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PRELIMINARY EXTERNAL-DOSE ESTIMATES FOR FUTURE BIKINI ATOLL INHABITANTS

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Abstract

With the objective of evaluating the potential radiation doses that may be received by the returning Bikinians, a survey was conducted during June 1975 of the residual radioactivity in the terrestrial environment on Bikini and Eneu Islands of Bikini Atoll. The survey included measuring environmental gamma-ray exposure rates for use in evaluating the external gamma doses, and collecting numerous soil, lens water, and vegetation samples for use in assessing the internal doses via pertinent food chains. This report describes the gamma-ray exposure rate measurements and their use in conjunction with population statistics and expected life styles for evaluating the potential external gamma-ray doses associated with various options for housing locations on Bikini and Eneu Islands. (The evaluation of the internal dose contribution via food chains will be published in subsequent reports.)

The results of the survey reveal that the external exposure rates on Bikini Island are highly variable. Values near the shores are generally of the order of 10-20 μR/hr, while those within the interior average about 40 μR/hr with a range of roughly 30-100 μR/hr. Eneu Island, however, is characterized by more or less uniformly distributed gamma radiation levels of less than 10 μR/hr over the entire island.

For the external dose determination a set of most likely living patterns was chosen. These were based upon the various options for housing locations along the lagoon road and within the interior portions of Bikini Island as well as along the lagoon side of Eneu Island. As expected, living on Eneu Island results in the lowest doses: 0.12 rem during the first year and 2.7 rem during 30 years. The highest values, 0.28 rem during the first year and 5.7 rem over 30 years, may potentially be received by inhabitants living within the interior of Bikini Island. Other options under consideration produce intermediate values.

Introduction

A radiological survey of Bikini and Eneu Islands of the Bikini Atoll was conducted during June 1975 to assess the potential radiation doses that may be received by the returning Bikinians. Bikini Atoll was one of the U.S. nuclear weapons testing sites in the Pacific. It is situated in the northern part of Micronesia in the Central Pacific Ocean about 3600 km southwest of Honolulu. The atoll consists of a number of small islands on an elliptical coral reef surrounding a lagoon with major and minor axes having land area is about 6 km^2, and the land height generally averages 3-5 m above mean sea level. The islands vary in size from small sandbars of a few hundred square meters in area to islands having areas of about 2 km^2. The islands of most importance for immediate habitation are Bikini and Eneu Islands.

A total of 23 nuclear tests took place during the testing period. Most of the tests were conducted on barges anchored in the lagoon or on the reef. All islands were subjected to varying degrees of close-in fallout. Generally, the prevailing winds transported the radioactive debris clouds toward the southwest. One exception, however, occurred during the Bravo event when unexpected changes in the wind directions caused the cloud to travel toward the east over Bikini Island. Most of the radioactive contamination on Bikini Island is due to this event.

This recent survey was designed to evaluate the potential external gamma doses associated with proposed housing locations on Bikini and Eneu Islands, and to evaluate the potential doses received through the major terrestrial food crops on the atoll. The survey teams therefore directed their efforts in three major areas: (1) Gamma-ray exposure rate measurements and surface soil collections will provide a means for evaluating the external gamma doses associated with proposed housing locations. Gamma spectral analyses of the soil samples will provide information on the fractional contributions of different radionuclides to the external dose. This will enable us to evaluate long-term whole-body doses from this exposure pathway. (2) Collection of lens water samples will supply information on the radionuclide activity levels in the groundwater and on the cycling of radionuclides in the atoll ecosystem. In addition, salinity measurements and lens capacity measurements were made at each well to determine the quality and quantity of water available to the Bikini people for irrigation and/or drinking. (3) Vegetation-soil collections will provide information concerning the radionuclide concentrations in critical food products to evaluate the dose contribution via food chains. It will also provide information on the correlation between soil type, soil radionuclide concentrations, and radionuclide concentrations in key food plants and indicator plant species, which is necessary in order to develop predictive models.

This is the first in a series of reports which will be based upon the June 1975 survey data; it is directed only at preliminary estimates of the external gamma-ray doses. The report describes our techniques for measuring geographical variability of the gamma-ray exposure rates on Bikini and Eneu Islands and how we used the resulting data in conjunction with population statistics and expected living patterns to estimate the external gamma doses. Estimates of the integral first-year and 30-year doses associated with various options for housing locations on Bikini and Eneu Islands are presented and compared with appropriate guide values. The reader should note that these estimates are still preliminary in nature and may undergo changes when all of the results of the survey become available. Further information concerning radiation doses that may potentially be received via groundwater and various food chains will be published upon the completion of the analyses of the many soil, vegetation, and water samples that were collected during the survey.

Techniques Used to Measure Gamma-Ray Exposure Rates

Since the external dose is expected to be almost entirely due to gamma-emitting radionuclides, with only minor contributions from alpha and beta emitters, it was essential to obtain the best possible description of the geographical variability of the gamma-ray exposure rates on Bikini and Eneu Islands. Several techniques were used to measure these exposure rates, since each technique has its own set of limitations (i.e., nonlinear energy response, portability of equipment, and extent of geographical coverage). These techniques included making measurements with the use of portable, hand-held NaI scintillation detectors, a commercially available pressurized ion chamber, and two types of thermoluminescent dosimeters (TLDs).

The portable scintillation detectors consisted of a 2.5-cm-diam × 3.8-cm-long NaI crystal with ratemeter readout. The instruments were calibrated with a ^{137}Cs point source on the primary calibration range of the National Environmental Research Center, Las Vegas, Nevada. Since the response of this instrument is energy-dependent, it overresponds when the gamma flux is due to scattering from a buried area source rather than from a point source as used in the calibration. Therefore it was necessary to normalize these measurements to those obtained by the pressurized ion chamber. This instrument utilizes a stainless steel sphere filled with high-pressure ultrapure argon. The current produced by the radiation-induced ionization within the chamber is measured by a sensitive electrometer with digital readout. The instrument exhibits an essentially flat energy response over all gamma-ray energies of interest to this survey. It was calibrated by the manufacturer and verified by several ERDA laboratories.

Measurements of the exposure rates at 1 m above the ground were made with the NaI scintillators at about 2500 locations on a 30-m rectangular grid over the entire surface of Bikini Island and at about 200 locations on a 120-m grid on Eneu Island. Comparison measurements between the pressurized ion chamber and the NaI scintillators were made at roughly 200 locations selected from within the interior portions of the islands, the village areas, and along the beaches.

In addition, the gamma exposure rates are currently being measured by means of LiF and CaF_2:Dy TLD chips that were placed at some 80 locations on the two islands. The LiF chip displays an essentially flat energy response and excellent thermal stability. Our extensive experience with this chip in a variety of environmental radiation measurement programs at Livermore as well as the Enewetak survey indicated that the results obtained by this detector may also serve as an excellent reference to which measurements obtained by other techniques can be compared. The CaF_2 TLDs have an enhanced energy response at low energies and may be used to detect possible low-energy radiation fields. An attempt is also being made to assess the contribution of the beta radiation to the total exposure rate by placing absorbers of various thicknesses over arrays of TLDs at three selected locations on Bikini Island. The beta radiation is believed to be principally due to ^{90}Sr-^{90}Y activities in the soil.

The chips were annealed on the atoll immediately prior to being placed on the islands for the roughly three-month exposure period which ends during September 1975. At that time, the chips will be retrieved for readout at LLL. Calibration and signal fading studies are being carried out by exposing separate sets of chips to a ^{137}Cs point source before and after the exposure period. The results of the TLD measurements will appear in a later report on this survey.

Results

The geographical variability of the gamma exposure rates for Bikini and Eneu Islands are shown in Figs. 2 and 3. These data, expressed in units of microroentgens per hour (μR/hr), have been normalized to the output from the pressurized ion chamber. Note that the levels for Bikini Island are considerably higher than those for Eneu Island. Also note the complex patterns displayed on Bikini Island. This complexity may possibly be due to the inhomogeneity in the original fallout pattern produced by the Bravo event as well as the extensive earth-moving activities performed over the entire island as part of the agricultural rehabilitation program. The exposure rates near the shores are typically of the order of 10-20 μR/hr, while the elevated interior values vary over a wide range of roughly 30-100 μR/hr. The interior portions of the island may be visualized as having a general background of about 30-40 μR/hr with numerous irregularly shaped areas exhibiting elevated levels superimposed in a random fashion over this general background. Eneu Island, on the other hand, is characterized by low (less than 10 μR/hr) and more or less uniformly distributed gamma radiation levels over the entire island. These exposure rates are expected to be accurate to within approximately 10%, although final confirmation of this must wait until the results of the TLD program become available. No corrections have been made for the natural background contribution.

Based upon our experience at Enewetak Atoll[1] and the data of Bennett and Beck[2] collected during the 1967 Bikini survey, we expect the primary contribution to the gamma exposure rates to be due to ^{137}Cs and ^{60}Co activities in the soil. Trace quantities of other gamma emitters such as ^{125}Sb, ^{155}Eu, and ^{241}Am are expected to contribute at most a few percent to the total exposure rates. The gamma spectral analyses of the several hundred soil samples collected on both islands will reveal the current mix of these radionuclides.

External Dose Estimation

In addition to the gamma-ray exposure rates, one needs to consider the expected living patterns of the future inhabitants in order to evaluate the external dose problem. Of course, many uncertainties are inherent in the prediction of future living patterns. However, the following cases, shown in Table 1, have been proposed as a reasonable selection of possible conditions that would cover the range of doses that could be received by any sizable segment of the population.[3] This will allow any other reasonable

Table 1. Assumed living patterns.

Case	Description
1	No use of Bikini Island for the present as a housing or food production area. Use of Eneu Island for housing and food production. Unrestricted use of fish throughout the atoll.
2	Limited use of Bikini Island with residence in houses already constructed. No additional house construction on Bikini Island for the present. Use of coconuts grown on Bikini Island. Other food crops grown on Eneu Island only. Unrestricted use of fish from all parts of the atoll. Use of Bikini Island lens water for agriculture only.
3	Limited use of Bikini Island with the following remedial actions taken: (a) placing 5 cm of clean coral gravel around the existing houses out to a distance of 10 m, and (b) removal of the top 20 cm of soil and replacement with clean soil out to a distance of 10 m around the houses. All foods grown on Bikini Island are acceptable except pandanus and breadfruit. Unrestricted use of fish throughout the atoll. Use of Bikini Island lens water for agriculture only.
4	Limited use of Bikini Island with Phase II houses constructed only along the lagoon road within area 2 of Fig. 4. Remedial actions 3a and 3b are taken. Use of coconuts grown on Bikini Island. No use of pandanus and breadfruit from Bikini Island. Unrestricted use of fish throughout the atoll.
5	Phase II housing construction according to the Preliminary Bikini Atoll Master Plan, but no use of pandanus and breadfruit from Bikini Island. Unrestricted use of fish throughout the atoll. Lens water for agriculture and washing only.
6	Phase II housing constructed according to the Preliminary Bikini Atoll Master Plan. All foods grown on Bikini Island are acceptable. Unrestricted use of fish throughout the atoll. Lens water used for agriculture and washing only.

pattern to be inferred by proper utilization of the results obtained for these cases. Note that the cases also include assumptions on the food production and consumption plans of the returning population. This information is only required for the internal dose assessment via the specific food chains, and hence is not pertinent to the external dose calculations.

The cases are based upon the assumption that the people will reside on either Bikini or Eneu Island in accordance with the Preliminary Bikini Atoll Master Plan.[4] For purposes of this report, the cases are primarily directed toward assessing the external dose associated with various options for housing locations on the two islands. The first case is based on the assumption that the people will live only on Eneu Island. The remaining cases assume residence on Bikini Island at different village sites with various remedial actions being taken to reduce the exposure rates. Thus, cases 2-4 assume the residences are situated along the lagoon road on Bikini Island, areas 1 and 2 in Fig. 4, while cases 5 and 6 assume the people will live within the interior portions of the island,

Table 2. Population breakdown by age and geographical living patterns.

	Infants and small children	Children and adolescents	*Men*	*Women*
Age bracket (years)	0-4	5-19	20+	20+
Fraction of population (%)	16	41	22	21
Fraction of time spent in respective areas (%):				
Inside home	50	30	30	30
Within 10 m of home	15	10	5	10
Elsewhere in village	5	10	5	10
Beach	5	5	5	5
Interior of island	5	15	20	15
Lagoon	0	10	10	5
Other islands	20	20	25	25

shown as area 3 in Fig. 4. As far as the *external dose assessment* is concerned, cases 5 and 6 are identical. Since the expected living patterns are most likely to differ between the various age groups, it is necessary to utilize the age distribution data presented in Table 2. These data were obtained from the 1974 census taken on Kili Island of the 784 persons who claim land rights on Bikini Atoll.[4] The geographical living patterns, also shown in Table 2, were assumed to be similar to those expected for the returning Enewetak people.[1]

Even though the gamma-ray exposure rates vary widely, it was necessary, for the purpose of the external dose calculations, to derive the most reasonable values of the mean exposure rates for each specific geographical area under consideration. These are shown in Table 3. The mean exposure rates for specific areas on Bikini Island were obtained by weighting the mean exposure rates within each contour interval with the area within the contour. Since the exposure rates on Eneu Island are relatively uniform, the mean exposure rates were chosen by inspection of Fig. 3. Since this survey did not include the other islands of the atoll, it was necessary to rely on data from previous surveys to estimate the contribution the radioactivities on these islands make to the total population dose. Gamma exposure rate data reported by Bennett and Beck,[2] Held,[5] Lynch et al.,[6] Gustafson,[7] Smith and Moore,[8] and Robison et al.[9] were used for this purpose. Their results in conjunction with a simplified area weighting scheme yielded the values presented in Table 3. It should be pointed out that these are rough estimates since the data are scarce and were collected over a span of almost ten years. The exposure rate over the lagoon was estimated to be 3.3 μR/hr due to the cosmic ray contribution and an additional

Table 3. Estimated mean exposure rates (μR/hr) used for the dose calculations.

Case	Village island	Village	Interior	Beach	Lagoon	Other islands
1	Eneu	4	4	1	3.5	50
2	Bikini	24[a]	42[b]	5	3.5	42
3	Bikini	24[a]	42[b]	5	3.5	42
4	Bikini	34[c]	42[b]	5	3.5	42
5	Bikini	53[d]	41[e]	5	3.5	42
6	Bikini	53[d]	41[e]	5	3.5	42

[a]Includes area 1 in Fig. 4.

[b]Includes areas 3 and 4 in Fig. 4.

[c]Includes area 2 in Fig. 4.

[d]Includes area 3 in Fig. 4.

[e]Includes area 4 less area 3 in Fig. 4.

0.2 μR/hr due to naturally occurring radionuclides in the sea water. Cases 3 and 4 demonstrate the effect of remedial action on reducing the gamma exposure rates.

Since the people spend a considerable fraction of their time in the immediate vicinity of their homes, it appears that it may be feasible to take certain remedial actions to reduce the exposure rates in this area. For instance, placing 5 cm of clean coral gravel around the houses out to a distance of 10 m, a common practice in the Marshall Islands, will reduce the exposure rates by a factor of 2. Removing and replacing with clean soil the top 20 cm of soil out to a distance of 10 m from the houses will reduce the exposure rates by a factor of 8. In addition, the shielding provided by the houses themselves will reduce the exposure rates by a factor of 2. Mixing or overturning of the topsoil will most likely not be effective since the soil has already been thoroughly disturbed by the agricultural rehabilitation activities.

Based upon the data of Bennett and Beck,[2] it appears that it may be reasonable to assume, for dose prediction purposes, that the gamma exposure rates on the islands are due to ^{137}Cs and ^{60}Co activities with respective contributions of 80% and 20%. This assumption will be reexamined by means of the gamma spectral analyses of the soil samples collected during this survey. Using this assumption and the information presented in Tables 2 and 3, we calculated the integral first-year and 30-year whole-body external gamma-ray doses for each age group for each living pattern presented in Table 1. The results were then combined by "folding in" the present population distribution. The effect of radioactive decay was included in the calculation; however, the additional reduction in exposure rates due to possible weathering or agricultural crop production processes was not included.

Table 4. Estimated integral whole-body external gamma doses for first year and for 30 years. Values include contribution due to natural background radiation of about 0.027 rem for first-year dose and 0.80 rem for 30-year dose. For comparison, Federal Radiation Guide values (total of external and internal doses) for individuals are 0.5 rem for first year and 5 rem for 30 years.

Case	Description	Estimated doses (rem)	
		First-year	30 year
1	Village on Eneu Island	0.12	2.67
2	Residence in houses already constructed along lagoon road on Bikini Island.	0.20	4.16
3	Residence in houses already constructed along lagoon road on Bikini Island with following remedial actions taken:		
	a. Placing 5 cm of gravel around houses	0.20	4.04
	b. Removing and replacing top 20 cm of soil around houses	0.19	3.87
4	Residence in Phase II houses constructed along lagoon road within area 2 of Fig. 4 with following remedial actions taken:		
	a. Placing 5 cm of gravel around houses	0.22	4.47
	b. Removing and replacing top 20 cm of soil around houses	0.21	4.29
5	Residence in Phase II houses constructed within the interior of Bikini Island	0.28	5.59
6	Residence in Phase II houses constructed within the interior of Bikini Island	0.28	5.59

Difference between Ext. and Ext. Int. = 4.79 - 3.36 = 1.43 R in 30 yrs
= .253 - .173 = .080 in one year

The results of these calculations and a comparison with appropriate recommended guide values are given in Table 4 for each case under consideration. Of course, one should keep in mind that these cases are only approximations of the expected living patterns and should regard the results accordingly. The minimum external doses, as one might expect, may be realized by living on Eneu Island. Estimated values, including natural background, are 0.12 rem during the first year and 2.7 rem over 30 years. A significant fraction of these values is due to exposure received while visiting other islands having higher contamination levels. Future inhabitants of the existing houses constructed along the lagoon road on Bikini Island, case 2, may expect to receive first-year and 30-year integral doses of 0.2 and 4.2 rem respectively. Remedial actions, cases 3a and 3b, reduce the 30-year values by a few tenths of a rem. These values would increase somewhat if the Phase II houses were constructed within area 2 of Fig. 4, cases 4a and 4b, due to the higher gamma exposure rates measured in this area. If, on the other hand, the Phase II houses were built within the interior of Bikini Island instead of along the shores, cases 5 and 6, one would expect the external dose levels to increase

For Bikini Interior, add 0.08 Rem/yr and 1.43 Rem/... compared to Bikini.

Table 5. External 30-year doses for each age group.

Case	Infants and small children	Children and adolescents	Men	Women
1	2.52	2.52	2.85	2.88
2	3.80	4.09	4.34	4.39
3a	3.62	3.96	4.30	4.26
3b	3.35	3.79	4.19	4.09
4a	4.16	4.39	4.63	4.69
4b	3.89	4.21	4.53	4.51
5	5.69	5.53	5.37	5.83
6	5.69	5.53	5.37	5.83

to about 0.28 rem during the first year and 5.6 rem over 30 years. The dose variations between the various age groups for each are given in Table 5. Since the adults are expected to spend a considerable fraction of their time within the interior of Bikini Island as well as on other islands, their dose levels are slightly higher than those for the children. These differences, however, are expected to be somewhat overestimated because aging is not considered in the calculations.

These doses may be compared with the appropriate guide values, given in the title of Table 4, which are those set forth by the International Commission on Radiological Protection. While these guidance values for exposures of individuals and of population groups are not a dividing line between safety and danger, any exposures approaching these guides are cause for careful evaluation of the situation, and exposures exceeding the guides would require consideration of remedial measures to reduce exposures and bring them within the guidelines. Inhabitants in the existing houses on Bikini Island are expected to receive external whole-body radiation exposures that are approximately 40% of the annual guide value and about 70% of the 30-year guide value. This leaves little margin for additional radiation doses that may potentially be received by intake of radionuclides via groundwater and various food chains. From the data of Table 4, it is clear that residents in houses built within the interior of Bikini Island will receive 30-year external radiation doses exceeding the guide value.

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Figure Captions

Fig. 1. Map of Bikini Atoll.

Fig. 2. The geographical variability of the gamma-ray exposure rates (μR/hr) measured 1 m above the ground on Bikini Island. Unfortunately, the exposure rate contours shown in this photograph to delineate areas having different contamination levels are not clearly visible in this black and white reproduction of the original color photograph. The straight lines drawn across the island denote boundaries of land parcels (watos) owned by the families whose names appear in the upper part of the photograph. The numbers in the lower part of the photo denote the number of bouses within each wato that are planned as part of Phase II (upper number) and Phase III (lower number) construction plans.

Fig. 3. The geographical variability of the gamma-ray exposure rates (μR/hr) measured 1 m above the ground on Eneu Island.

Fig. 4. A map of Bikini Island showing specific areas of interest for the dose calculations. Existing houses are situated within area 1. Areas 2 and 3 are proposed village sites for future housing units. The interior portion of the island is denoted by area 4.

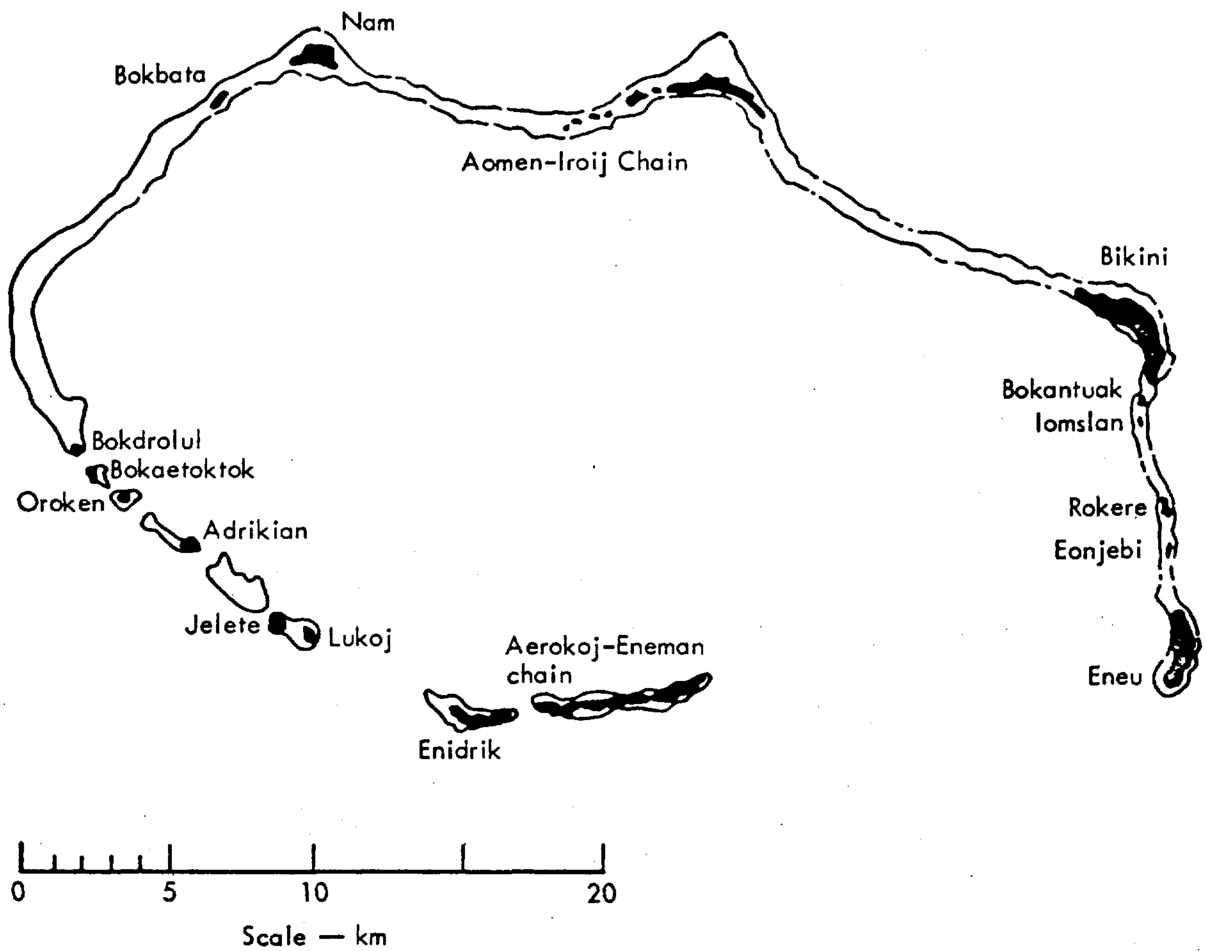
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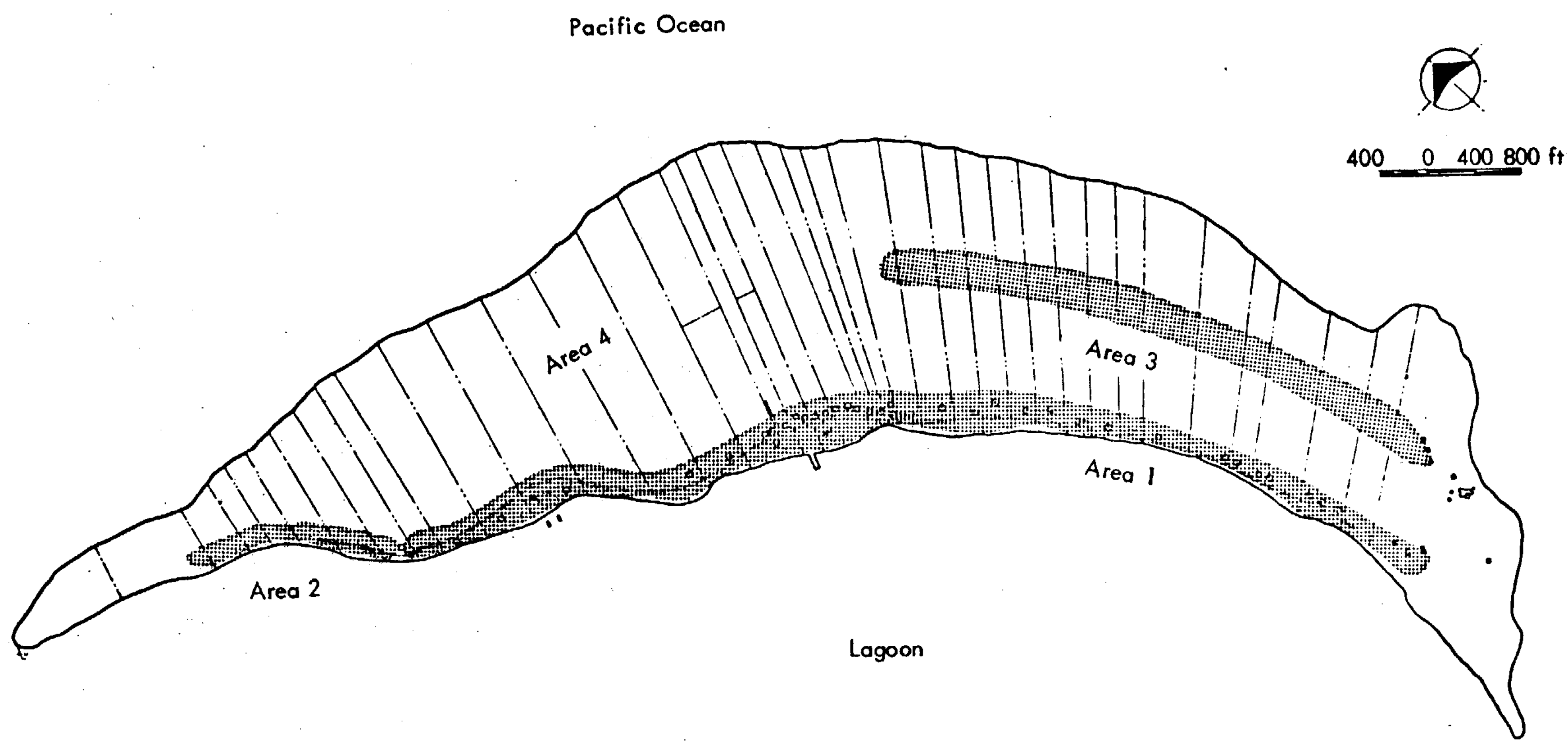
Fig. 1.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Area 4
Area 3
Area 1
Area 2
Lagoon

Fig. 4.