ITEM 7

G. A. Riley

Preliminary Report on the
Oceanography of Bikini Atoll.
JTF-1 013B1b

PRELIMINARY REPORT
ON THE
OCEANOGRAPHY OF BIKINI ATOLL

JTF 1

Oceanographic Section
Technical Staff

013B1b

1. SUMMARY

The atomic blast will contaminate directly a volume of water which is small compared to the total volume of the lagoon. This small water mass will increase in size, with corresponding decrease in the concentration of contaminant, by current transport and by the processes of horizontal and vertical diffusion. The water mass contaminated internally by the blast will be spread the full length of the lagoon within about two days. Radioactive materials deposited with the plume or by convective rains following the blast will be spread more widely and will reach the edges of the lagoon sooner, but their concentration probably will be relatively low.

The current system is particularly important in predicting events subsequent to the blast. The description presented here is the result of a survey conducted during March and April. Further studies will be made in June to determine whether conditions have changed significantly. The system consists primarily of a wind driven surface current flowing in a WSW direction with an average speed of 0.3 knot (varying slightly with wind velocity), extending to a depth of about 40 feet where it gives way to a thicker and slower (0.1 knot) ENE bottom current. These two currents form a continuous, rotary circulation, with bottom water upwelling at the eastern end of the lagoon to join the surface flow and surface water sinking at the western end.

Oceanic water flows into the lagoon continuously over the eastern and northern reefs. The total volume of flow is about three percent of the volume of the lagoon per day. Continuous outflow occurs through the western part of Enyu Channel. Elsewhere, channels, passes, and the western reef, the current reverses with the tide. The tidal flow is strongest through the southwestern passes, but the tidal interchange is relatively ineffective in flushing the lagoon. It is estimated that only 40% of the water leaving the lagoon on the ebb tide is true lagoon water. The remainder is oceanic water that has come into the lagoon on the preceding flood tide. Not much more than 10% of the water entering on the flood tide becomes thoroughly mixed with lagoon water and carried into the general lagoon circulation.

By far the larger part of the water in the central part of the lagoon has therefore come in over the eastern and northern reefs. As this water flows in, it is absorbed into the rotary circulation of the lagoon, thus gradually renewing the lagoon water, while at the same time the latter is being flushed out of the southwestern passes at a rate of 3.2% per day. At this rate of flushing, any given mass of water in the lagoon will on

the average be reduced to one-half its original volume in 22 days and to one-tenth its volume in two and a half months. The rate of flushing will presumably be somewhat slower than average for water in the northwestern part of the lagoon, which has a relatively closed circulation, and faster in the eastern and southern portion, which is more exposed to tidal interchange.

At the time of test Able a patch of contaminated water will be formed at the surface in the target area. The contamination will move with the surface current in a WSW direction at a speed of about 0.3 knot (assuming a 10 knot easterly wind), so that its center will have moved about 7 miles from the center of the target area in the course of a day. At the same time its concentration will be reduced rapidly by vertical and horizontal diffusion. It is estimated that these processes will reduce the concentration to 1% of the initial value in two hours and to 0.0003% in one day (not counting radioactive decay).

In test Baker it is likely that the radioactive products will be uniformly distributed from surface to bottom. The patch of contaminated water, originally more or less circular, will be elongated rapidly by currents flowing west at the surface and east at the bottom. The contaminated water at the surface will be diluted by vertical mixing with underlying water at an estimated rate of 25% per hour. The reduction in the concentration of the bottom water moving eastward from the target area is expected to be about 8% per hour, the difference being due to the fact that the bottom current is three times as thick as the surface current.

Therefore part of the radioactive products will be carried away from the target area, but part will be transferred by vertical diffusion to the other current and will be carried back again. Thus a strip of contaminated water is developed, which lengthens westward with the speed of the surface current flow but with rapidly diminishing concentration, and eastward with the speed of the bottom current. The maximum concentration will remain to the eastward of the target area.

At the end of the first day the strip of contaminated water is expected to extend from Bikini Island to a point about 7 miles WSW of the target. The concentration at the western end of the strip is expected to be about 0.01% of the initial value, taking into account vertical and horizontal diffusion but neglecting radioactive decay. At the eastern end of the lagoon the average concentration will be about 1% of the initial value, but there may be patches of upwelling bottom water with a concentration of 10% or more.

At the end of two days the strip of contaminated water will extend from Bikini Island to the southwestern passes and will be about two miles wide. The maximum concentration in the eastern end will be less than 1% of the initial value and in the western end about 1×10^{-5}%.

It is difficult to carry the analysis beyond this point, but it is certain that further dilution will take place at a much slower rate, and it will probably require a week or two to reduce the maximum concentration to 0.1% of its original value.

If the winds were only 5 knots instead of 10, three or four days would be required to establish the condition described. If they were 20 knots, it would require about a day and a half. It is not possible to predict accurately what would happen in the case of flat calm or wind direction other than easterly since neither has been observed. It is certain, however, that the above predictions would have to be modified. It is probable that with several days of calm weather, the internal circulation of the lagoon would be destroyed and that radioactive products would be spread only by tidal currents and a very slow horizontal diffusion. With southerly winds, on the other hand, it is possible that the lagoon circulation would be accelerated by increased inflow through Enyu Channel.

After the second day contaminated water will begin to leave the lagoon by a series of ebb tide pulses through the southwestern passes. The amount leaving the lagoon will be very small at first and will increase during the first week or so to a maximum value of about 3% of the total contaminant in a day's time. Thereafter the rate of loss will be about 3% of the remaining contaminant per day.

2. GENERAL DESCRIPTION OF THE AREA

2.1 Morphometry

Bikini Atoll (see enclosed chart), centered at 11°35'N, 165°22'E, is roughly oval in shape, 23 miles long on the east-west axis, 13 miles north and south.

Measurements of the chart show that the total area of the lagoon is 641 km^2 (192 mi^2). About 40% of the lagoon has a depth of 25 to 30 fm. Bottom areas above and below these depths are progressively smaller except for the zone between 0 and 5 fm. which covers 8% of the lagoon area, twice that of the next deeper zone. The isolated coral heads, neglected in the measurements, would slightly increase the area of the shallowest zone.

The total volume of the lagoon below lowest low water is estimated to be 28 km^3. Of this volume, about 72% lies below the general sill depth of 7 fm. in Enyu Channel. Only about 4% of the water lies below the 30 fm. bottom of the deepest sill, Eniirikku Pass.

One-third of the circumference of the atoll is composed of islands. They constitute the only portion of the rim over which flow of water is completely prevented. Between the islands are long stretches of shallow reef which together make up about half the circumference of the atoll. They are exposed at lower low tides, and at high tides are covered by up to five feet of water. There are eight passes or channels, which constitute about 20% of the circumference of the atoll, all on the south and southwestern side. The largest one, Enyu Channel, amounts to three-fourths of the total width of the passes and two-thirds of the cross-sectional area. Its sill depth is about 3 to 10 fm., and the underlying reef is visible from the surface throughout its length. In the deeper southwestern passes the remains of the reef are visible at the edges, shelving steeply toward the center of the channels, which cut deeply into the reef.

Table 1 summarizes the measurements of the periphery of the atoll and includes an estimate of the cross-sectional area of water in the passes and over the reefs.

Table 1. Measurements of the periphery of the atoll

	Periphery	Cross-section
Islands	33 km.	---
Reefs	47	.05 km^2
Passes	20	.30
Total	100	.35

2.2 Oceanography and meteorology

2.21 The current system of the region

Bikini Atoll lies in the North Equatorial Current, a westerly drift of water largely wind-driven by the NE Trades. The surface water flow is about half a knot. The velocity decreases with depth, but slight flow can be detected at depths of 200 fm. or more. The southerly limit of the current is believed to lie between 6° and 9°N at this longitude, but the available data are meager. It seems likely that the seasonal shift of the Trades and the North Equatorial Current is never large enough to place Bikini in the Doldrum Belt; however, it is mentioned in passing that if this should happen, the conclusions in this report about the current system inside and outside the lagoon would be invalid for the period in question.

The simple picture of a westerly current is modified and complicated by the presence of the atoll. Only the upper few feet of water can flow unimpeded into the lagoon. The remainder splits and passes around the obstruction, giving rise to eddies and to variations in the direction of flow which extend some distance around the atoll. These currents will be described in more detail in a subsequent report.

The temperature of the surface water is about 80° to 82°F. There is a virtually mixed layer of water in the upper 300 to 400 feet, in which the decrease in temperature with depth is at most 2°. Thus the water that enters the lagoon is relatively homogeneous. From the surface to the depth of the deepest sill, no observation has been obtained of a variation of as much as 1°.

A tide station was operated inside the lagoon off Bikini Island at latitude 11°37'N, longitude 165°31'E, and another on the seaward side of the sand spit north of the island. The observed times of high and low water agreed with the predicted tides for Bikini (USCGS) within the limits of accuracy of the equipment. The observed tidal range averaged 87% of the predicted range. Lowest low water corresponded to a reading of 1.19 feet on the tide staff. The station is believed to be representative of conditions over the entire lagoon for the following reasons: (a) The size of the channels permits easy communication with the ocean. (b) No appreciable tidal lag has been found between observations inside and outside the reef. (c) Winds are steady and storm tides unlikely.

The large Pacific tidal wave that caused extensive damage in Alaska and Hawaii on 2 April was recorded at Bikini at 1530 as a single wave raising the water level one and a half feet

above normal for a period of twenty minutes. It was preceded and followed by twelve hours of unusually high seiches, many of them exceeding one foot, with periods of 13 to 15 minutes.

Small lagoon seiches of periods somewhat longer than one hour and heights up to 0.2 foot have been recorded frequently. They are of no importance in evaluating the circulation of the lagoon.

According to HO Misc. 11275, the waves generated inside the lagoon should be 1.5 feet high at the anchorage area, 2.5 feet in the middle of the lagoon, and 3.5 feet at the western end with an 18 knot wind. With a 10 knot wind they should be respectively 1 foot, 1.5 feet, and 2 feet. The periods should be between 2 and 3 seconds. These values agree with observations.

The trade winds give rise to large breakers on the exposed eastern and northeastern reefs. With an 18 knot wind, the breakers were found to be about 10 feet high. If the winds decrease during the summer, these waves will become smaller, and should be about 4 feet high with a 12 knot wind.

A swell recording unit has been in operation inside the lagoon near Bikini Island, which has shown the existence of swell about a foot high and with a period of 9 seconds. Although generally too small to be noticeable from large ships at anchor, it breaks sharply against shore on the lagoon side of the reef. It is believed that this swell is not related to the waves generated by the trade wind, since the period differs and since the bottom drops off too steeply off Enyu for the waves to be refracted inside. They are believed to have come through the channel from the south and to have been generated in the southern hemisphere. During July and August, the winter season in the southern hemisphere, they may be as high as five feet in the target area.

2.23 Meteorology

Table 2 is a summary of meteorological observations obtained during the present investigation, and Figures 1 and 2 show daily wind averages and the diurnal variation in wind speed. It is

Table 2. Weather observations from Bikini

	Mean air temperature	Amount clouds	Primary wind direction	Wind speed
March	82.6	6.8	ENE	20
April	81.7	6.4	ENE	18

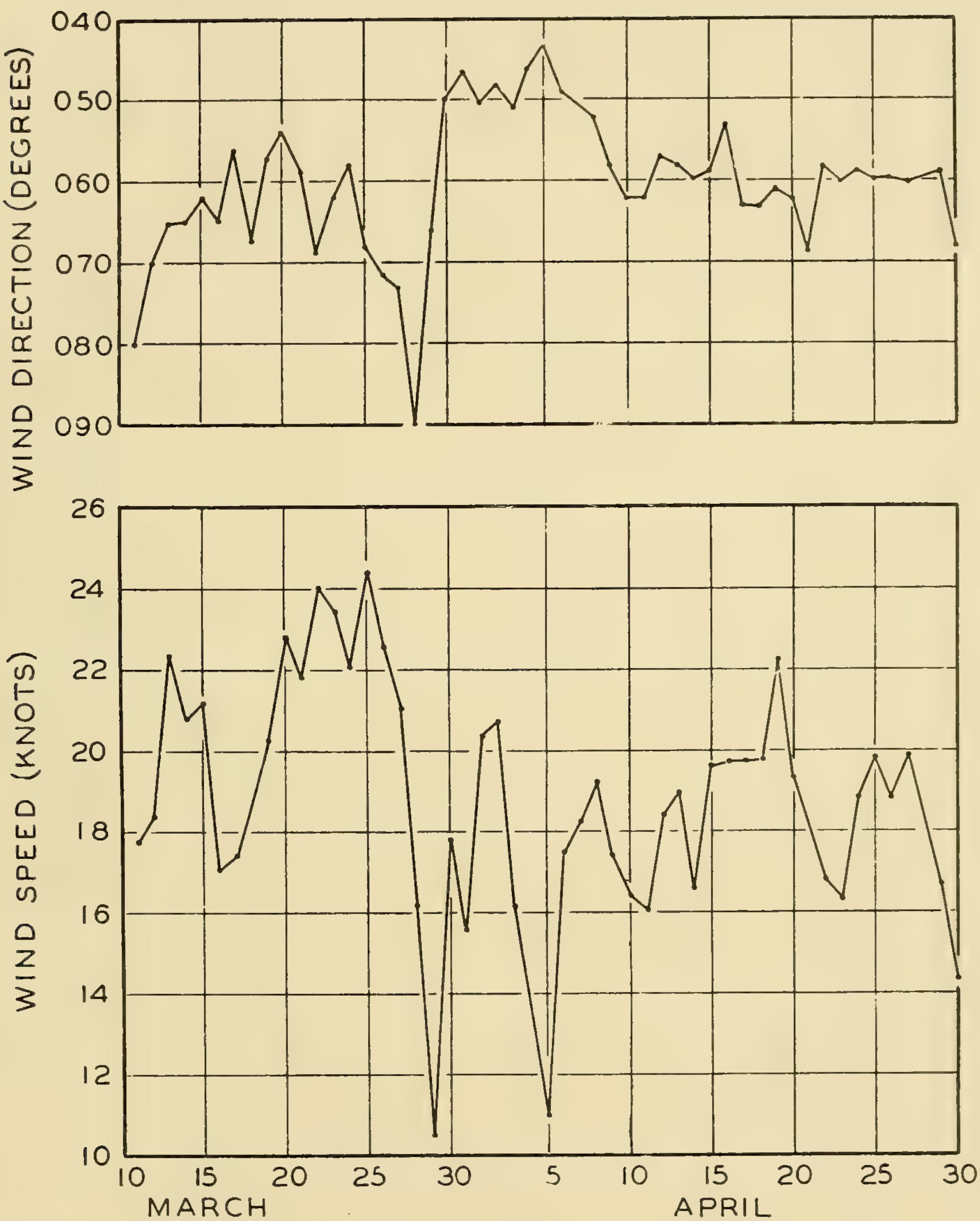

FIGURE I

AVERAGE WIND SPEED AND DIRECTION

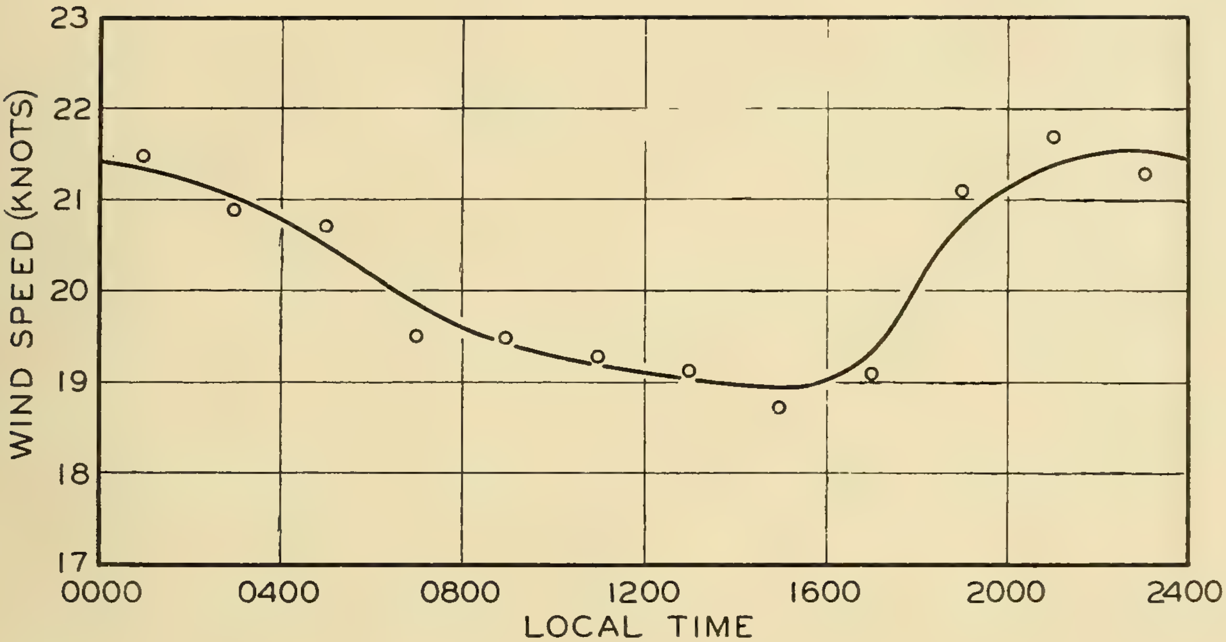

FIGURE 2

DIURNAL CYCLE OF WIND SPEED

by no means certain that the observed diurnal variation is typical, for the May observations showed practically none.

The wind observations are subject to a certain amount of error, first because the velocity was measured with an anemometer 90 feet above the water so that the recorded winds were stronger than surface values would be, second because readings were made during only 10 minutes of each hour. The measurements are sufficiently accurate, however, to serve the purpose of correlation with oceanographic phenomena.

3. OCEANOGRAPHY OF THE LAGOON

3.1 Currents

Three methods were used to measure currents: (a) current meters, by which the velocity was determined at various depths from surface to bottom and the direction to a depth of about 100 feet, the limit of visibility; (b) current poles, which determined the average drift of the upper fifteen feet of water over periods of from eight hours to a day and a half: (c) dye marker, which was used primarily in the channels and over the reefs, where other methods were impracticable.

Figure 3 shows the general drift of the surface water of the lagoon as determined by current pole observations. Data obtained by all three methods are presented in Figures 4 to 7.

The circulation of the lagoon as determined by the current measurements is as follows:

(a) Over the eastern and northern reefs, continuous inflow results from the fact that outside currents and wave action maintain a gradient in water level between the outer reefs and the lagoon amounting to about 1.5 feet.

(b) Continuous outflow occurs through the western part of Enyu Channel. The volume of this flow is a little more than half the inflow over the reefs.

(c) Elsewhere on the periphery of the lagoon the direction of flow changes with the tide. The ebb is stronger than the flood through the southwestern passes.

(d) The dominant features of water movement inside the lagoon are a wind-driven surface current flowing in a generally WSW direction and a return current along the bottom.

(e) The surface current extends to a depth of 40 feet or more. Its velocity varies with the wind as shown in Figure 8. Throughout the entire lagoon the current is influenced to some extent by the tide, decreasing on the flood and increasing on the ebb and with a more pronounced southerly component on the ebb. Near the southwestern passes the flood tide is strong enough to reverse the surface current.

(f) Part of the surface current leaves the lagoon through the passes and channels with each ebb tide; however, the outflow accounts for only about 30% of the total transport into the western end of the lagoon. The remainder sinks and returns as an ENE bottom current, carrying with it some outside water that has come into the lagoon on the flood tide. The bottom current

FIGURE 3
CURRENT POLE DRIFT - DIRECTION AND SPEED (KNOTS)

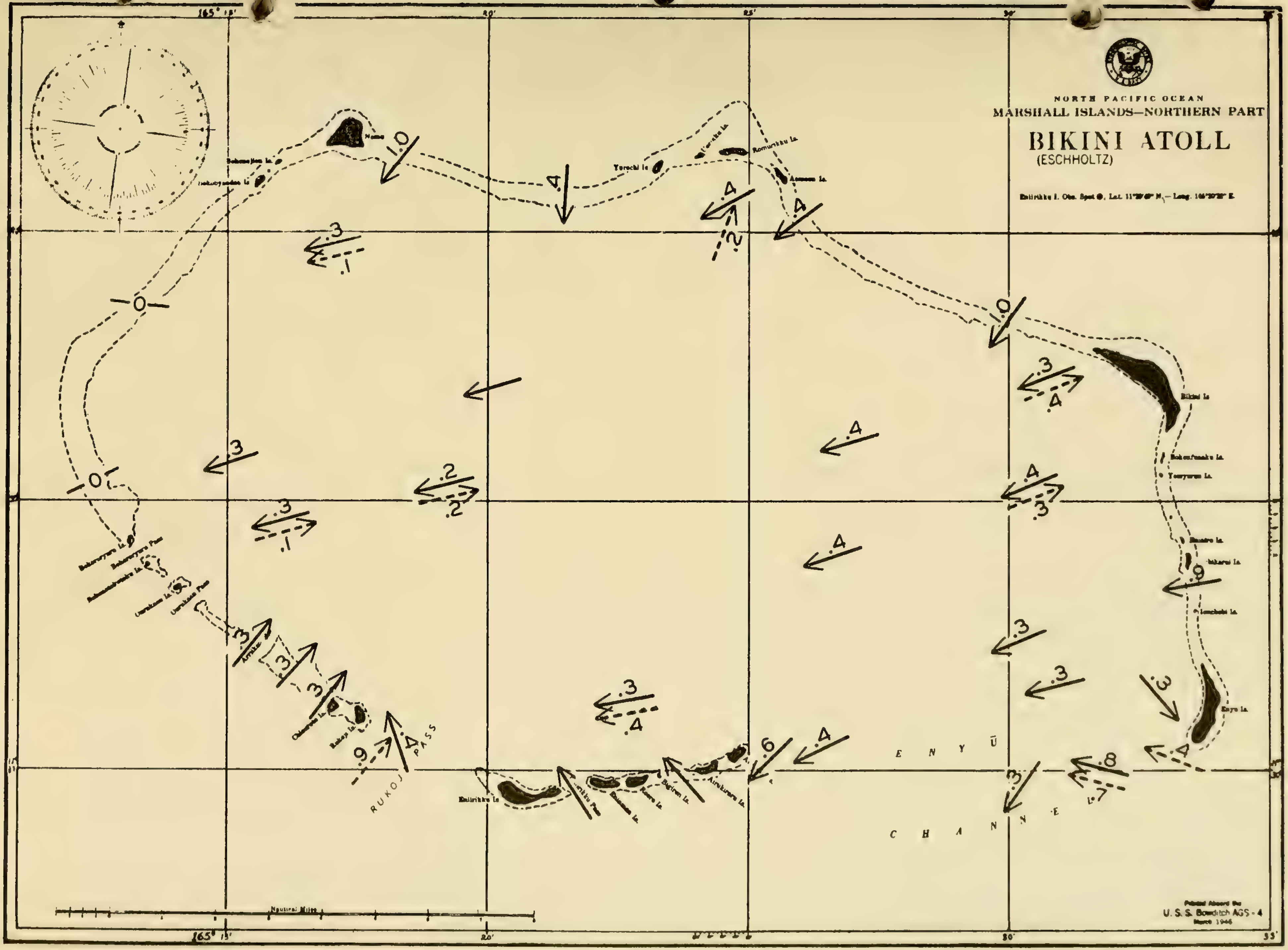

FIGURE 4

CURRENT VELOCITY (KNOTS)-**HIGH TIDE**-AT SURFACE (⟶) AND AT BOTTOM (- - ->)

FIGURE 5

CURRENT VELOCITY (KNOTS)-EBB TIDE-AT SURFACE (⟶) AND AT BOTTOM (- - ->)

FIGURE 6
CURRENT VELOCITY KNOTS-LOW TIDE-AT SURFACE (⟶) AND AT BOTTOM (- - ->)

FIGURE 7

CURRENT VELOCITY KNOTS - **FLOOD TIDE**-AT SURFACE (⟶) AND AT BOTTOM (- - - ->)

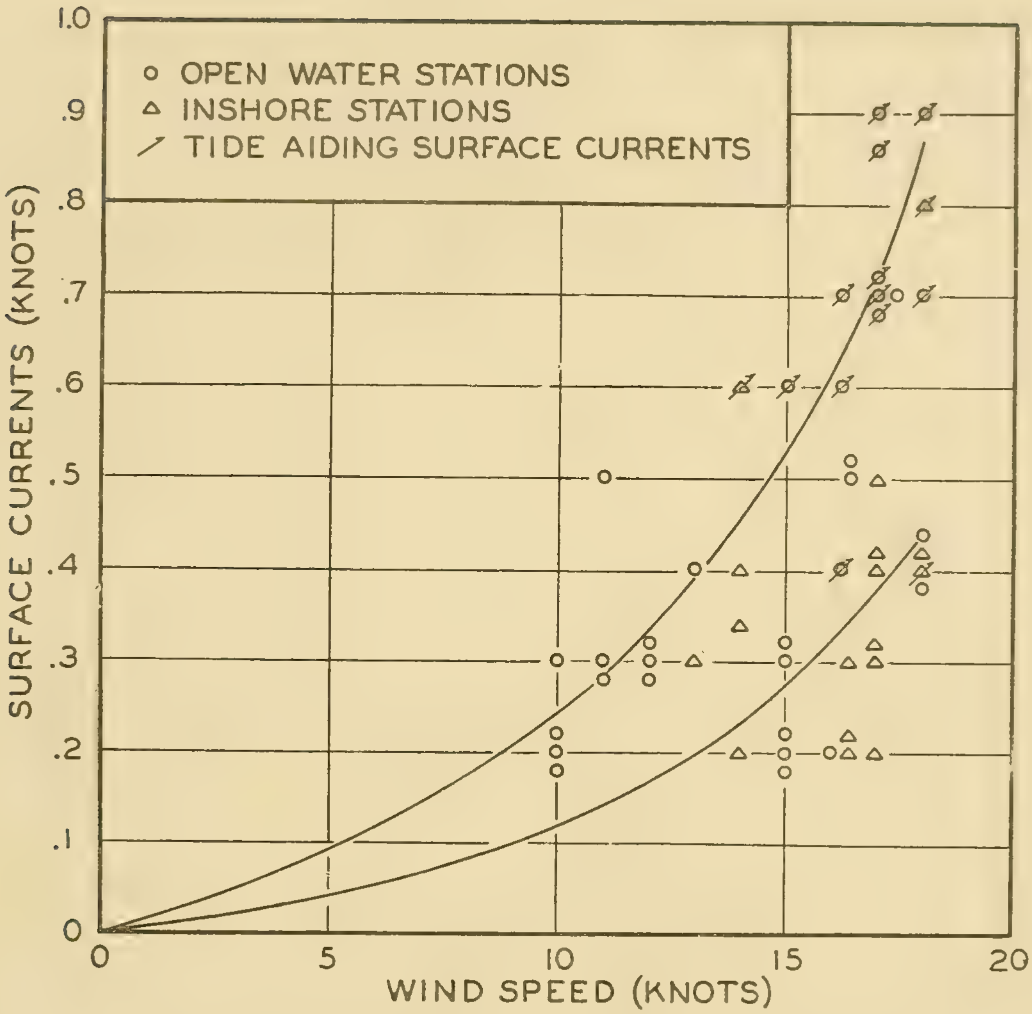

FIGURE 8
EFFECT OF WIND ON CURRENT SPEED

is thicker than the surface current but slower and more compressed laterally (occupying about the central one-half to two-thirds of the area of the lagoon). Its mass transport is probably between 70% and 90% that of the surface current. Like the latter, it is affected by the tide, the speed decreasing on the ebb and the direction changing near the passes.

(g) From Bikini Island westward there is a current which runs at mid-depths just inside the northern reefs and more or less parallel to them. It increases in size and thickness as it progresses westward. The salinity of the water in this current (see section 3.21) indicates that it is reef water of fairly recent origin. Its final disposition in the western end of the lagoon has not been studied, but presumably some small part is lost over the western reefs or through the westernmost passes, while the remainder joins the bottom current.

(h) Summarizing these observations: The lagoon derives its water by continuous inflow over the northern and eastern reefs and by tidal interchange along the rest of the periphery, of which the southwestern passes are the most important. the lagoon has an active internal circulation which consists primarily of a westerly wind-driven surface current and a return flow along the bottom.

The current measurements presented in this section are the framework that will be used in fulfilling the practical requirements of the report, namely the determination of the path of contamination in the lagoon and the rate of flushing. However, before preparing the final estimate it is necessary to examine the variations in temperature and salinity in the lagoon, which add to the general knowledge of lagoon circulation and serve as an independent check on the quantitative results.

3.2 Measurements of temperature and chemical constituents

3.21 Horizontal variations in temperature and chemical constituents

Since the waters of Bikini lagoon are derived from the relatively homogeneous surface layer of the surrounding ocean and are subject to continual interchange with it, it is not to be expected that a high degree of variability would occur in the lagoon. However, the small variations that have been observed are useful in analyzing the general system of circulation.

Variability can arise in three ways: (a) In the surface water of the surrounding ocean there are slight north-south gradients in temperature and salinity, the temperature increas-

ing southward and the salinity decreasing. Thus the water entering the lagoon from the north is about 0.1°C colder and 0.3°/oo more saline than that which enters the southern passes.

(b) Superimposed on this basic difference is a reef effect. During the short period of its passage over the reef, the water is subjected to an intensification of the surface processes of heating, cooling, and evaporation which in deeper water would be distributed downward by vertical mixing. The salinity of the water coming over the reef is constantly increased by evaporation. Assuming what appears to be a reasonable value for evaporation of 0.5 cm. per day, the salinity will be increased 0.01 to 0.03°/oo, depending on the width of the reef and the strength of the current. The greatest flow over the reefs is on the northern side of the lagoon. Therefore the effect of the reefs is to make the north-south gradient in salinity slightly stronger in the lagoon than it is in the oceanic water outside. The effect of the reefs on temperature appears to be important only locally. The water is heated one to two degrees as it comes over the reef during the day and is cooled at night. The temperature is therefore more variable than it is elsewhere in the lagoon, but the net effect on lagoon temperature appears to be negligible. Because of the effect of surf, and possibly by the photosynthesis of reef algae during the daytime, the oxygen content of the water is higher near the reef than in the main body of the lagoon. These variations are used in a later section to analyze diffusion rates.

(c) What has been said of surface exchanges over the reef applies to a lesser extent to the lagoon as a whole. In the open ocean, the effects of surface heating and evaporation are readily distributed through a mixed layer 300 to 400 feet deep. In the lagoon, with an average depth of 175 feet, these effects are more pronounced. It is estimated that evaporation will increase the salinity of the lagoon an average amount of 0.01°/oo in three days.

The distribution of salinity in the lagoon, shown in Figures 9 to 12, is initially dependent on these three factors but is modified by the existing current pattern. In general, the evidence gained from examination of the salinities corroborates the current data previously shown. The current observations and the additional evidence derived from study of the salinities are combined to produce the current patterns shown in Figures 13 and 14, which although somewhat idealized appear to be logical.

The direction of the currents in the north and northwestern part of the lagoon indicates that it is an area of relatively closed circulation. The high salinity of the area is additional evidence. The presence of water with a salinity about 0.1°/oo higher than any incoming water is indicative that some of it remains in the same general area a minimum time of 30 days.

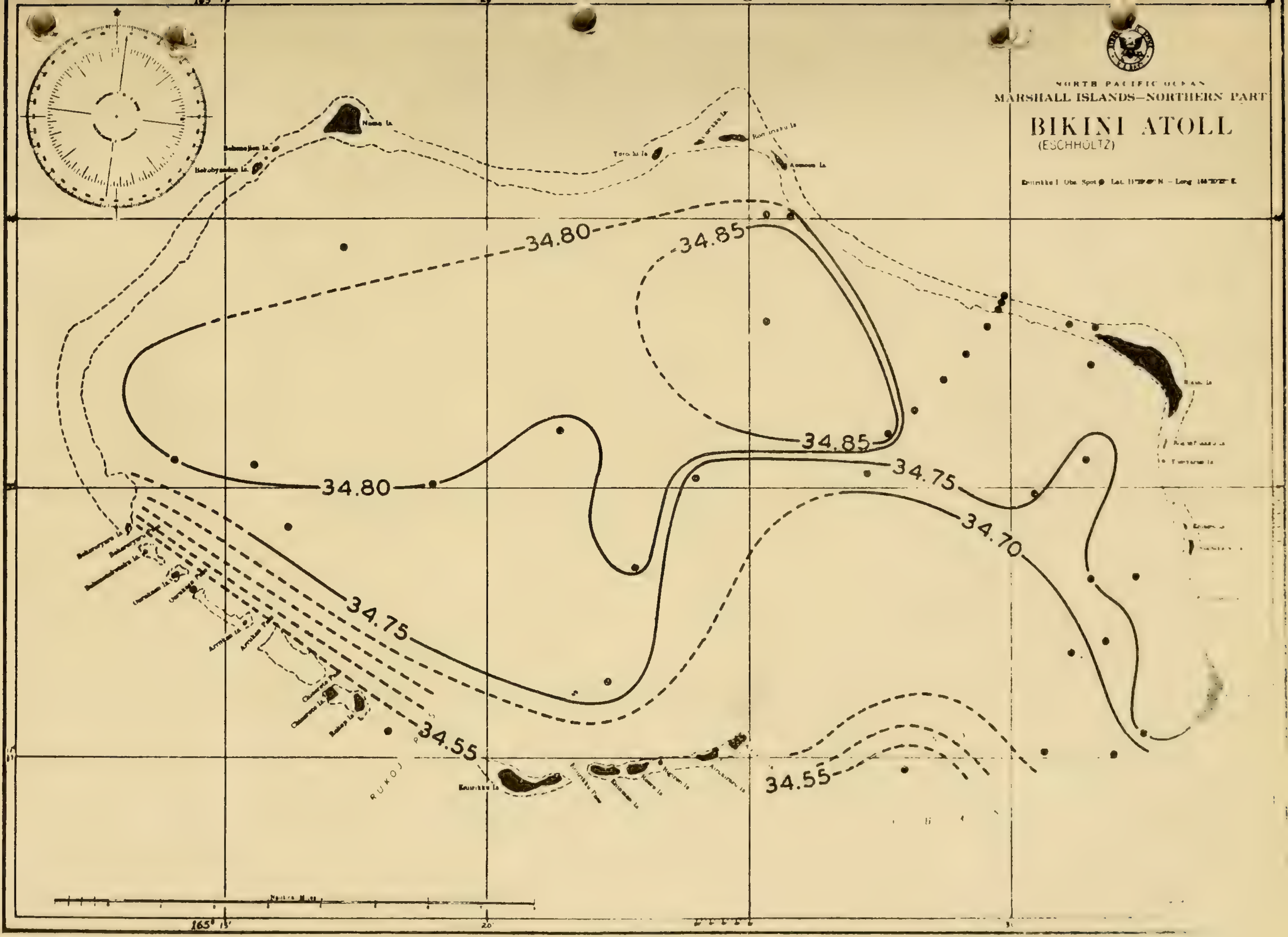

FIGURE 9

SURFACE SALINITY (‰) - **FLOOD TIDE**

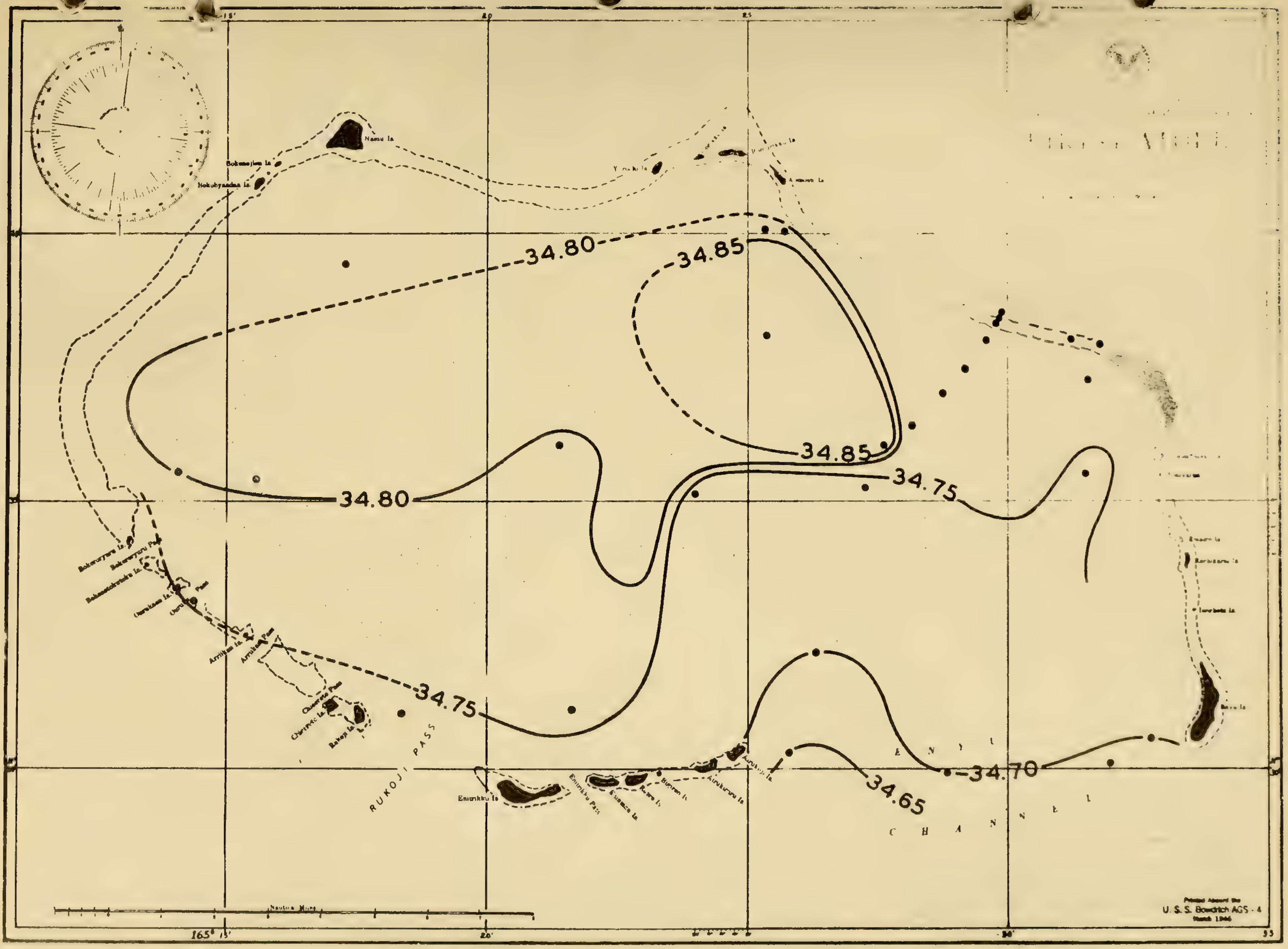

FIGURE 10
SURFACE SALINITY (‰) - EBB TIDE

FIGURE II
BOTTOM SALINITY (‰) - FLOOD TIDE

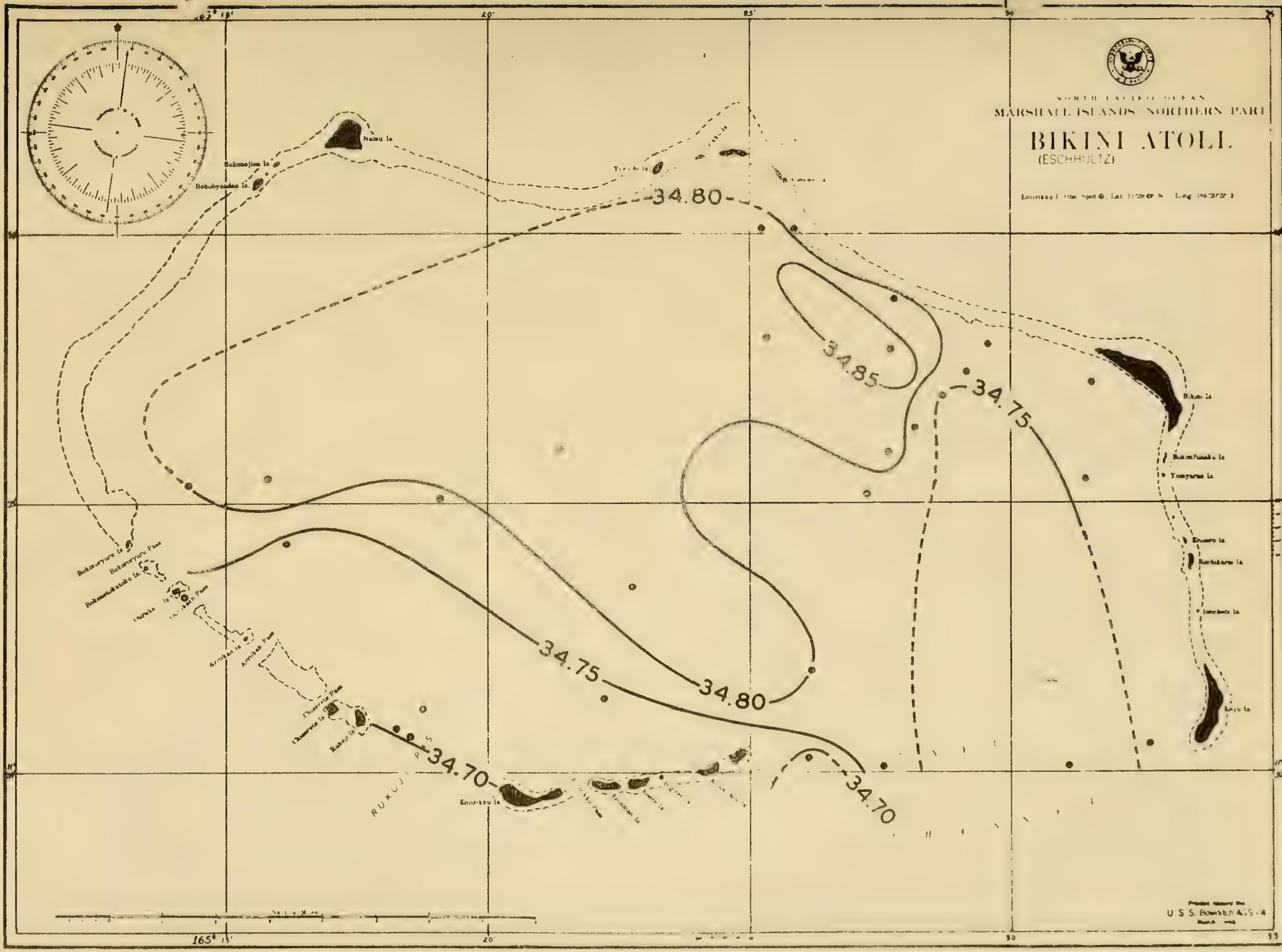

FIGURE 12
BOTTOM SALINITY (‰) - EBB TIDE

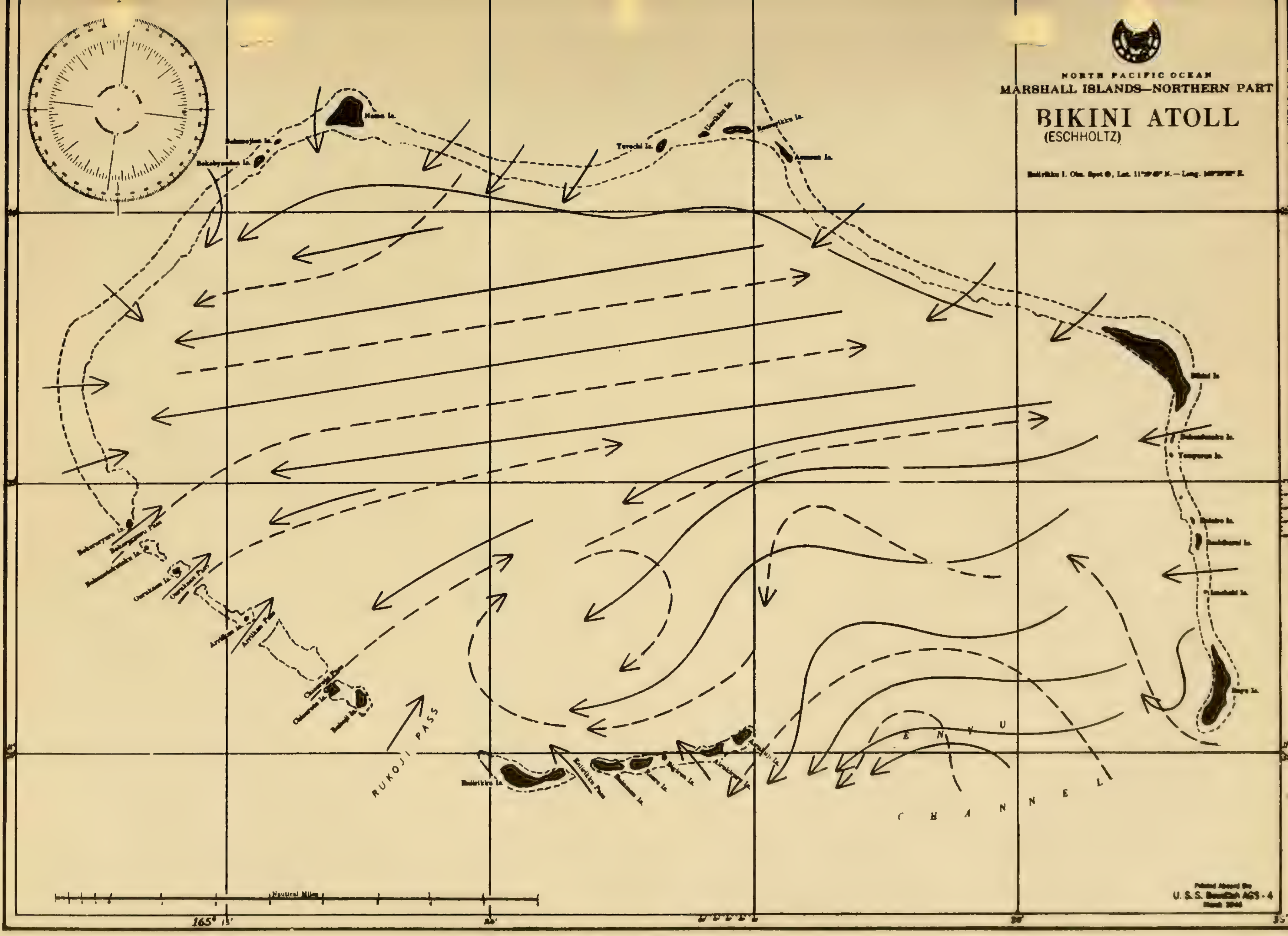

FIGURE 13
SCHEMATIC REPRESENTATION OF **FLOOD TIDE** CURRENTS
AT SURFACE OR INTERMEDIATE DEPTH (⟶) AND AT BOTTOM (-->)

FIGURE 14
SCHEMATIC REPRESENTATION OF **EBB TIDE** CURRENTS
AT SURFACE OR INTERMEDIATE DEPTH (——>) AND AT BOTTOM (- - >)

The opposite extreme is the water near the southwestern passes, where horizontal salinity gradients of 0.10°/oo per mile indicate rapid mixing with water from outside. Collections made here at different phases of the tide show that the isohalines drift one to two miles during a tidal cycle.

The presence of a tongue of high salinity water extending from the central part of the lagoon toward Enyu Channel is indicative of a complicated current pattern in this part of the lagoon. It is of little practical significance and therefore has not been studied in detail, but there is little doubt that one or more eddies exist between the saline central water and the fresher water to the south.

The salinities in the southeastern part of the lagoon adjacent to Enyu Channel are of some help in clarifying the rather obscure results of the current measurements. The latter show that there is continuous outflow from this area through the western third of Enyu Channel and from the southwestern passes by way of a narrow band of current just inside the southern reefs. Obvious sources of flow into the area are the eastern part of Enyu Channel, the eastern reefs, and the main body of lagoon water to the north and west. The salinity distribution indicates that of these possible sources, Enyu Channel is the most important. The expansion and contraction of the 34.75 isohaline proves the existence of tidal interchange. The curvature of all the isohalines demonstrates the presence of an eddy centered somewhere near the middle of the reef in Enyu Channel, such that water flows in through the eastern part of the channel and outward on the western side.

Study of temperature distribution has added nothing to the general picture of current patterns. Diurnal temperature v[illegible]tions are of a large enough magnitude so that a pa[illegible]cular [illegible] mass cannot retain identifiable temperature characte[illegible] long. Therefore the observations can be used only for studying rapid mixing processes between water masses of pronounced characteristics, such as inflow near the reefs.

3.22 Vertical variations in temperature and chemical constituents

Vertical variations arise in two ways: (a) by horizontal movements of water masses having different characteristics, and (b) by diurnal changes.

One of the best examples of the first type is found near the reefs where the incoming water is warmer during the daytime

than the lagoon water proper. The reef water therefore overlies the lagoon water initially, producing temperature differences between surface and bottom that may be as much as 1°F but more typically are a few tenths of a degree. This is illustrated in Figure 15, a temperature profile obtained by a series of bathythermograph lowerings along a line extending westward from Bikini Island. Similar variations have been noted in salinity, phosphate, and oxygen. Differences in oxygen are particularly marked, since the reef water is highly oxygenated by surf effects.

Figures 16 and 17 show diurnal variations in temperature and chemical constituents at two stations. Variations at the surface are only slightly greater than in deep water, which is largely due to rapid vertical diffusion of the products of surface heat exchange. The amount of diffusion is of course dependent on wind velocity. Figure 18 shows the maximum observed difference between surface and bottom temperature plotted against wind velocity. The curve is extrapolated to zero velocity on the assumptions that (a) the total heat increment is about 300 g. cal. per cm^2 per day and (b) the vertical temperature curve is proportional to a normal curve for total energy absorption in moderately clear water.

3.3 Interchange between lagoon and oceanic water

The current measurements described in section 3.1 can be used to estimate the volume of water moving into or out of the lagoon at any given time. A certain amount of error is unavoidable in this estimate, but there are two ways to check the general validity of the results: (a) During a complete tidal cycle the total inflow must equal the total outflow. (b) During any shorter period of time the difference between inflow and outflow must equal the change in the volume of the lagoon as determined by the change in water level.

Application of current measurements to the problem was carried out as follows:

(a) The cross-sectional area of current in each channel and pass was determined by measurement of the chart. Cross-sectional areas along the reefs were estimated by measuring the length of the reef and assuming the approximately correct depths at high and low tide of 130 and 30 cm. respectively, and an average depth of 80 cm. during ebb and flood.

(b) The average velocity of flow was determined across each reef, channel, and pass at high tide, ebb, low tide, and flood.

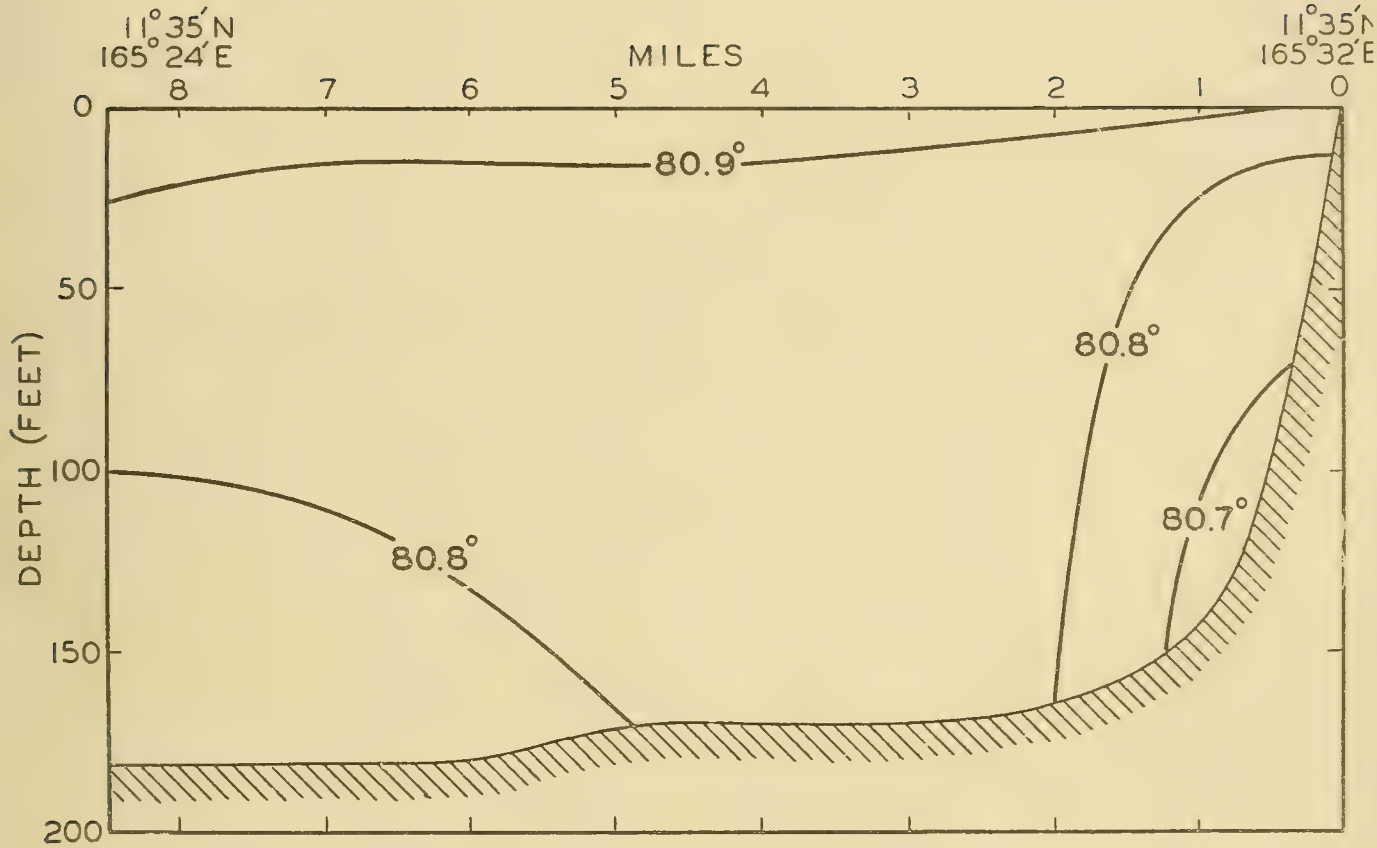

FIGURE 15

VERTICAL TEMPERATURE SECTION OFF EASTERN REEF (°F)

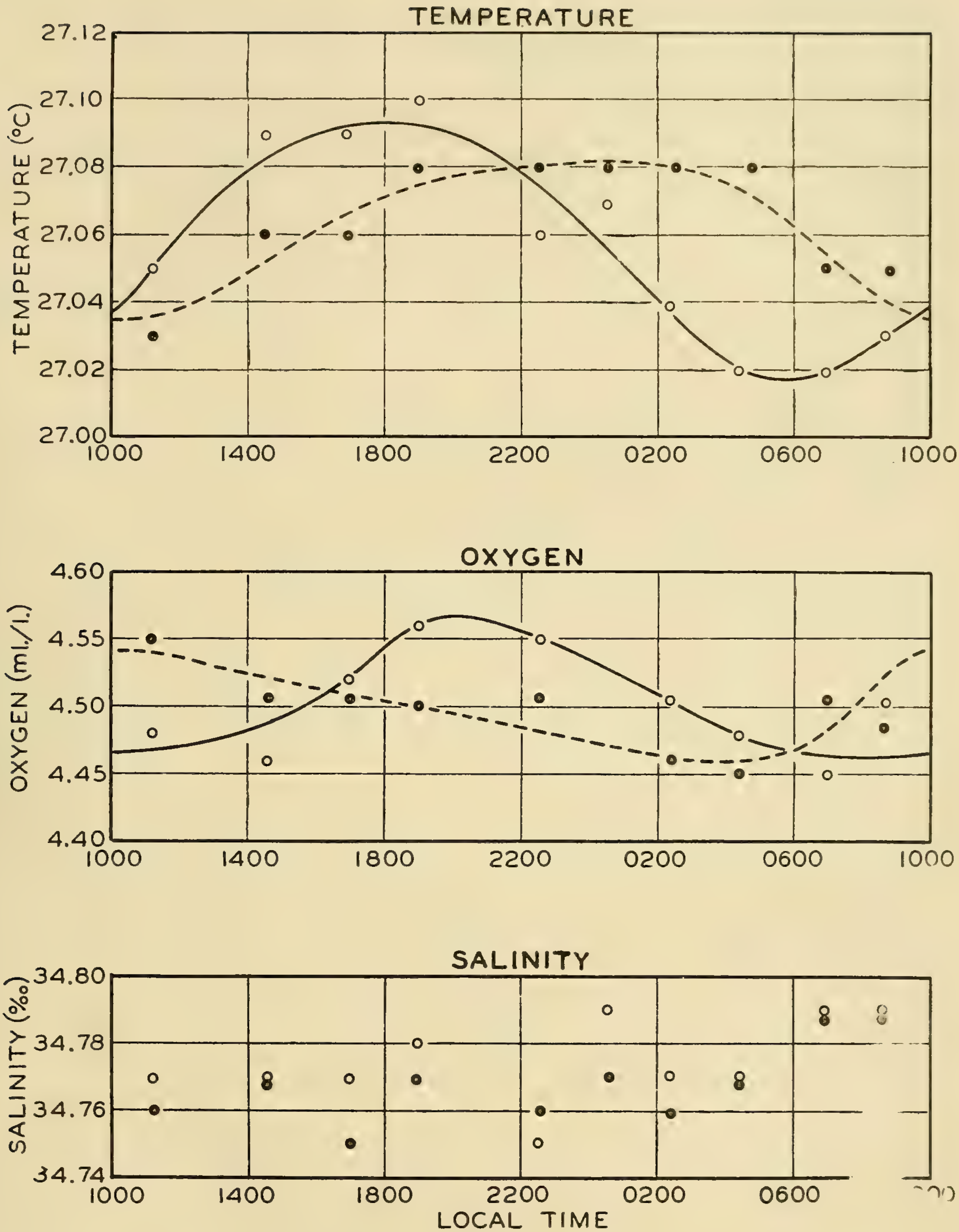

FIGURE 16
DIURNAL CYCLES OF TEMPERATURE, OXYGEN, AND SALINITY IN EAST-CENTRAL LAGOON AT SURFACE (o——) AND AT BOTTOM (•- - -)

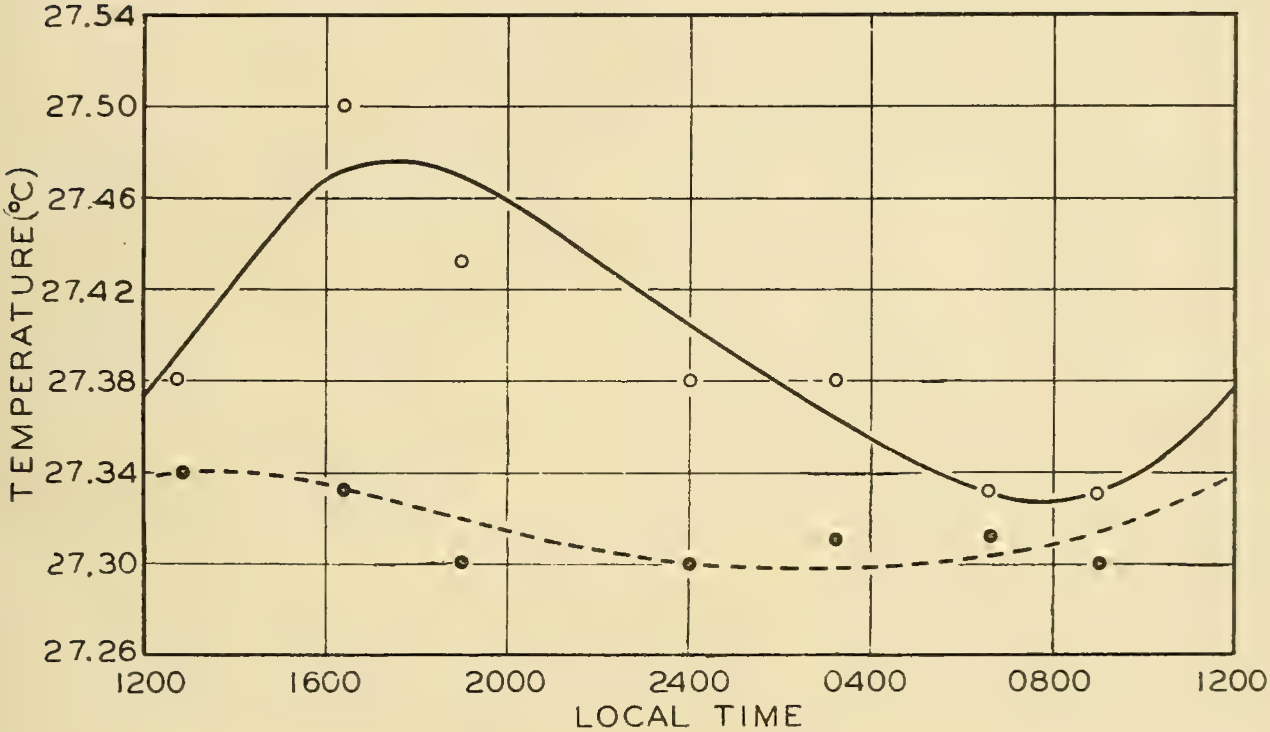

FIGURE 17
DIURNAL CYCLE OF TEMPERATURE IN WEST-CENTRAL LAGOON
AT SURFACE (o——) AND AT BOTTOM (•– – –)

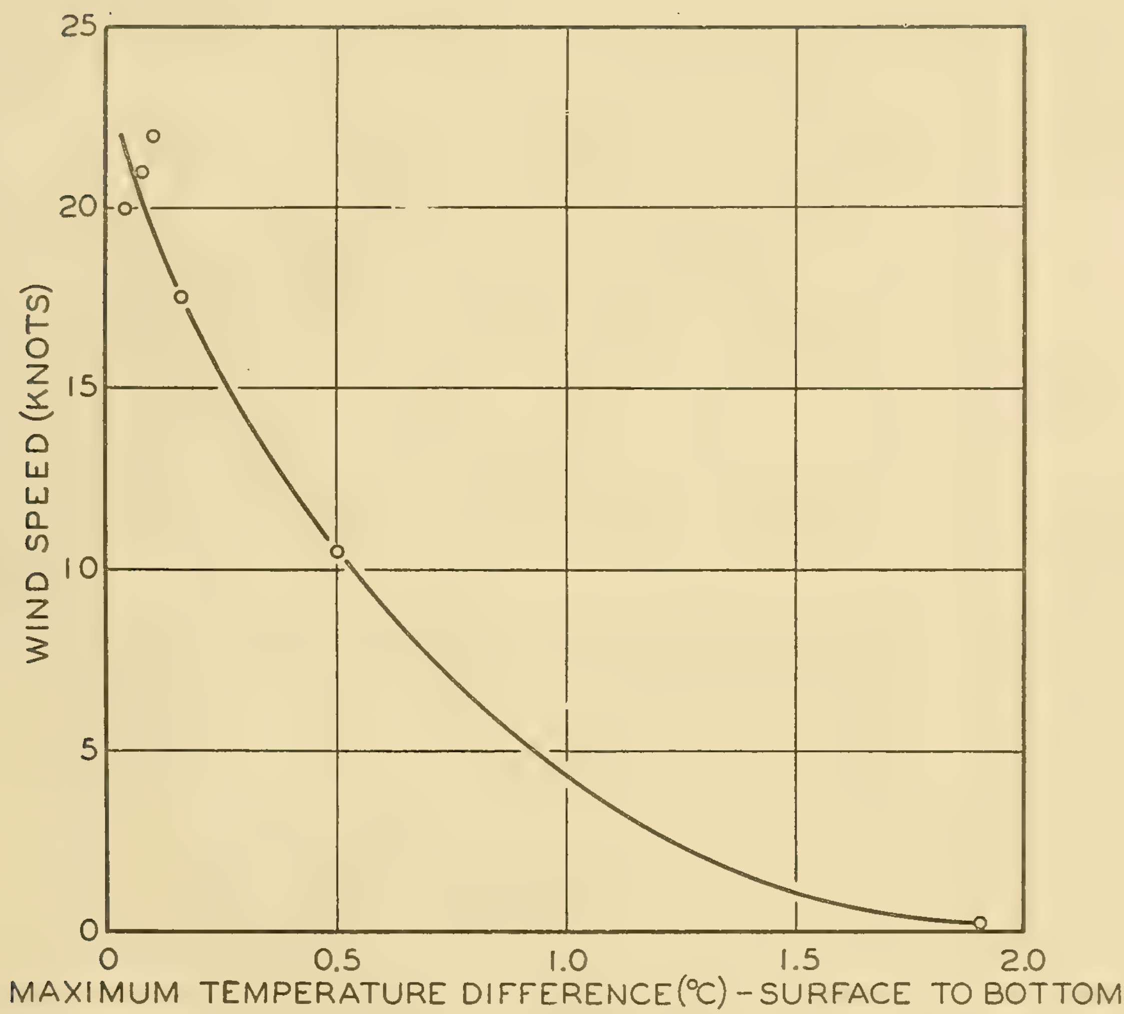

FIGURE 18
EFFECT OF WIND ON DIURNAL TEMPERATURE GRADIENTS

(c) The volume of flow was obtained by multiplying velocities and cross-sectional areas. Two correction factors were introduced for flow in the passes. The measurements were made in the middle of the passes where flow is at a maximum. By oceanographic theory the average flow in the pass at any given moment should be about three-fourths of the maximum flow, and the figures are corrected accordingly. In the second place, the rate of flow in the passes is not constant throughout ebb or flood. The change in velocity with time is roughly a sine curve, and the average rate of flow can be approximated by multiplying the flow at mid-ebb and mid-flow by the factor $2/\pi$. Table 3 shows the results of the calculations.

Table 3. Calculated flow into and out of the lagoon

Reefs	Length cm x 10^5	Depth cm x 10^3	Velocity cm/sec.* Tide stage H	E	L	F	Volume (cm^{3}x 10^9/sec.) Tide stage H	E	L	F
Boby-Namu	0.5	Varies	20	10	10	25	0.13	0.04	0.02	0.10
Namu-Yuro	8.4	with	40	40	30	45	4.35	2.70	0.75	3.02
Amen-Bikini	9.8	stage	40	50	25	40	5.10	3.90	0.74	3.14
Bikini-Enyu	5.4	of	30	40	20	30	2.10	1.73	0.32	1.30
Boby-West	8.5	tide	0	-15	0	20	0.00	-1.02	0.00	1.36
West-Boro	6.3		-5	-5	5	5	-0.41	-0.25	0.09	0.25
					Sum		11.27	7.10	1.92	9.17
Channels										
Rukoji	3.5	0.87	-5	-15	-5	45	-1.5	-4.5	-1.5	13.7
Enyu	15.7	1.22	-2.5	-3.0	-2.5	-2.0	-4.8	-5.8	-4.8	-3.8
					Sum		-6.3	-10.3	-6.3	9.9
Passes										
All SW	2.0	2.94	-10	-100	-15	50	-5.9	-59.0	-8.9	29.4
Rukoji**	0.6	3.66	-5	-25	-5	50	-1.1	-5.5	-1.1	11.0
Eniirikku	0.4	5.50	-5	-25	-5	35	-1.1	-5.5	-1.1	7.7
					Sum		-8.1	-70.0	-11.1	48.1
Corrected sum - paragraph (c)							-6.1	-33.4	-8.3	22.9

(d) The net exchange of water is determined from the duration of each stage of the tide and the volume of flow during that time, as shown in Table 4.

* Positive values denote inflow, negative values outflow.

** Rukoji is a narrow, deep pass with shallow reefs on each side. The type of flow is different in the pass from that over the reefs, and they are therefore listed separately.

Table 4. Net transport (x $10^{14}cm^3$)

Tide stage Duration (hours)	High 0.5	Ebb 5.8	Low 0.5	Flood 5.2
Reefs	0.21 -0.01	1.75 -0.28	0.03	1.72
Channels	-0.12	-2.15	-0.12	2.56 -0.71
Passes	-0.11	-6.97	-0.15	4.29
Sum	-0.03	-7.65	-0.24	7.86

Net inflow 7.86
Net outflow 7.92

During a mean tide of 100 cm., the value used in all calculations, the change in the volume of the lagoon is 6.4 x $10^{14}cm^3$, or 2.3% of its total volume. This value is about 20% lower than the estimate obtained in Table 5. The difference, however, is not large enough to affect the essential validity of the results.

The tables show that although the net transport is outward at high, ebb, and low tides, some water is brought in over the northern and eastern reefs. Moreover, some water is lost through Enyu Channel at flood tide. The total transport of water across the periphery of the lagoon is therefore larger than the net tidal transport. A budget of total transport can be obtained by calculating the sum of all positive values and the sum of all negative values as shown in Table 5.

Table 5. Total transport (x$10^{14}cm^3$)

	Inflow	Outflow
Reefs	0.21 1.75 0.03 1.72	-0.01 -0.28
Channels	2.56	-0.12 -2.15 -0.12 -0.71
Passes	4.29	-0.11 -6.97 -0.15
Sum	10.56	-10.62

The total transport into and out of the lagoon is therefore estimated to be about 10.6 x 10^{14} cm^3 per 12 hours, or 3.8% of

the total lagoon volume. The reservation is made, however, that these values may be as much as 20% too high.

A final check on the validity of the data, particularly with respect to the relative proportion of water that comes in over the reefs as compared with that derived from the channels, can be obtained by calculating the salt budget. It has been observed that water entering the lagoon over the reefs has a salinity of about 34.80°/oo, along the southern passes and channels it is about 34.50°/oo, and the average salinity of water flowing out during the ebb is 34.63°/oo. Combining these observations with estimated volumes of flow, the results are as shown in Table 6. The error is about 1%.

Table 6. Salt budget

		Estimated total volume of water	Salinity	Total transfer of salt
Inflow	Reefs	3.71×10^{14}	34.80	12.9×10^{11}g
	Channels, passes	6.85	34.50	23.6
	Total	10.56		36.5
Outflow		-10.62	34.63	-36.8

Thus the total transport into and out of the lagoon is established with a fair degree of accuracy. There remains only the question of the dispersal of water inside the lagoon. Taking the figures from Table 6, the water coming in over the reef with a salinity of 34.80°/oo constitutes 35% of the total inflow, while 65% is channel water with a salinity of 34.50°/oo. If these proportions were mixed completely, the resultant salinity of the lagoon would be about 34.61°/oo. Instead, the average salinity of the lagoon is nearly 34.80°/oo. The difference is too large to be accounted for by evaporation. The most logical explanation of the apparent discrepancy is that rapid and relatively complete mixing occurs only in the immediate vicinity of the passes and channels, and part of the water entering this area on the flood tide is lost on the ebb without becoming incorporated in the main mass of central lagoon water. Again utilizing observed salinity values for purposes of calculation, the water in the passes on the ebb tide, with an average salinity of 34.63°/oo, has a percentage composition of 43% central lagoon water (salinity 34.80) and 57% ocean water (34.50) which has been in the lagoon only a short time. The results of this estimate are summarized as follows:

(a) It is assumed that the total inflow and outflow are equal and have a value of 10.6×10^{14} cm^3 per 12 hours.

(b) 57% of the total outflow or $6.0 \times 10^{14} cm^3$ is of recent oceanic origin by way of the southern passes and channels. It has been in the lagoon only during one or a few tidal cycles and has not had time to become thoroughly mixed with the water in the central part of the lagoon. The remaining 43% or $4.6 \times 10^{14} cm^3$ is lagoon water.

(c) The total inflow can be allocated as follows:
(1) 35% or $3.71 \times 10^{14} cm^3$ per 12 hours comes in over the northern reefs and joins the main mass of lagoon water.
(2) 65% or $6.85 \times 10^{14} cm^3$ comes in through the southern passes and channels, of which 6.0 is transient according to (b) above, and the remaining 0.85 is transported into the central part of the lagoon.

(d) Therefore of the total interchange of $10.6 \times 10^{14} cm^3$ per 12 hours, $4.6 \times 10^{14} cm^3$, or 1.6% of the total volume of the lagoon, perform a slow flushing of the lagoon as a whole, while the remainder rapidly flushes a small area in the south and southwestern part of the lagoon.

The estimates of total inflow and outflow, based on a mean tide of 100 cm., are adequate for determining the average rate of flushing over a considerable period of time. During shorter periods the rate will vary from about 50% of the calculated values (neap tide) to 160% (spring tide). Still larger variations are obtained in the relative amounts of water passing over different parts of the periphery of the lagoon.

3.4 Vertical diffusion

In section 3.22 it was shown that vertical mixing is effective in maintaining a relatively uniform temperature in the lagoon. Diurnal heating in the absence of wind would increase the temperature about 2°C at the surface during the day. The increase at the bottom would be less than 0.01°. Actually, however, the surface increase was never more than about 0.2°. The rest of the heat was transferred downward by vertical diffusion, and the temperature change at lower levels was correspondingly increased. The rate of vertical transfer is readily determined for any particular temperature distribution: the constant in the equation, known in oceanographic literature as the coefficient of eddy diffusivity and designated by the symbol A_v, can then be used to determine the rate of transfer of any property of the water with any assumed initial distribution. This method is essential in determining the rate of dilution of contaminated water after the blasts.

There are two inherent difficulties in applying these methods in Bikini lagoon. First, the observed differences are small, so that the errors of measurement in any particular set of observations may be as much as 40% of the total difference. Second, it was not possible to sample the same body of water at successive intervals, which introduces random oceanographic variations.

The errors are to a considerable extent eliminated by smoothing the curves and by using several independent methods of computation. These methods were:

(a) The relationship between wind velocity and surface current gives values of eddy viscosity, which in uniform water should be numerically equal to A_V.

(b) The diffusion coefficient was computed from the diurnal temperature variations previously described.

(c) At noon, and especially during low tide, the water flowing in over the eastern and northern reefs is appreciably warmed during its passage, its salinity is raised, and it becomes rich in oxygen. The mixing of this characteristic water from a "line source" with the rest of the water in the lagoon provides another method of computing vertical diffusion which is of particular interest because of its analogy with the surface contamination expected in test Able.

Method (a) and method (b), for the eastern station gave values of A_V around 200 to 250 cm^2 per second. Method (b) for the western station gave values much higher than are reasonable, indicating that processes other than vertical diffusion were active. The result is believed to be due to sinking of surface water, which effectively brings the surface temperature fluctuations to greater depths by other means than turbulence. The sinking is the result of the gradual slowing down of water which is being driven against the western reefs, and seems to be distributed over a large part of the western lagoon.

Method (c) leads to somewhat smaller values of eddy diffusivity near the reefs. This may be partly due to upwelling, partly to the fact that the "line source" is located near the surface, where the scale of turbulence must be suppressed by the existing boundary. However, theoretical considerations indicate that A_V will increase to a value of about 250 at a depth of 2.5 m. and probably changes little if any from that depth down to very near the bottom.

These figures will be used in the section that follows to determine the rate of dilution of radioactive products by vertical diffusion.

4. DECONTAMINATION ESTIMATE

The factors exclusive of radioactive decay that must be considered in calculating the rate of decontamination after the blasts are horizontal and vertical diffusion and current direction and velocity. Since all these factors are considerably affected by weather, it is impossible to make a precise prediction that will fit all cases. But barring a radical change such as reversal of wind direction, the results should be of the right order of magnitude. The present section is based on the assumption of a 10 knot ENE wind at the time of the tests. A further section will attempt to describe what would be likely to happen with certain other wind conditions.

Assume that the explosion produces a volume of uniformly contaminated water with a radius of about 400 m. As horizontal diffusion begins to operate, the size of the patch of contaminated water will increase, a gradient in concentration will develop from the center of the patch toward its periphery, and the concentration in the center will decrease gradually. An oceanographic theory developed by G. F. McEwen predicts that the effect of diffusion will be as shown in Table 7.

Table 7. Reduction of contamination by horizontal diffusion (% of initial concentration, radioactive decay not included)

Time in hours	Distance in meters from the center		
	0	800	1600
0	100	0	0
4	99	0	0
12	67	2.7	0.03
24	33	6.8	0.7
48	11	5.3	1.7

Further dilution will take place by vertical diffusion, and this effect can be determined from the measurements described in the previous section. At the time of test Able, the contamination will be largely confined to the immediate surface layer. Assuming for purposes of calculation that at the end of three minutes the radioactive products will have become uniformly distributed through the upper 2.5 m., then further dilution of this surface layer is expected to take place according to the figures in Table 8.

The patch of contaminated water will be carried WSW from the target area at a rate of about 0.3 knot. The contaminated water that is diffused down into the bottom layer will be carried back toward the target area. This removal of contaminated

Table 8. Reduction of surface contamination by vertical diffusion in test Able (% of concentration 3 minutes after blast)

Time	Concentration
3 min.	100
15	32
30	22
1 hour	15
2	11
4	7.5

water by the counter current is important in maintaining a high and relatively uniform rate of reduction of concentration in the surface layer, a reduction that is estimated to continue at a rate of about 25% to 30% per hour after the first four hours.

In test Baker it is assumed that the contamination is initially distributed in a cylinder of 400 m. radius extending from the surface to the bottom. The part of the cylinder in the surface current, namely the upper one-fourth, will move in a WSW direction at a speed of 0.3 knot. The lower three-fourths will move ENE with the bottom current at 0.1 knot.

As the patch of contaminated surface water moves away from the target area, vertical mixing with uncontaminated water underneath will reduce the surface concentration about 25% per hour. The material lost from the surface layer will be carried back toward the target area by the counter current. Reduction of concentration will also occur in the patch of contaminated bottom water moving eastward from the target area, but the rate of reduction will be only about one-third as high, or 8% per hour, because of the greater thickness of the bottom layer. From this figure, the amount of contaminant moving into the surface layer at any time is readily determined.

Since a part of the radioactive material diffuses out of the patches of contaminated water and into the opposite current moving back past the target area, the net result of the current system and vertical diffusion will be to produce a long, narrow strip of contaminated water passing through the target area along a WSW-ENE axis. The strip will be gradually broadened by horizontal diffusion, but this effect is of relatively minor importance. Table 9 shows the estimated reduction in concentration of contaminant by horizontal and vertical diffusion.

At the end of the first day the eastern end of the strip of contaminated water is expected to reach Bikini Island. The

Table 9. Calculated maximum concentration of radioactive materials in the surface water after test Baker (% of initial concentration, radioactive decay not included)

Time in hours	0	1	2	4	12	24	48
Downwind from target:							
Distance travelled miles	0	0.3	0.6	1.2	3.6	7.2	14.4
Horizontal diffusion	100	100	100	99	67	33	11
Vertical diffusion	100	75	56	32	3.2	0.1	10^{-4}
Combined effect	100	75	56	32	2.2	.03	10^{-5}
Upwind from target:							
Distance travelled miles	0	0.1	0.2	0.4	1.2	2.4	-
Horizontal diffusion	100	100	100	99	67	33	-
Vertical diffusion	100	14	13	11	6	2	-
Combined effect	100	14	13	11	4	0.7	-

analysis cannot be carried beyond this point with any degree of accuracy since both the mathematical theory and the oceanographic factors involved are very complex. Considerable upwelling of bottom water occurs near Bikini Island. Since this water will have a higher concentration of radioactive material than the surface water, the area between the target and Bikini is more likely to be dangerous than any other part of the lagoon. The maximum concentration in this area probably will not be more than 13.5% of the initial value. This figure is based on vertical diffusion alone, since horizontal diffusion is expected to be much reduced in the bottom layer. There is considerable likelihood that upwelling will occur over a broad enough area to dilute the contaminant considerably; however, it is better to be conservative and consider that there may be patches of water with 10% or more of the original concentration of contaminant.

At the end of two days most of the bottom water at the eastern end of the lagoon will have upwelled to the surface and will have been diluted by vertical diffusion as it moves westward with the surface current. The rate of diffusion will be decreased, since it will be mixing with bottom water that is already slightly contaminated. However, rough estimates indicate that none of the water in the target area will contain as much as 1% of the original concentration of contaminant, although higher concentrations may persist near the reef for another day.

The other end of the strip will have reached the southwestern passes at the end of the second day, and henceforth a small amount of radioactive material will be discharged from the lagoon on each ebb tide.

The nature of the diffusion process is such that the rates will decline rapidly after the first two days except insofar as random variations in current direction carry patches of contaminated water into uncontaminated areas, leading to rapid dilution. If the radioactive material were spread uniformly through the southern half of the lagoon, the concentration would be reduced to 0.1% of the initial value, but it seems unlikely that this could occur in less than one to two weeks. It is clear that the natural processes of current flow and vertical diffusion act together to maintain a gradient in concentration with the greatest amount in or near the target area, and the gradient will be destroyed only very slowly by horizontal diffusion and random variations in currents.

After the first few weeks, further dilution will take place only by tidal interchange. Since the major path of contaminated water lies south of the area of most complete stagnation, it is expected that the radioactive materials will be removed at least as rapidly as the average lagoon flushing rate of about 3% per day. This will require two and a half months to reduce the concentration by a factor of 10.

An unpredictable but probably small quantity of radioactive material will become attached to bottom sediments and sinking organic matter, from which it will be liberated gradually over a long period of time and will be a minor source of contamination, particularly in the eastern part of the lagoon where upwelling of bottom water is most pronounced. It is not expected to be of any practical significance at the surface but might be hazardous to diving operations.

5.EFFECT OF WEATHER ON LAGOON CIRCULATION AND DECONTAMINATION

The quantitative estimate of the decontamination rate presented in the previous section required certain basic assumptions about the weather, particularly as regards wind direction and speed. These factors are of the greatest importance in determining the circulation of the lagoon in general and the dissipation of radioactive products in particular. The calculation was based on what appeared likely to be the prevailing conditions at the time of the blast, namely an ENE wind with a speed of about 10 knots. Different conditions would require modification of the predictions, and over a limited range of variations the modifications can be made accurately. The effect on the lagoon of winds between 10 and 20 knots is well known. The curves can be extrapolated to 5 knots with no great error. These are simply questions as to rates of diffusion and water transport.

The curves previously shown in Figure 8 are a fair indication of the effect of wind on current transport. With winds of 5 knots, the rate of flow of the surface current would be reduced to 0.1 to 0.2 knot, and it would require three or four days for the contamination to spread the full length of the lagoon. Horizontal and vertical diffusion would also be reduced. The east-west gradient in radioactive products would be less pronounced. Upwelling of bottom water in the eastern end of the lagoon would be likely to produce patches of water with high concentrations of contaminant for three days or more.

With a 20 knot wind on the other hand, the rate of flow would be increased to 0.5 knot, and the contaminant would spread across the lagoon in about one and a half days, but the east-west gradient would be stronger and more persistant.

Since the available weather data indicate a decrease in wind velocity during the summer and a shift in the average direction toward the east or southeast, it is barely possible that the test might come at a time when these changes are extreme, namely no wind or a southerly wind. There has been no opportunity to determine what would happen in such cases. Any predictions are largely speculatory, but a few general comments can be made.

It is believed to require twelve to twenty-four hours for a wind driven current to be generated or for it to cease when the wind stops. Therefore in a prolonged period of calm weather the rotary circulation of the lagoon would soon be destroyed. There would remain only the slow movements generated by tidal interchange. Vertical and horizontal diffusion would be greatly reduced. It seems likely therefore that a large concentration of

contaminant would remain in the target area and the latter would be unsafe for re-entry until wind currents were again generated.

A southerly or southeasterly wind would change the direction of the lagoon circulation but otherwise would not change the previous description of the spread of radioactive products. It seems possible although by no means certain that the rate of flushing of the lagoon would be drastically altered if southerly winds persisted long enough to alter the direction of the oceanic current outside. The most likely guess is that water would then flow in constantly along the full length of Enyu Channel at a rate of about 10% of the lagoon volume per day and would be flushed out by tidal interchange across the northern and western reefs and through the southwestern passes. This would rapidly clear the target area and triple the observed rate of flushing.

Veering winds during or after the tests would alter the direction of flow of the currents so that the path of contaminated water would no longer be a straight line across the lagoon and back. This would increase the horizontal spread of radioactive materials, and the rate of vertical diffusion would be maintained at the initial high level for a longer period of time. The net result probably would be that the rate of dilution during the first few hours or the first day would not be greatly altered but that subsequent dilution would be greatly accelerated.

6. APPENDIX ON OCEANOGRAPHIC METHODS

6.1 Current measurements

Measurements of surface currents were obtained by the current pole method. The poles were 12 to 16 feet long. Some of them were four inches square; others were made of smaller strips of wood with aluminum fins inserted to increase the cross-sectional area. They were weighted so as to hang vertically with about one foot exposed above the surface of the water. A light aluminum staff was rigged to the upper end of each pole, bearing some device to aid in sighting the pole. Various methods used at one time or another or in combination were pennants, life jacket dye marker (bags of fluorescein, which left a trail of green dye in the water), lights, and radar reflectors. Three or four poles were used simultaneously. They were set out one to two miles apart, and their position was determined every few hours by coming alongside and taking bearings on beacons or other landmarks. At night, and at considerable distances from land, radar ranges were used for obtaining fixes.

Along the reefs and in the channels, the currents were studied by dropping dye bombs from an airplane and photographing the dye patches at frequent intervals over a period of 15 to 30 minutes. It was largely the surface currents that were measured by this method, but packages of dye lashed to the bombs left a trail in the water as the bombs sank, permitting some conclusions as to subsurface currents. The dye bomb method proved to be particularly useful on the reefs and in any circumstance in which a high degree of variability required a large number of nearly simultaneous observations.

Vertical profiles of current velocity were obtained with a Von Arx current meter. It consisted of a propellor mounted in a tube oriented to the current by means of a vane on one end. Each turn of the propellor induced a small electrical potential that was used to determine the number of revolutions, from which the current velocity was computed. The current direction was determined by observation of the vane through a water glass. The current was measured at depth intervals of 5 to 20 feet from the surface to bottom. The direction could be determined to a depth of about 150 feet, the limit of visibility in the lagoon waters. An underwater floodlight was used for night stations. It was necessary to exercise considerable care in the current meter work since swinging of the ship at anchor introduced an error. Dye marker and the cable angle were used to determine the times when valid measurements could be made.

6.2 Measurement of temperature and chemical constituents

The distribution of temperature and chemical constituents has provided information on diffusion rates, lateral mixing, and currents. Reversing thermometers and Nansen bottles were used to measure the temperature and collect a water sample at any desired depth. The Nansen bottle is a tubular instrument with a valve at each end. The bottle is lowered with the valves open so that the water passes freely through the bottle. A "messenger" sent down the wire trips a mechanism which releases the upper end of the bottle so that it turns upside down, closing the valves and entrapping a water sample. The thermometer mounted on the side of the Nansen bottle is designed so that turning it upside down breaks the thread of mercury, and the thermometer records the temperature at the time of reversal.

The salinity of the water samples was determined by the Knudsen method based on a chloride titration with silver nitrate. The Winkler method was used for oxygen analyses, and the Atkins-Deniges method for phosphate.

6.3 Tides and swell

Tides were measured by two standard tide gauges. One was located in shoal water in the eastern part of the lagoon near Bikini Island, the other on the outer reef. Portable 24-hour gauges were also used occasionally in various places. Swell was computed from an instrument which measured short period pressure fluctuations on the bottom in shoal water.