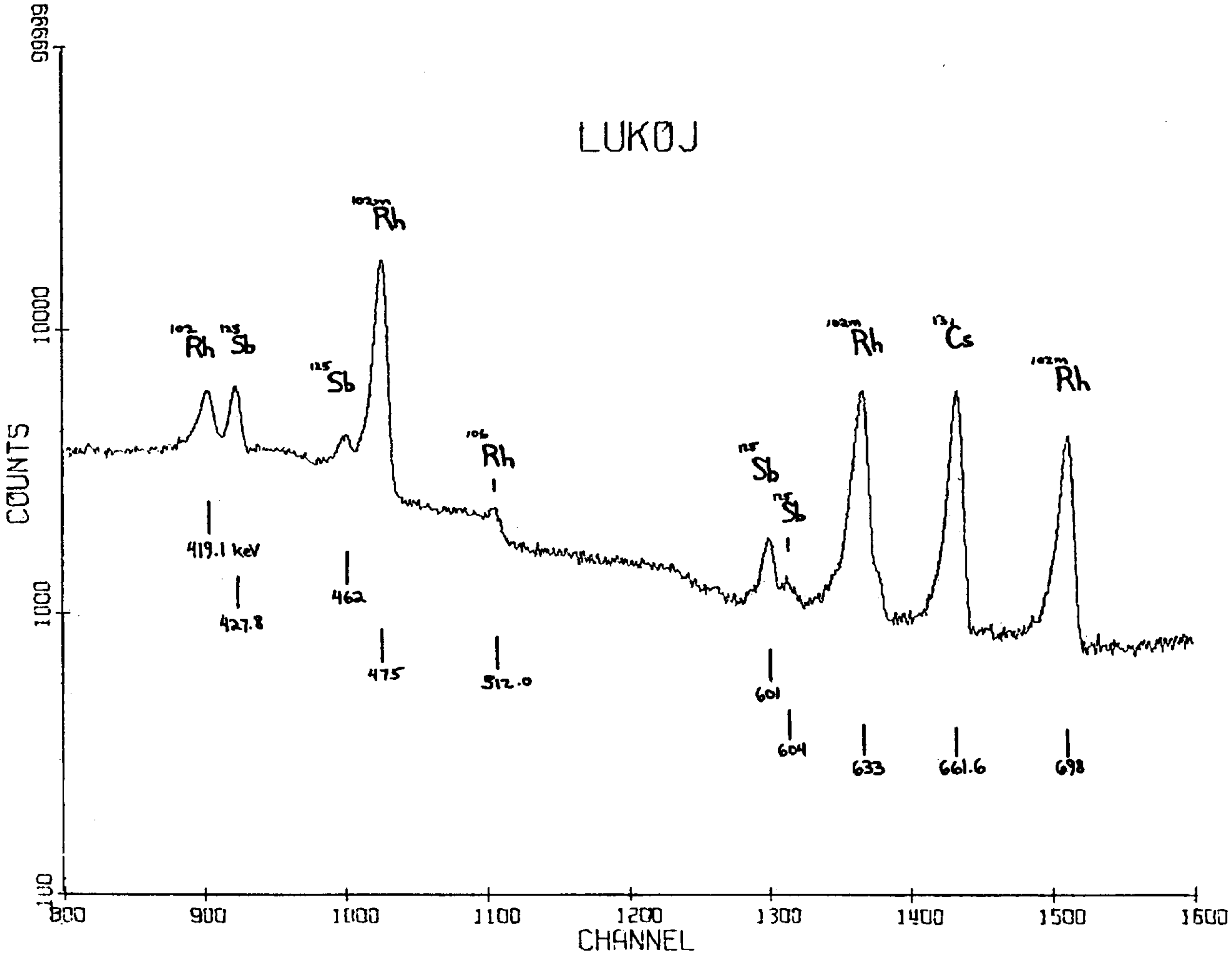

Figure 10b. Ge(Li) spectrum of soil sample taken from Lukoj Island.

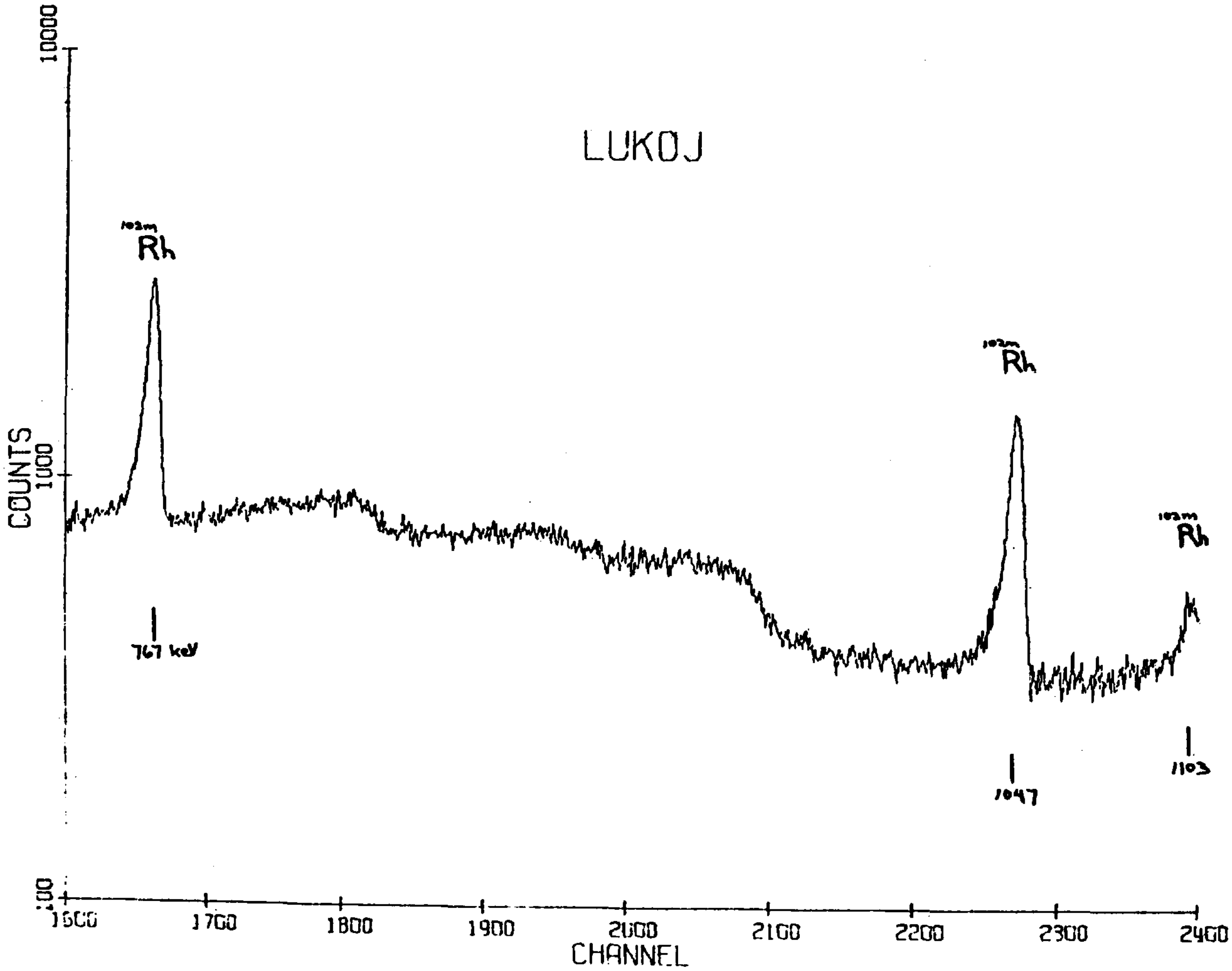

Figure 10c. Ge(Li) spectrum of soil sample taken from Lukoj Island.

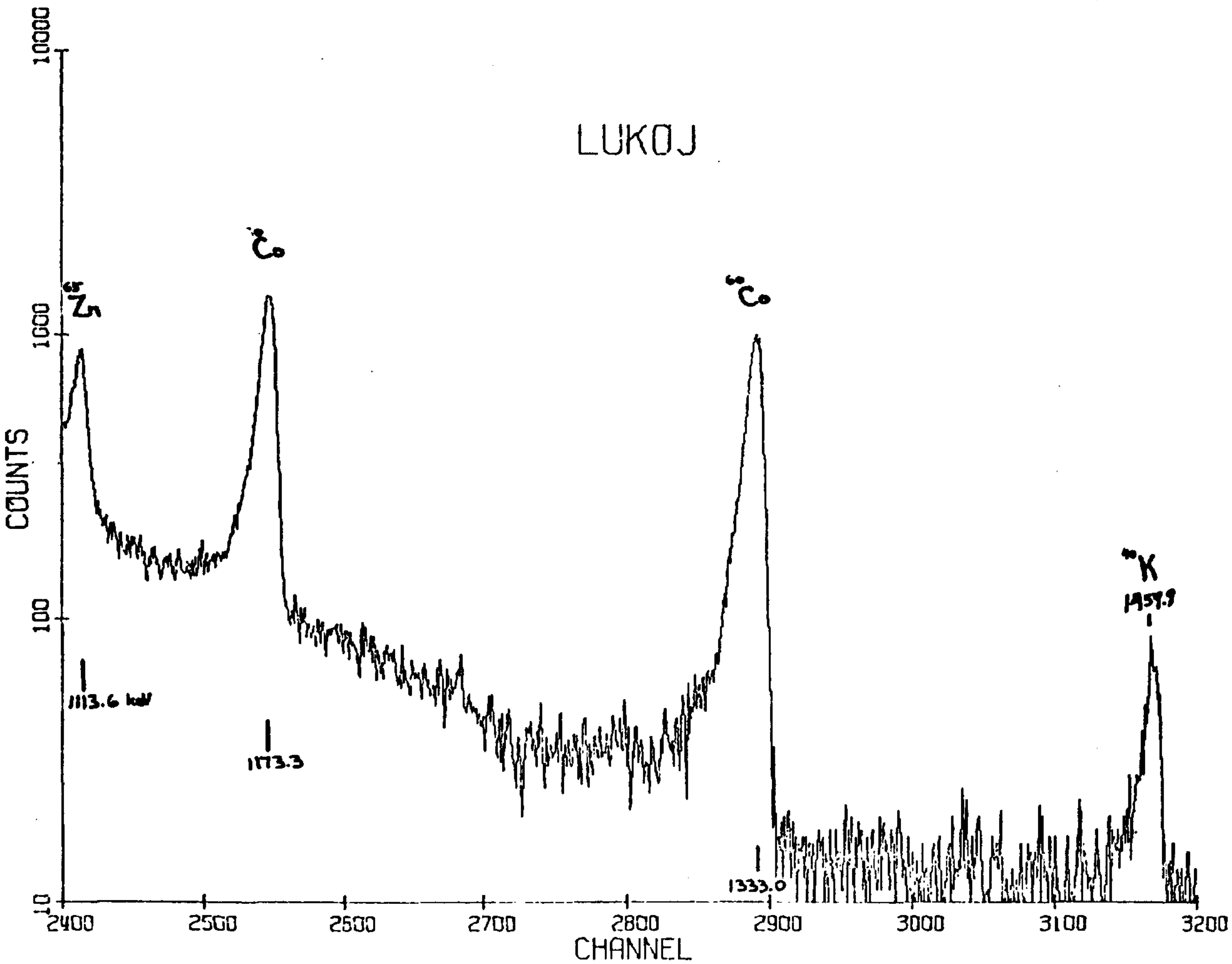

Figure 10d. Ge(Li) spectrum of soil sample taken from Lukoj Island.

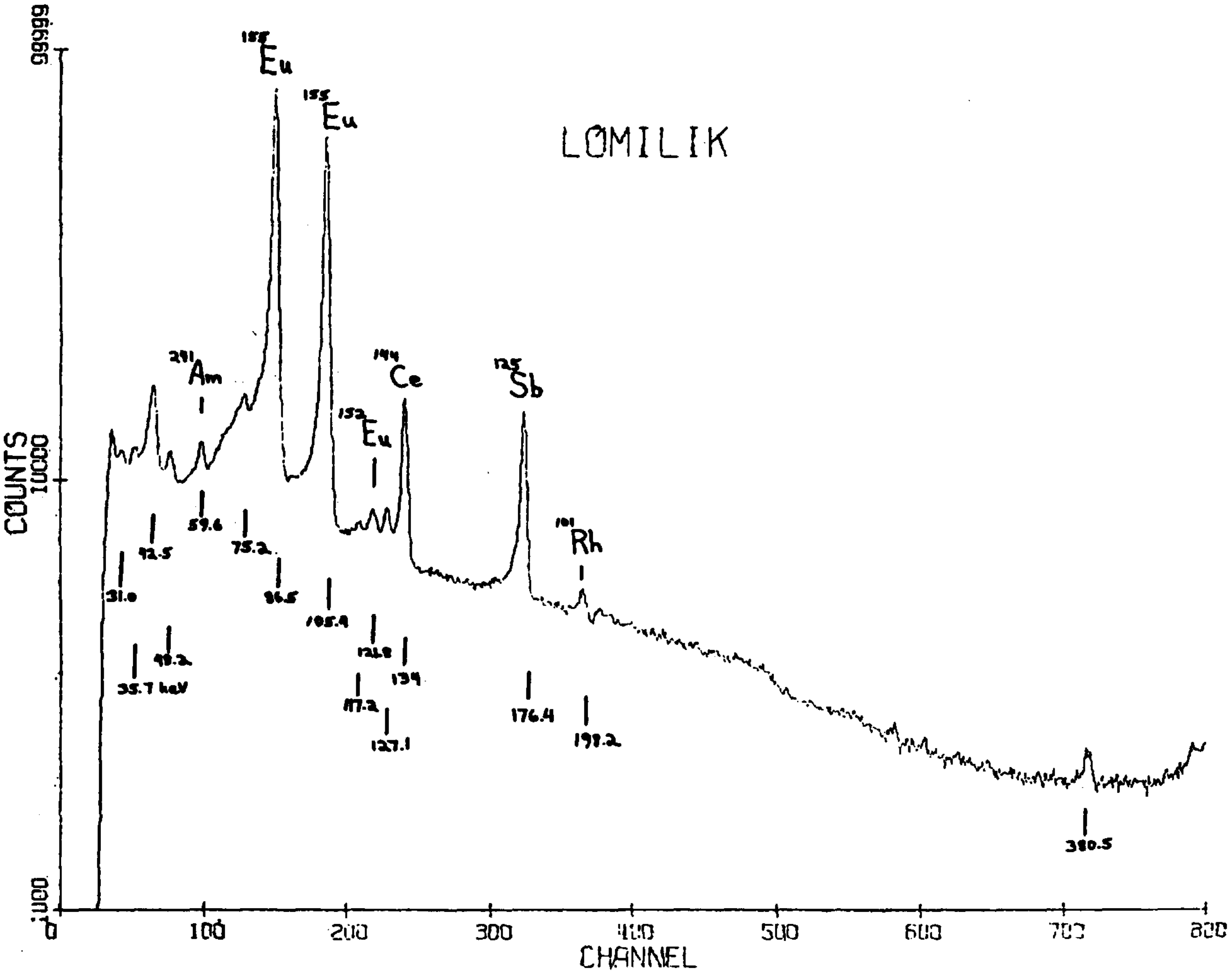

Figure 11a. Ge(Li) spectrum of soil sample taken from Lomilik Island, Aomen-Iroij Complex.

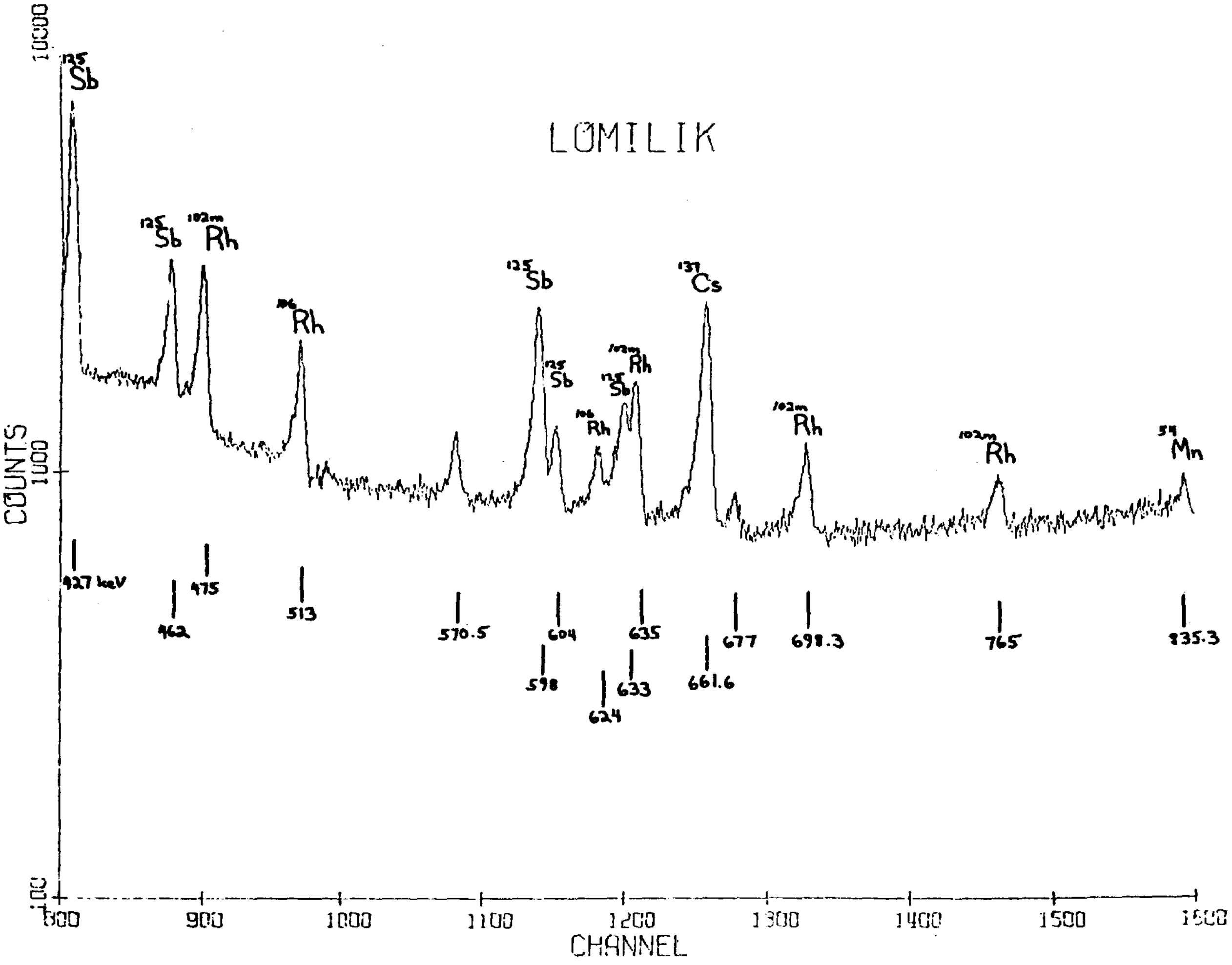

Figure 11b. Ge(Li) spectrum of soil sample taken from Lomilik Island, Aomen-Iroij Complex.

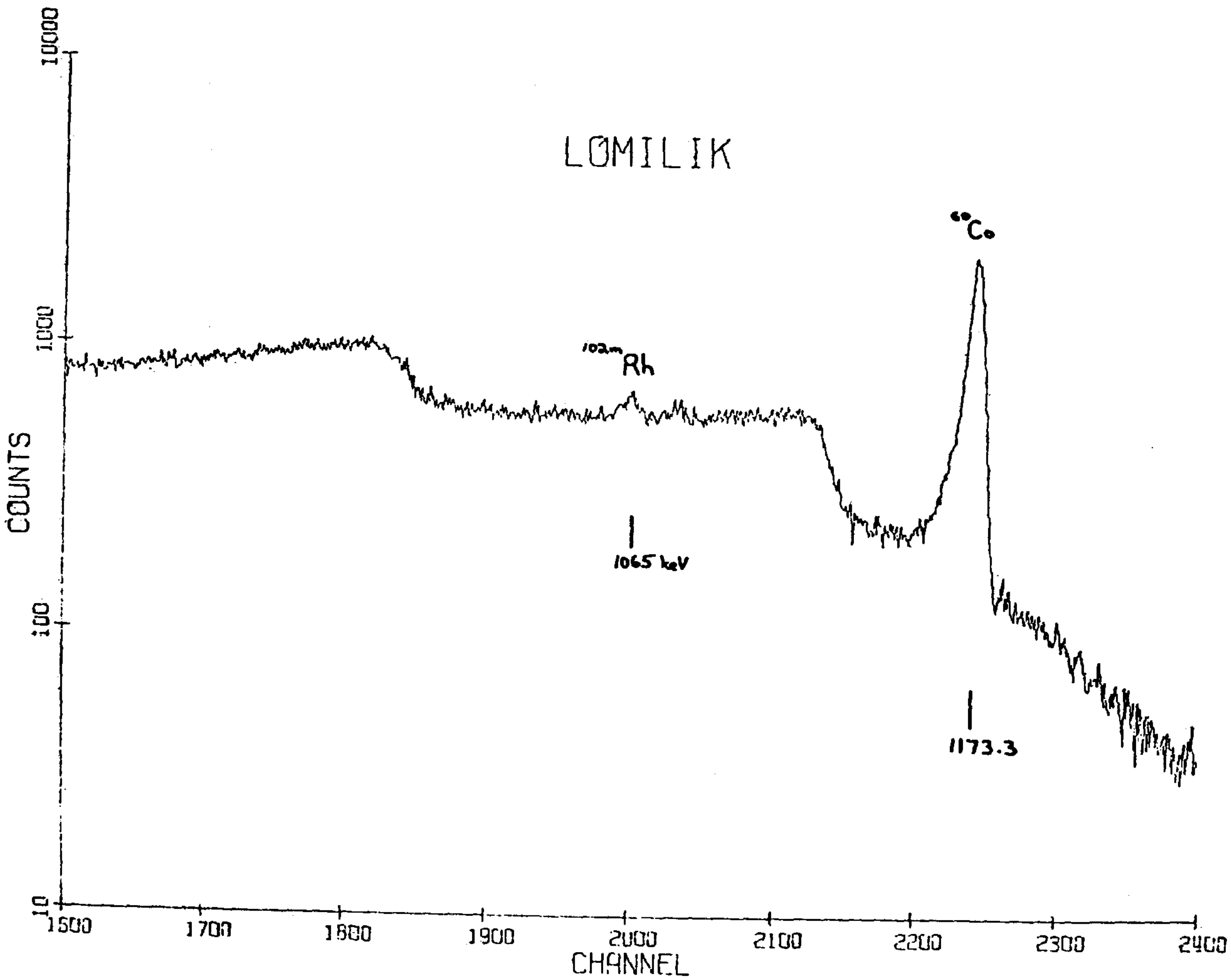

Figure 11c. Ge(Li) spectrum of soil sample taken from Lomilik Island, Aomen-Iroij Complex.

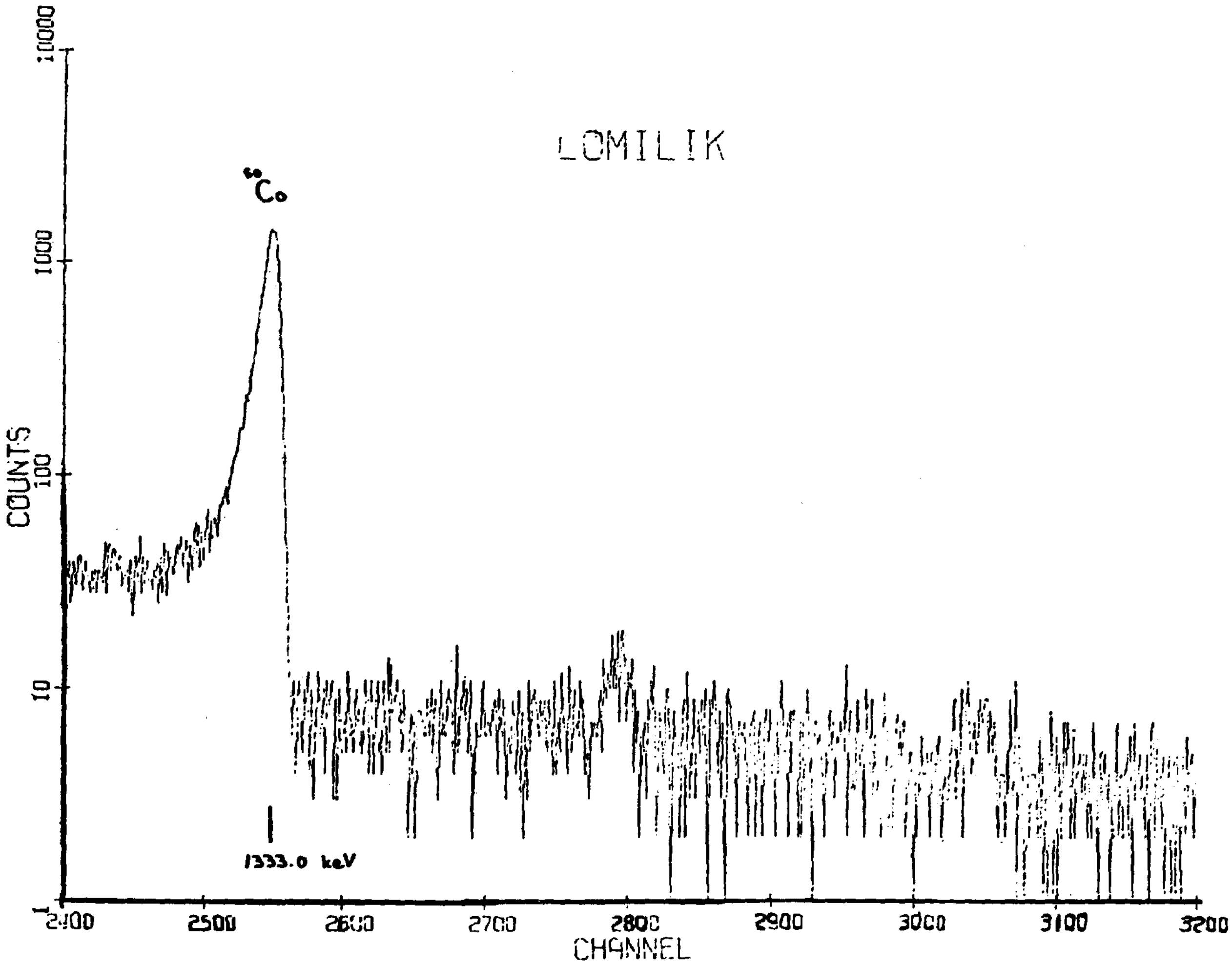

Figure 11d. Ge(Li) spectrum of soil sample taken from Lomilik Island, Aomen-Iroij Complex.

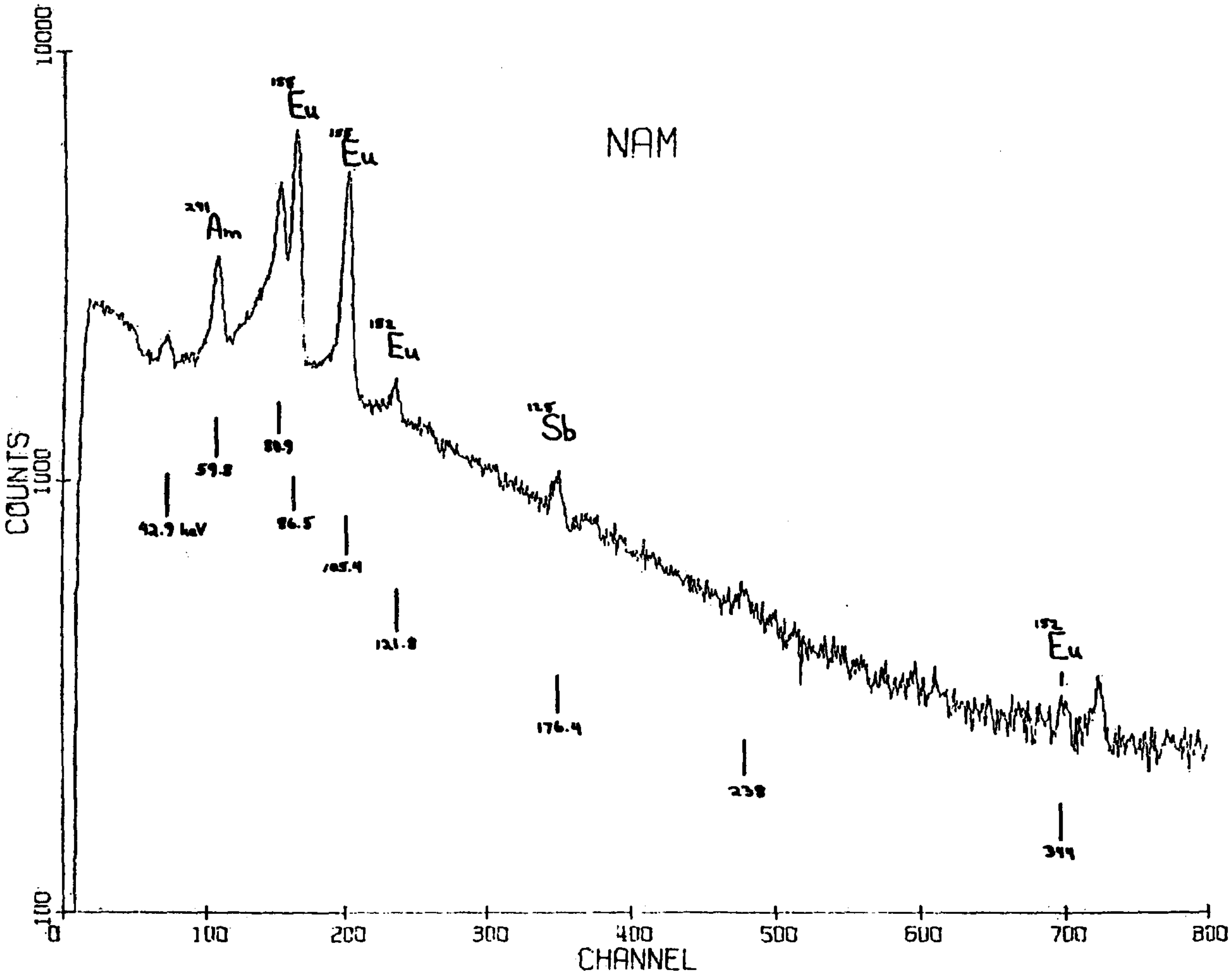

Figure 12a. Ge(Li) spectrum of soil sample taken from Nam Island.

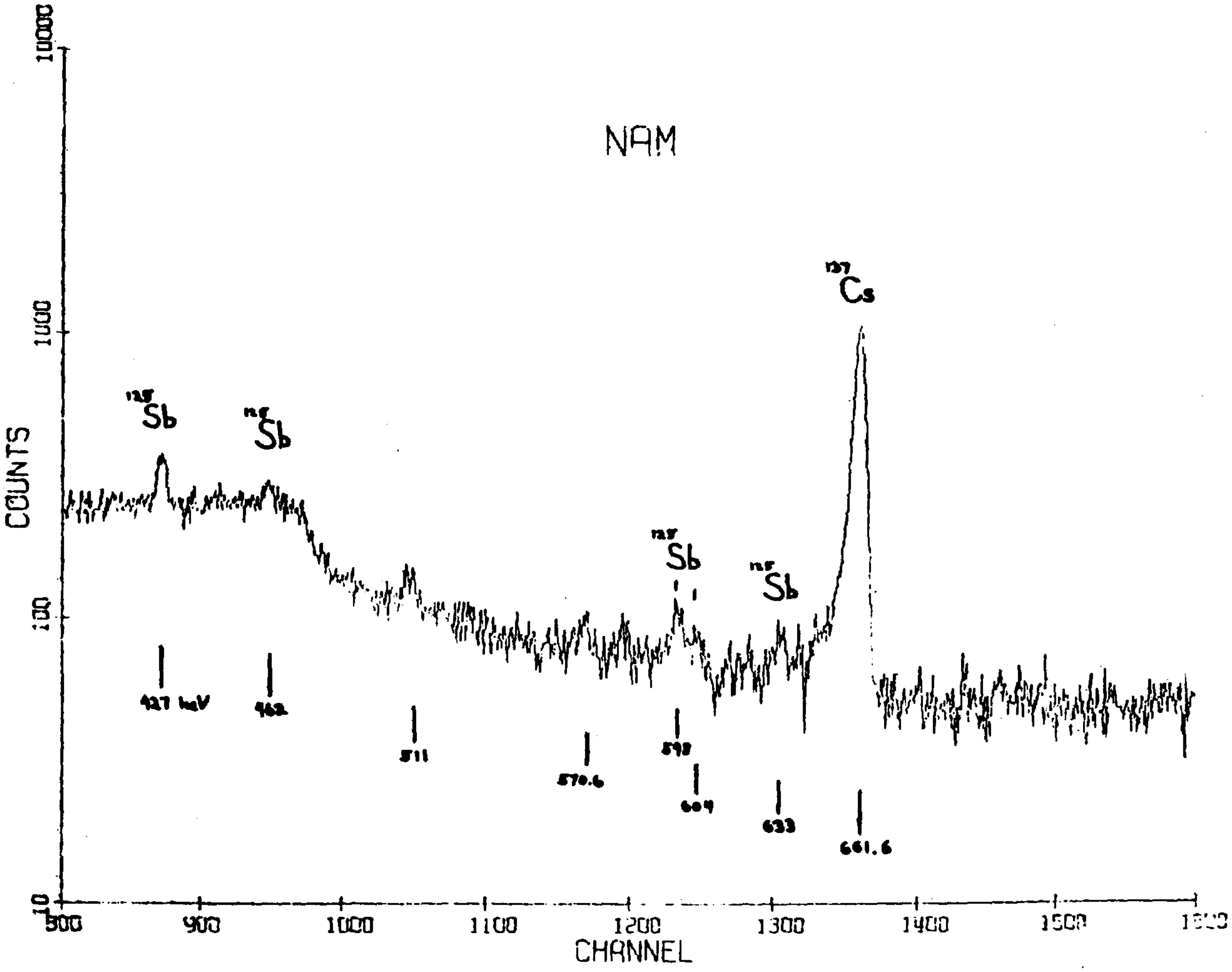

Figure 12b. Ge(Li) spectrum of soil sample taken from Nam Island.

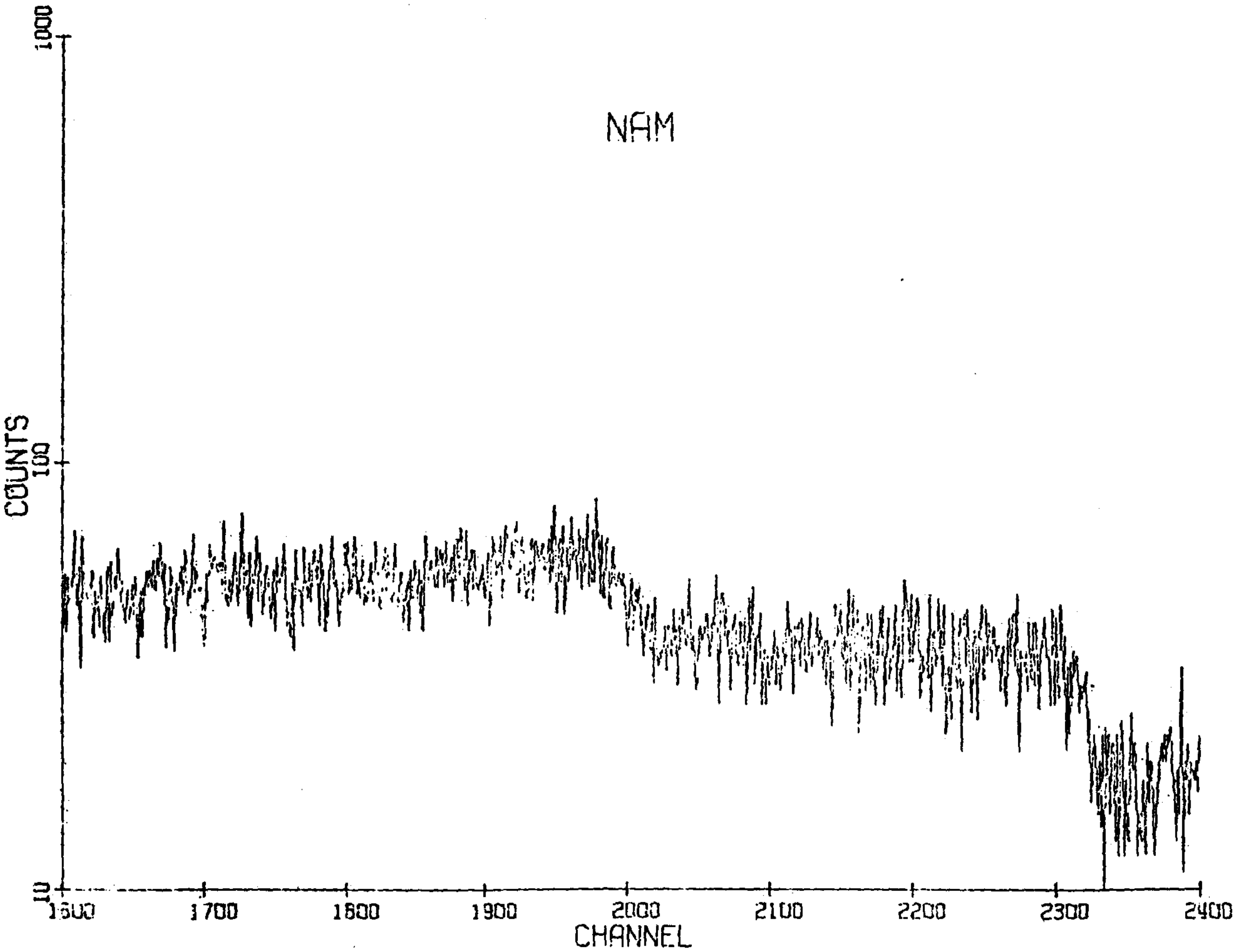

Figure 12c. Ge(Li) spectrum of soil sample taken from Nam Island.

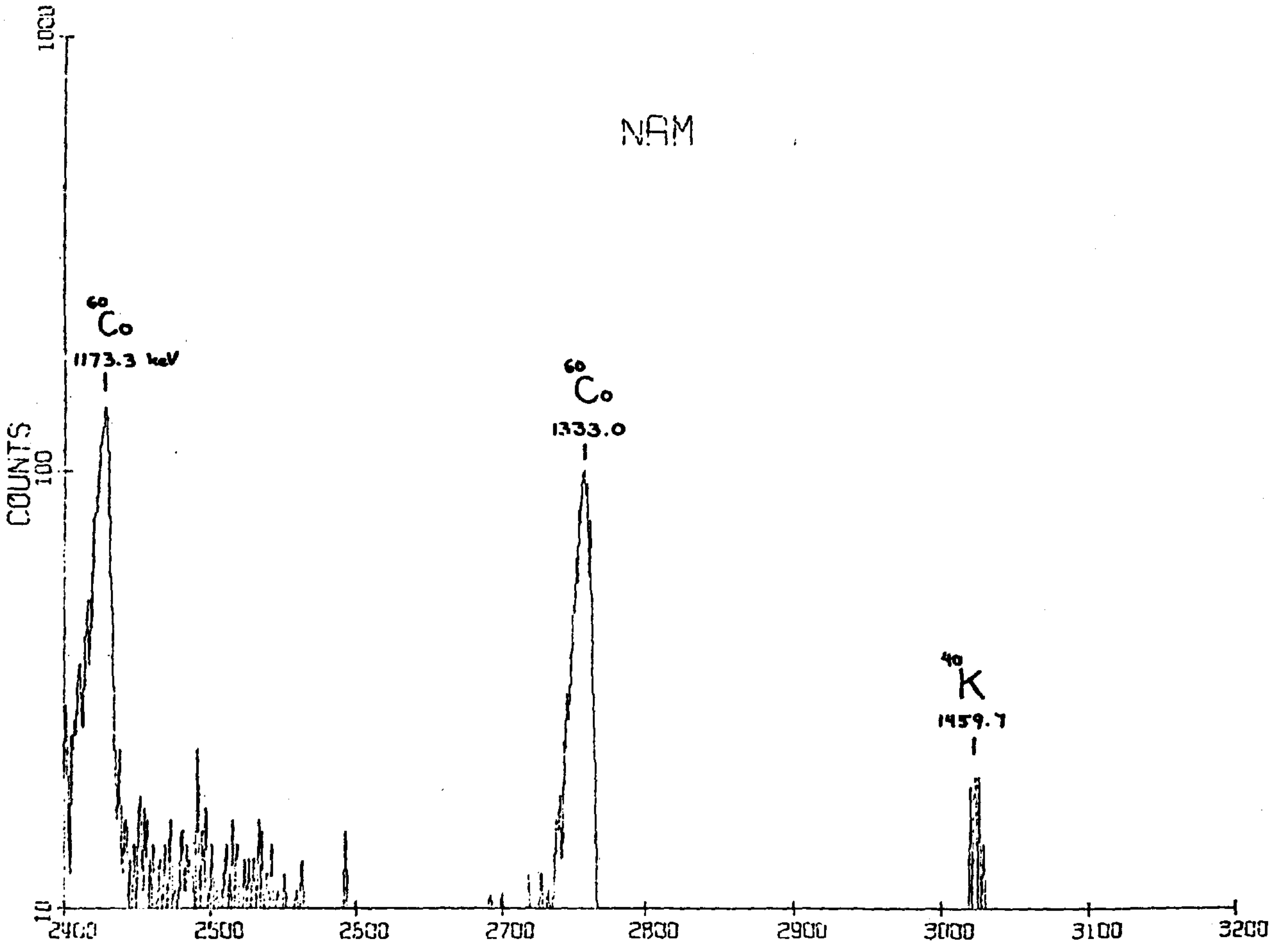

Figure 12d. Ge(Li) spectrum of soil sample taken from Nam Island.