RADIOLOGICAL AND CHEMICAL STUDIES OF GROUND WATER AT ENEWETAK ATOLL
2. Residence Time of Water in Cactus Crater

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GROUND WATER AT ENEWETAK ATOLL
## 2. Residence Time of Water in Cactus Crater

ABSTRACT

This is the second in a series of reports on a ground water study at Enewetak Atoll conducted jointly by the Lawrence Livermore Laboratory and the University of Hawaii under the sponsorship of DOE division of Biology and Environmental Research. The purpose of this study is to provide data characterizing ground water for possible use by returning Marshallese and to investigate the hydrology and recycling of radionuclides in an atoll environment. This report describes fluorescent dye tracing used to assess the flushing characteristics, dilution rate, and water dispersal in Cactus Crater. A simple model explains experimental observations in terms of tidal effects. The mean residence time of water in the crater is about 2.6 days, depending on the tidal range; mixing is complete within 24 hours and water loss occurs mainly by overflow at high tide. This paper also addresses possible consequences of filling the crater with contaminated soil for disposal.

INTRODUCTION

From 1948 to 1958, Enewetak Atoll in the Marshall Islands, U.S. Trust Territory of the Pacific Islands, was the site of 43 nuclear explosions, 24 of which occurred on or near Runit Island on the eastern side of the atoll. Two events, Lacrosse in 1956 and Cactus in 1958, left water-filled craters on the northern tip of the Runit ocean reef (Fig. 1). The west side of Cactus is easily reached by a jeep road with a small beach at the end.

Preliminary experiments, some of which are described in Ref. 1, showed that Cactus Crater was a suitable natural aquarium in which to study radionuclide cycling in a marine environment. The nuclides ^{60}Co, ^{102m}Rh, ^{137}Cs, ^{155}Eu, $^{238,239,240}Pu$, and ^{241}Am exist in the range of a few tens of picocuries per gram in the sediments; in addition, the sheltered location and convenient volume of the crater make both chemical and biological experiments feasible.
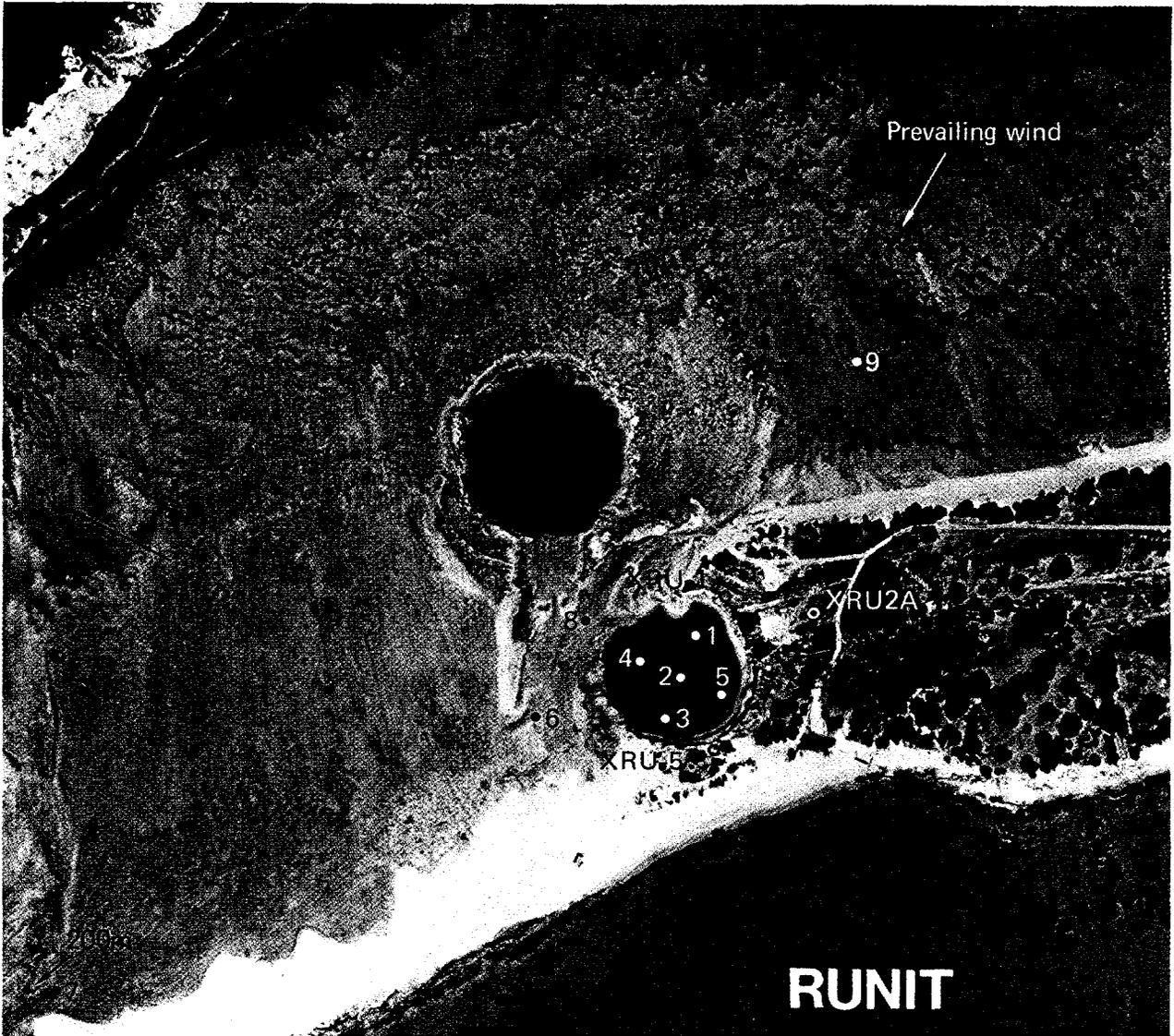
- **Open water sampling stations**
- **Well sampling stations**

Fig. 1. Northern end of Runit Island. Lacrosse is the upper crater, Cactus the lower. The lagoon is at the bottom of the picture. Tide height is about 2.5 ft.

Samples of indigenous periphyton and Helimeda algae show levels of a few picocuries per gram of most of these isotopes, and water concentrations range from 0.01 to 0.1 pCi/l.

The crater is also part of the northern Runit groundwater system that has been under study since early in 1974 as part of a larger program in atoll hydrology.[2,3] A knowledge of the flushing characteristics of the crater is therefore desirable both for experiments conducted within the crater as well as to assess the

hydrodynamics of the groundwater system. Fluorescent dye tracing was used to evaluate the flushing characteristics, dilution rate, and water dispersal on the northern reef of Runit Island.
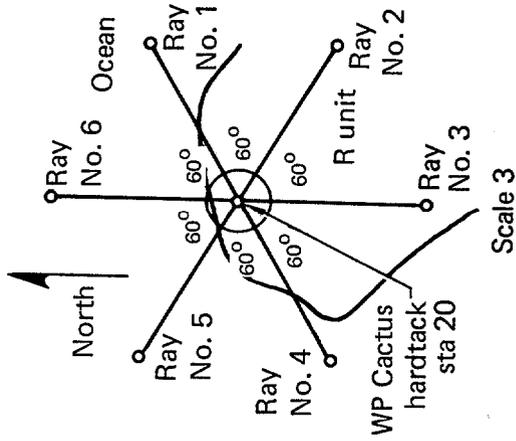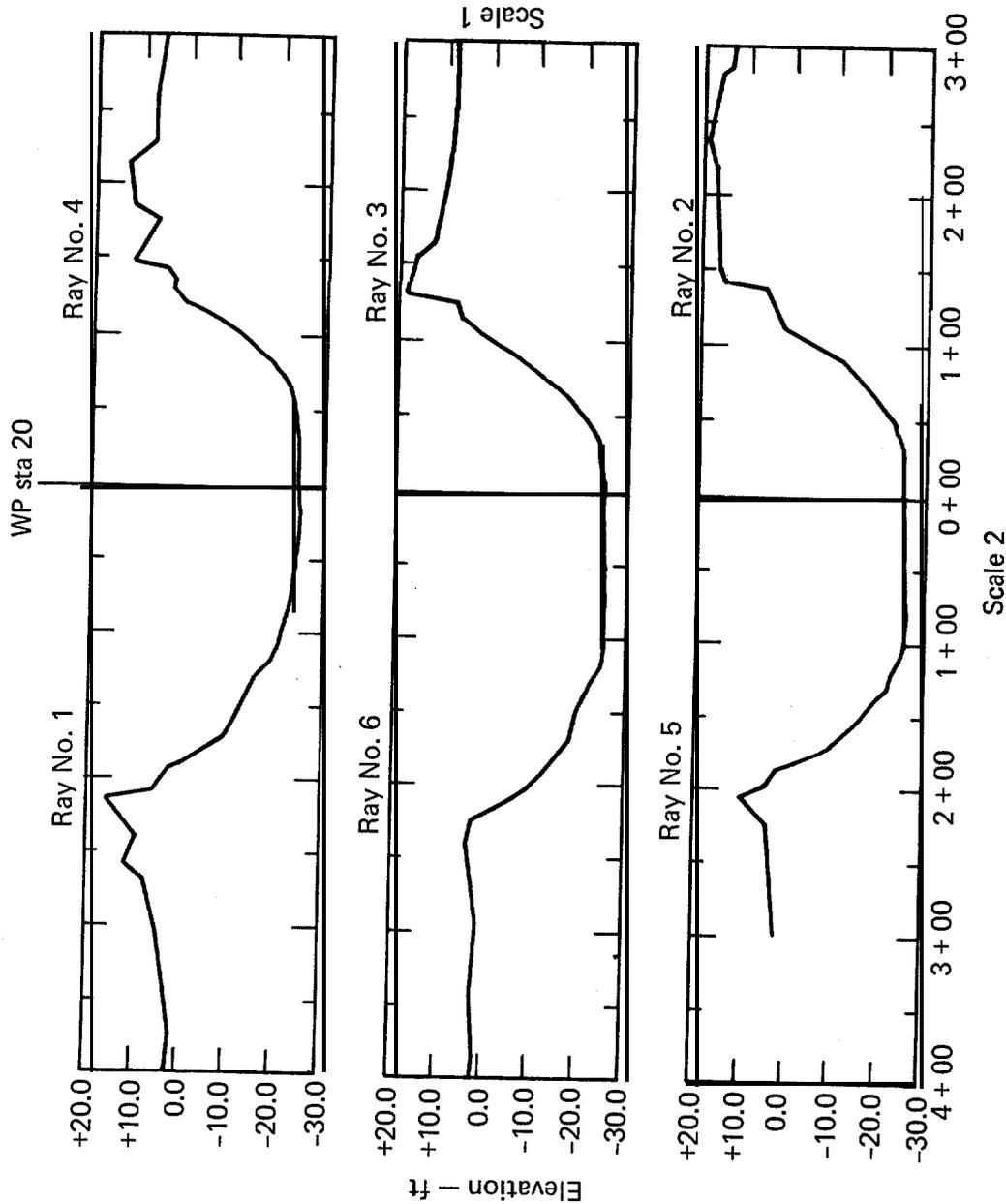
As a result of the general clean-up operations in preparation for the return of the native population to Enewetak, a plan has been proposed to use the crater to dispose of Pu-contaminated soil. The crater would be completely filled and the study area lost. However, knowledge of the original hydrology can help predict migration patterns of any radionuclides subsequently released from the fill material to the subterranean water.

PHYSICAL CHARACTERISTICS OF CACTUS CRATER

Cactus Crater was formed in May 1958 by the 18-kt Cactus event detonated 3 ft above the surface of the island.[4] The profile of the resulting crater is shown in Fig. 2. The crater is awash at high tide, but at low tide it is effectively cut off from surface water recharge by a low sill on its northeast side. Crater volume is determined by estimating the slope of the sides, as well as the area of the bottom and the surface area as a function of tide height. Depending on how these estimates are made and whether the volume is calculated as the frustum of a cone or a spherical segment, a volume at mean sea level of 3 to $3.5 \times 10^4 m^3$ may be calculated with $3.26 \times 10^4 m^3$ as a reasonable average. A volume can be similarly calculated for any tidal height; Fig. 3 shows the variation of crater volume with the state of the tide, assuming a conical frustrum. Actually, the crater begins to overflow somewhere around a height of 1.3 ft and volume beyond this height represents water displaced.

Ocean

Ray No. 1

Ray No. 6

Ray No. 2

R unit

60° 60° 60°

60° 60°

60° 60° 60°

North

Ray No. 3

Scale 3

Ray No. 5

Ray No. 4

WP Cactus hardtack sta 20

Graphic scales

1. ⌐ 0 10 20 30 ft

2. ⌐ 0 30 60 90 ft

3. ⌐ 0 100 200 300 ft

Soundings were taken with lead line April 3, 1964.

Scale 1

Ray No. 4

WP sta 20

Ray No. 1

Ray No. 3

Ray No. 6

Ray No. 2

Ray No. 5

+20.0 +10.0 0.0 -10.0 -20.0 -30.0

+20.0 +10.0 0.0 -10.0 -20.0 -30.0

+20.0 +10.0 0.0 -10.0 -20.0 -30.0

Elevation — ft

3+00 2+00 1+00 0+00 1+00 2+00 3+00 4+00

Scale 2

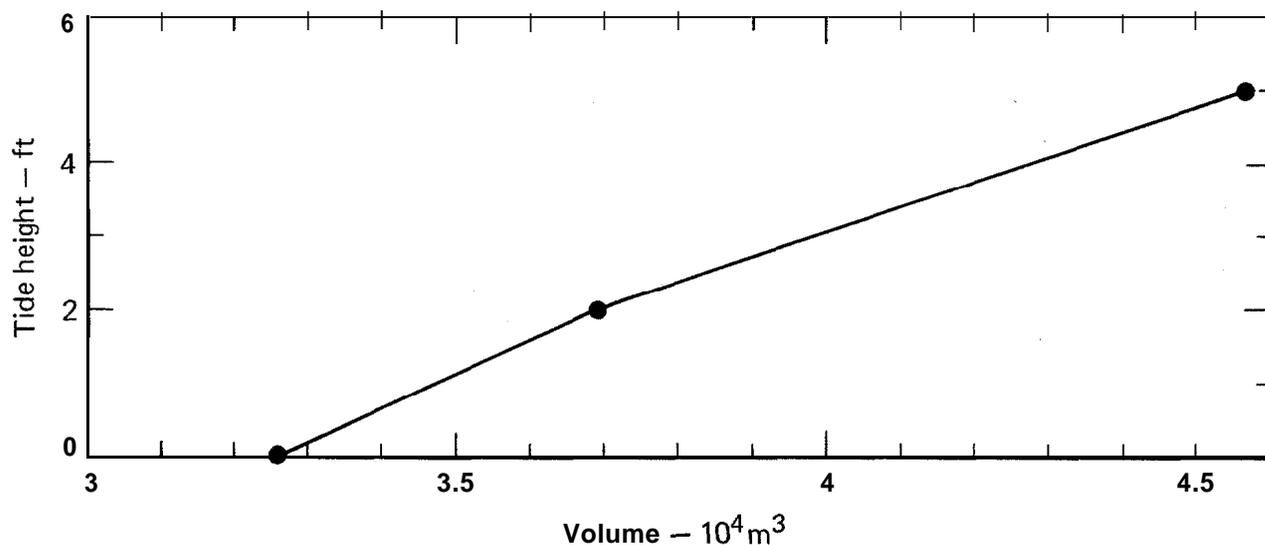Fig. 2. Profile of Cactus crater. Datum is mean sea level.

-4-

Fig. 3.   Apparent crater volume as a function of tide height.

EXPERIMENTAL

Several fluorescent dyes have been used for water tracing; however, only uranine and various forms of rhodamine are now widely used.   From the information in Ref. 5, we decided to use sulpho rhodamine B for the Cactus crater tracer study.   Subsequent to our work, Smart and Laidlaw[6] recently discussed the properties of eight fluorescent dyes for their utility in quantitative tracing work, including sensitivity and limits of detection, effect of water chemistry on fluorescence, photochemical and biological decay rates, adsorption losses on equipment and sediments, toxicity, and cost.   They concluded that rhodamine WT was slightly more cost effective than sulpho rhodamine B However, they also felt that, were

the approximately 25% higher cost per volume of water labeled not a factor, then sulpho rhodamine B would be a better choice because of its good adsorption resistance.   Thus, our choice of sulpho rhodamine B for the crater work has proved to be a good one even in the light of more recent data.

Sulpho rhodamine B has maximum excitation at 565 nm and maximum emission at 590 nm.   We measured fluorescence with a commercial filter fluorometer and a green phosphor lamp that provided continuous emission from 500 to 570 nm with a maximum at 530 nm; the mercury lines at wave lengths of 404, 436, and 546 nm were superimposed.   The primary filter was a combination of a Wratten 58 (peak

at 525 nm) and a Corning 1-60 (peak at 550 nm) that produced a narrow band-pass filter with a peak at 546 nm. The secondary filter was a combination of a Corning 3-66 plus a Corning 4-97 that produced a sharp cut-off between 580 and 560 nm. Figures 4a and 4b illustrate the optical properties of the composite primary and secondary filters as well as the relative excitation and emission spectra of sulpho rhodamine B. The overall combination of lamp, filters, and phototube gave a lower limit for reliable measurement of the dye of about 0.5 μg/l and a blank value of about 0.2 μg/l. Some of the blank resulted from light scattering in
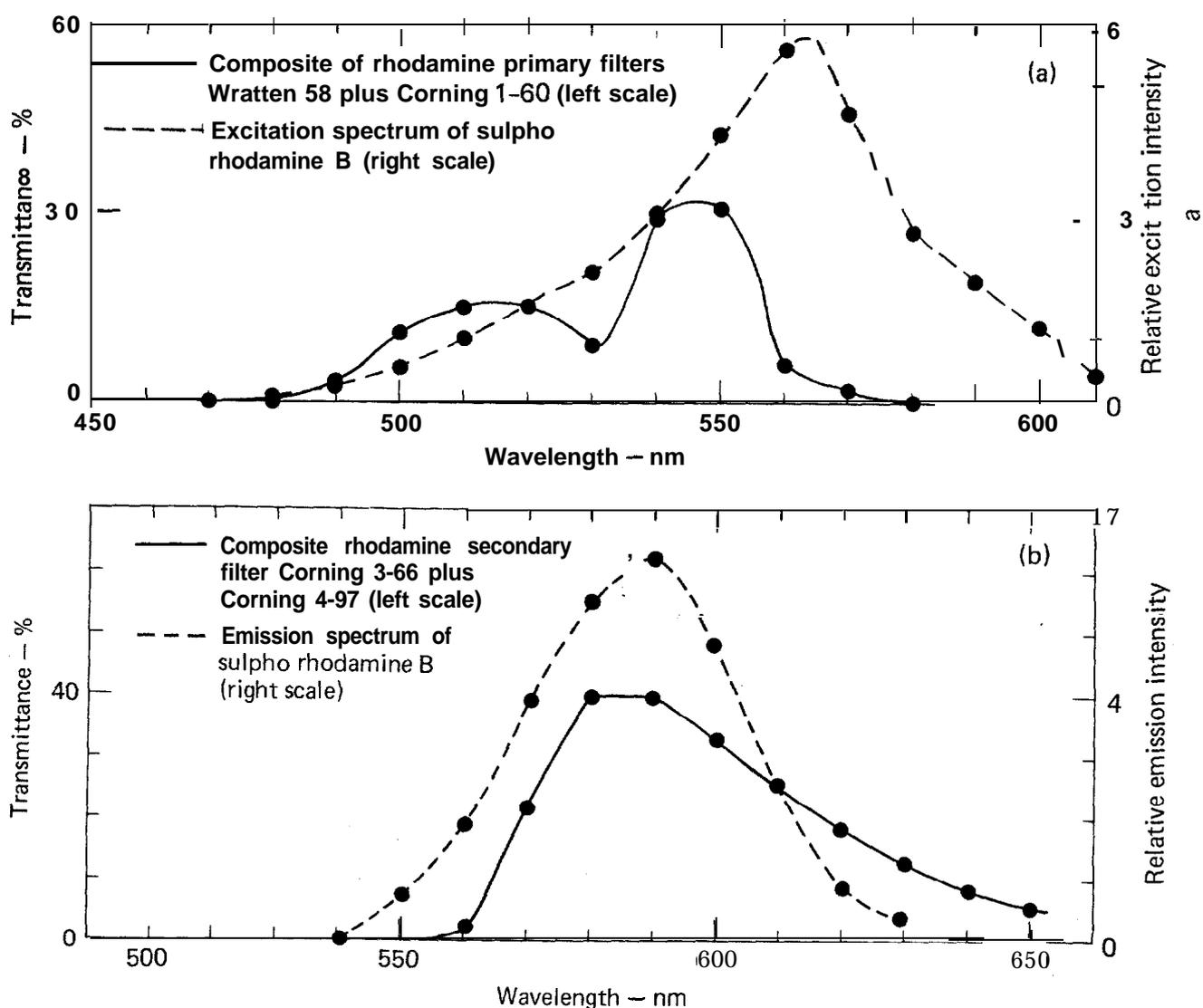

Fig. 4(a). Rhodamine excitation spectrum and transmission characteristics of fluorometer primary filter; (b) rhodamine emission spectrum and transmission characteristics of fluorometer secondary filter.

-6-

the samples but most was caused by fluorescence in naturally occurring compounds. The blank was practically negligible in open ocean seawater.

INJECTION METHODS

Three separate experiments were performed in April and October 1976, and May 1977. In the first feasibility experiment, approximately 150 g of sulpho rhodamine B were injected as seawater solution about 10 cm below the surface on the edge of the sand spit on the eastern side of the crater at low tide. In the second experiment, 2 kg of dye in seawater solution were injected on the surface at the crater center at low tide. For the third and most complete experiment, 2 kg of dye were dissolved in seawater in a plastic bag that was weighted and lowered to the bottom at the center of the crater at low tide. A diver then descended, opened the bag, and spread the dense solution over a few square metres to a depth of 1 to 2 m. An effort was made to keep the final injection volume as small as possible to estimate the time required to mix the dye uniformly throughout the crater.

SAMPLING STATIONS

Sampling stations were set up inside and outside the crater; their locations are shown in Fig. 1. The five stations inside the crater were placed to form an array parallel to and across the prevailing wind. These stations were located by lines stretched at right angles across two crater diameters; station numbers were marked by tabs attached to these lines. At each station, samples were taken at three depths: a few centimetres below the surface, approximately 10 cm off the bottom, and at an intermediate depth of either 2.7 or 5 m. They were collected by one or two people on a polystyrene raft equipped with a battery-operated pump and plastic tubing. Samples at all stations (including those outside) were collected in 60-ml amber glass bottles and stored out of direct sunlight.

The outer edge of the ocean reef is about 1 ft higher than the lagoon and water from waves breaking on the reef south and east of the crater flows in a current generally northwest along the reef. There is a channel between Cactus and Lacrosse through which a current 1 m deep and up to 1 m/s flows at high tide. The current joins with water flowing through and around Lacrosse and flows in a northwestern direction generally parallel to the sand spit. It finally exits into the lagoon through a break in the spit about 200 m northwest of the left edge of the picture in Fig. 1. Buoys were anchored at stations 6, 7 (not shown

in Fig. 1), 8, and 9 as reference marks and surface samples were collected in conjunction with the crater sampling. Station 6 was located in the reef flat away from the main stream of the along-shore current to sample water flowing directly downwind from the crater. At low tide, this station was usually dry. Station 7 was located at the break in the sand spit between the reef flat and the lagoon to measure the fraction of Cactus water flowing into the lagoon by this route. Water continuously flows through this break and it was expected that the fraction originating in Cactus crater would vary with tide height. If so, the level of radionuclides would vary considerably depending on the mix of ocean and reef water. In addition, schools of reef fish, a possible Marshallese food source, are frequently found here. Station 8 was set up in the channel between the two craters to sample the amount of Cactus water leaving by that path. Samples from station 9, located in the current upstream from Cactus, monitored the water entering the study area and would have detected any flow in this direction caused by eddies, effects of a receding tide, or a period of low winds. This station, like station 6, was usually dry at low tide. Samples were collected at stations 6 through 9 by merely wading into the water,

rinsing and filling a sample bottle a few centimetres below the surface.

In addition to the reef flat stations, samples were collected from wells around the crater perimeter. These wells are shown on Fig. 1 and were included as part of the general groundwater studies described in Ref. 2. To take the samples, a weighted bottle was lowered just beneath the water surface, retrieved, and emptied into an amber collection bottle.

TYPICAL TIDAL CYCLE IN CACTUS CRATER

At low tide, depending on the tide height, the water level in the crater is about 20 to 40 cm below the level of the reef flat on the north and northwest sides, and there is no visible flow either into or out of the crater. If water is flowing along the reef between the two craters, none enters Cactus. As the tide rises, the depth of the alongshore current increases and Cactus fills from the bottom until it joins the current through the small channel just southeast of station 8. At this time, there are a few centimetres of water on the reef around station 6. As the tide continues to rise, water begins flowing into Cactus over the sand spit on the eastern side, and finally, at higher tides, most of the northeast side is awash. The streamlines in Fig. 1 illustrate the

flow that starts counterclockwise around Cactus and then flows slightly northwest along the sand spit that separates the reef from the lagoon; the stream is joined all along its course by water flowing over the reef from waves breaking on the ocean side. This water finally exits into the lagoon through a narrow break in the sand spit (station 7). During the hours of highest tide, there is a strong flow across the northern quarter of the crater, driven by both the reef current and prevailing wind. As the tide recedes, the sequence of events is reversed until the crater is once more cut off from the reef.

RESULTS AND DISCUSSION

MECHANISM OF WATER LOSS

The third experiment in May and June of 1977 was the most extensive of the three. Table 1 presents a detailed account of the sampling results of this experiment, and Fig. 5 shows the tidal cycles during this time period. Samples taken prior to the dye injection indicate the level of background, or blank, and are essentially at the limit of detectibility for the fluorometer. The values probably represent a combination of natural fluorescence and a certain amount of scattering of the incident radiation by particulate material in the sample. The rather high values from XRU-1, -2A, and -5 probably represent natural fluorescence caused by the higher concentration of organic material in the ground water. These wells do show a considerable time lag
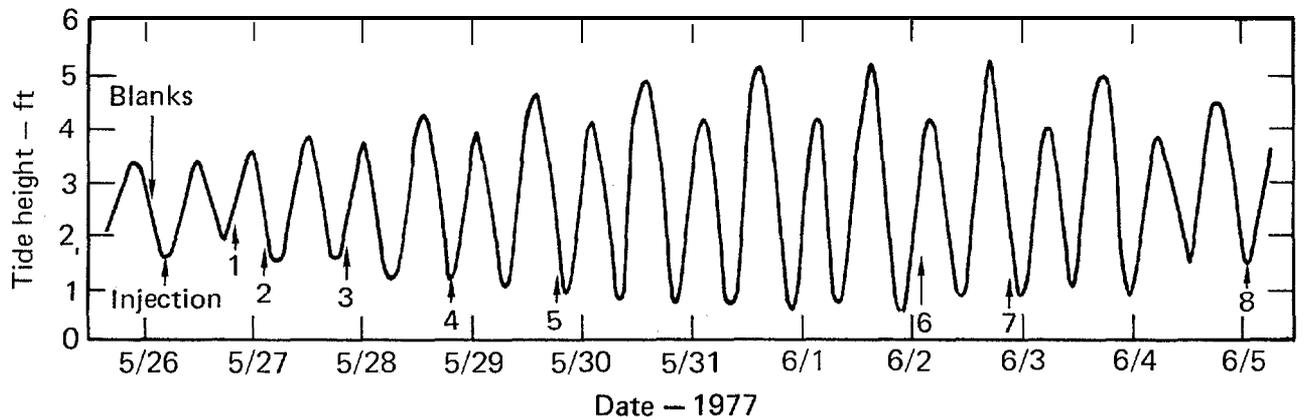

Fig. 5. Enewetak tides for the period from May 26 to June 5, 1977. Arrows indicate sampling times.

Table 1. Sulpho rhodamine-B concentrations (µg/ℓ), third experiment.

Date	Sampling time	Depth, m	Station 1	2	3	4	5	6	7	8	9	XRU-1	XRU-2A	XRU-5
Before dye injection														
5/26-77	1330-1430	Surface	-	0.15	-	-		0.05	-	0.25	0.20	1.05	0.93	1.13
After 2 Kg dye injected on the bottom at station 2 on 5/26/77 at 1700 hours														
5/27/77	0815-1024	Surface	41.0	43.6	50.0	45.0	43.6	0	2.3	2.45	0.04	0.88	1.70	1.05
		2.7	47.0	46.4	48.5	44.0	45.3							
		Bottom	34.9	66.0	37.2	35.2	37.5							
	1555-1640	Surface	38.1	37.0	35.5	35.0	36.9	30.0	15.8	18.2	0	0.73	0.83	0.89
		2.7	48.0	47.6	45.8	43.0	45.8							
		Bottom	62.0	40.8	38.5	42.3	56.5							
5/28/77	0825-1030	Surface	37.6	32.9	37.5	14.3	37.5	29.2	15.9	26.0	0.37	0.74	0.83	0.95
		2.7	35.0	37.2	34.3	34.1	38.1							
		Bottom	39.5	114.0	47.0	39.3	40.5							
5/29/77	0805-1000	Surface	24.5	24.4	24.4	24.0	25.5	9.6	17.2	23.4	0	2 15	0 78	.69
		2.7	24.1	25.5	23.5	23.9	24.0							
		Bottom	25.8	31.6	25.3	24.5	25.8							
5/30/77	0755-0920	Surface	15.9	17.0	17.8	16.6	16.0	11.1	10.4	17.0	0.10	3.50	0.80	1.15
		2.7	17.1	17.1	16.5	16.2	16.7							
		5.4	-	16.8	-	-	-							
		Bottom	16.4	16.1	16.4	17.2	16.5							

Table 1. (Continued)

Date	Sampling time	Depth, m	Station											
			1	2	3	4	5	6	7	8	9	XRU-1	XRU-2A	XRU-5
6/1/77	1405–1520	Surface	3.95	3.60	3.42	2.55	3.82	0.35	0.58	0.08	0.05	2.50	0.55	0.50
		2.7	6.15	6.10	6.98	7.05	6.28							
		5.4	.	6.89	–	–	–							
		Bottom	7.72	10.50	7.50	7.65	9.10							
6/2/77	0735–0850	Surface	u.82	4.42	4.30	4.34	4.33	2.84	0.78	u.50	0.35	3.49	0.87	1.28
		2.7	u.20	4.22	4.25	4.25	4.30							
		5.4	–	4.40	I	–	–							
		Bottom	5.12	10.40	u.70	5.00	4.30							
6/5/77	1455–1545	Surface	1.50	1.04	1.0	1.02	1.03	0.55	0.30	0.35	0.31	3.10	0.75	1.68
		2.7	1.60	1.24	1.07	1.10	1.15							
		5.4	–	1.20	–	–	–							
		Bottom	1.56	1.58	1.24	1.25	1.30							

for dye transfer from the crater and it is possible that the dye concentrations were still increasing when the experiment was concluded. It is then possible that the high blank values are remnants of the second dye experiment seven months previous; however, the apparent concentrations in these wells before the second experiment were about 0.5 $\mu g/l$. This concentration is almost certainly not an artifact of the first experiment when only 150 g of dye were used, but no samples were taken from these wells before the first dye injection in April, 1976.

Table 1 shows that water in the crater is completely mixed after 24 hours. The high value of 114 $\mu g/l$ at the bottom of station 2 on May 28 was due to a very localized high concentration area remaining at the injection point. A diver who inspected the bottom found several small pools of dye lying in pockets in the sediment and several areas of sediment where the dye had concentrated in spite of its nonadsorption characteristics. However, the total amount of dye not dispersed was only a few grams and did not appreciably affect the overall results of the experiment. Elevated concentrations persisted on the bottom at station 2 throughout the experiment. On May 28 and June 1 the surface samples at station 4 were

low relative to the other surface stations. Both of these samples were taken at relatively high tide, 2.3 and 3.0 ft, respectively, and were probably diluted somewhat by reef water flowing into the crater. However, the first sample from station 4 (taken on May 27 at 0815 hours) was also taken at a tide height of 2.8 ft, but for some reason the concentration was not unusually low. All other samples were taken when the tidal level was below 2 ft.

As expected, dye concentrations in stations outside the crater varied considerably more with time. Several of the stations, however, showed surprisingly high concentrations, in several cases approaching concentrations in the crater itself. While a rigorous comparison of concentrations at stations 6 through 9 with those inside the crater would have to consider a time lag due to flow and mixing rates, these effects appear to be negligible, even in the case of station 7. The flow time from station 9 to 6 is only about 5 to 10 min and the turbulence caused by the rough reef surface aids in mixing. After the tide has risen enough to connect the crater with the reef, there is essentially no time lag from the crater to stations 6 and 8. Also, at this time the alongshore current is reaching its maximum velocity and the

time difference to station 7 is probably 15 to 20 min at most with turbulence assuring good mixing of the fresh wave-deposited ocean water and the crater water. Because the crater water mixes with the reef water mainly during the hours of highest tide, no allowance has been made for sampling time differences.

Station 9, upwind and up-current from the crater, always had a low dye concentration. The range from 0 to 0.35 μg/l probably reflects natural background variation more than anything else. Stations 6 through 8 all showed much higher concentrations and Table 2 gives these as a percent of the crater concentration at the time of sampling. Only a very general pattern can be discerned from these stations. Stations 6 and 8 show high concentrations with 8 higher than 6

on the average. There is a slight inverse tidal dependence with the highest concentrations occurring on the lower tides and lowest concentrations at higher tides. This is, of course, explained by addition of untraced ocean reef water as the tide rises. At a tide height of about 1.2 ft, the crater is just awash and visual observation shows the dye flowing out the sill and through station 8. The fluorescence data confirm that most of the water at station 8 at this time comes from the crater. In the case of station 7, a somewhat clearer trend of dye concentration that varies inversely with the tide is seen. On its way to station 7, there is much more opportunity for the crater water to be diluted by wave-deposited untraced water. Again, a tide height of 1.2

Table 2. Reef station dye concentrations vs crater concentration and tide height.

Date	Sample time	Crater avg., μg/l	Station, % of crater			Tide height, ft
			6	8	7	
5/27	0900	44	0	5.6	5.2	3.0
5/27	1620	44	68.2	41.4	35.9	2.0
5/28		36	81.1	72.2	44.2	2.2
5/29		25	38.4	93.6	68.8	1.3
5/30		16	69.4	100.0	65.0	1.3
6/1		5.8	6.0	0	10.0	3.0
6/2		4.6	61.7	100.0	17.7	2.3
6/5		1.2	45.8	29.2	25.0	1.5

ft produces the highest concentrations of Cactus water at station 7 with a dilution of less than a factor of two all the way from station 8. Certainly, a large amount of the water in Cactus crater ultimately finds its way into the lagoon through this path.

Well sample data (Table 1) indicate very little mixing of the crater water into the ground water system, adjacent to the crater. Data from tide gauges show no tide lag between these wells and the lagoon so there is no hydrostatic head to aid the diffusion of the water out of the crater. XRU-1 showed a small but definite amount of dye intrustion after three days, while XRU-2A, which was much further from the crater, showed no real evidence of dye. It was thought that water might flow from the crater into the lagoon through the uncompacted reef, but data from XRU-5 did not confirm this. Taken together, these data indicate that most water lost from Cactus crater flows over the sill at high tide and continues northwest along the reef into the lagoon at the break.

RESIDENCE TIME OF WATER IN
CACTUS CRATER

Because the crater is well mixed and loses water principally by overflow during the rising tide, a rather simple model should describe the observed rate of dye loss. In this model, starting at low tide, the dye concentration falls as the tide rises and untraced water flows into the crater through the reef below the surface. This dilution continues with no loss until the crater begins to overflow. Further rising of the tide displaces water from the crater to the extent that the tidal rise is greater than the level at which the crater overflows. Dye is lost until, as the tide falls, the water level in the crater drops below the overflow level. No further loss then occurs until the next high tide. The critical parameter in this model is the tide height at which significant overflow and loss begins. We have considered two cases. In the first, we assume that loss begins as soon as the tide begins to rise; that is, water is displaced from the crater to the full extent of the tide. The second case allows for the fact that the crater has a lip of about 30 to 40 cm but this lip is somewhat permeable and its effective height is about 15 cm. In this case, flushing occurs only to the extent that the tide rises above 15 cm.

For simplicity, dye loss and concentration are calculated in steps at each tide change rather than continuously. The results for each case are shown in Table 3. For example, in the first case, 2 kg of dye are

Table 3. Calculated dye concentrations for experiment 3.

				No crater lip		15-cm lip
		Tidal	Crater volume,	Remaining dye,	Dye concentration,	Dye concentration,
Date	Time	height, ft	1×10^7	g	μg/l	μg/l
Before dye injection						
5/26/77	0443	2.1	3.72			
	1056	3.5	4.14			
After 2 Kg injected at 1700 h						
	1738	1.7	3.62	2000	55.2	55.2
5/27/77	0007	3.5	4.14	2000	48.3	49.9
	0619	1.9	3.67	1772	48.3	
	1221	3.6	4.16	1772	42.6	45.4
	1848	1.5	3.57	1521	42.6	
5/28/77	0111	3.9	4.25	1521	35.8	39.4
	0728	1.6	3.59	1285	35.8	
	1324	3.8	4.22	1285	30.5	34.5
	1938	1.2	3.50	1066	30.5	
5/29/77	0201	4.3	4.37	1066	24.4	28.5
	0824	1.2	3.50	854	24.4	
	1417	4.0	4.28	854	20.0	24.0
	2026	1.0	3.45	688	20.0	
5/30/77	0246	4.7	4.48	688	15.4	19.1
	0911	0.9	3.44	529	15.4	
	1507	4.2	4.34	529	12.2	15.6
	2111	0.8	3.41	415	12.2	
5/31/77	0329	5.0	4.57	415	9.1	12.0
	0956	0.7	3.39	308	9.1	
	1550	4.2	4.33	308	7.1	9.66
	2151	0.7	3.39	241	7.1	
6/1/77	0409	5.2	4.62	241	5.2	7.29
	1038	0.5	3.35	175	5.2	
	1635	4.2	4.33	175	4.0	5.82
	2233	0.7	3.39	i37	4.0	

Table 3.   (Continued)

| | | | | No crater lip | | 15-cm lip |
Date	Time	Tidal height, ft	Crater volume, 1×10^7	Remaining dye, g	Dye concentration, µg/1	Dye concentration, µg/1
6/2/77	0451	5.2	4.62	137	2.96	4.39
	1122	0.5	3.35	99	2.96	
	171.8	4.2	4.33	99	2.28	3.50
	2313	0.8	3.41	78	2.28	
6/3/77	0532	5.2	4.62	78	1.69	2.66
	1205	0.7	3.39	57	1.69	
	1802	4.0	4.28	57	1.33	2.17
	2355	1.0	3.45	46	1.33	
6/4/77	0614	4.9	4.54	46	1.01	1.70
	1250	0.8	3.41	35	1.01	
	1846	3.8	4.22	35	0.83	1.42
6/5/77	0037	1.2	3.50	29	0.83	
	0657	4.5	4.42	29	0.65	1.16
	1335	1.2	3.50	23	0.65	
	1934	3.6	4.16	23	0.55	1.00

injected when the tide is 1.7 ft and the crater volume is 3.62×10^7 1. Total dye is 2000 g and concentration is 55.2 µg/1. As the tide rises, this 2000 g is diluted to 4.14×10^7 1, giving a concentration of 48.3 µg/1. As the tide falls to 1.9 feet, the volume drops to 3.67×10^7 1, the difference of 0.47×10^7 1 being lost to overflow. At a concentration of 48.3 µg/1, this is a loss of 228 g, leaving 1772 g at the same concentration. This is diluted to 42.6 µg/1 in the next high tide with another

251 g lost, and so on. In the second case, the calculation is made in the same way but the volume for each tidal difference is reduced by 0.13×10^7 1, which is the average change in volume per 15-cm change in tide. This allowance reduces the flushing rate somewhat.

The last two columns of Table 3 give the dye concentrations for each tidal cycle for the two cases.

Figure 6 shows the agreement between the observed dye concentrations and the two model calculations for
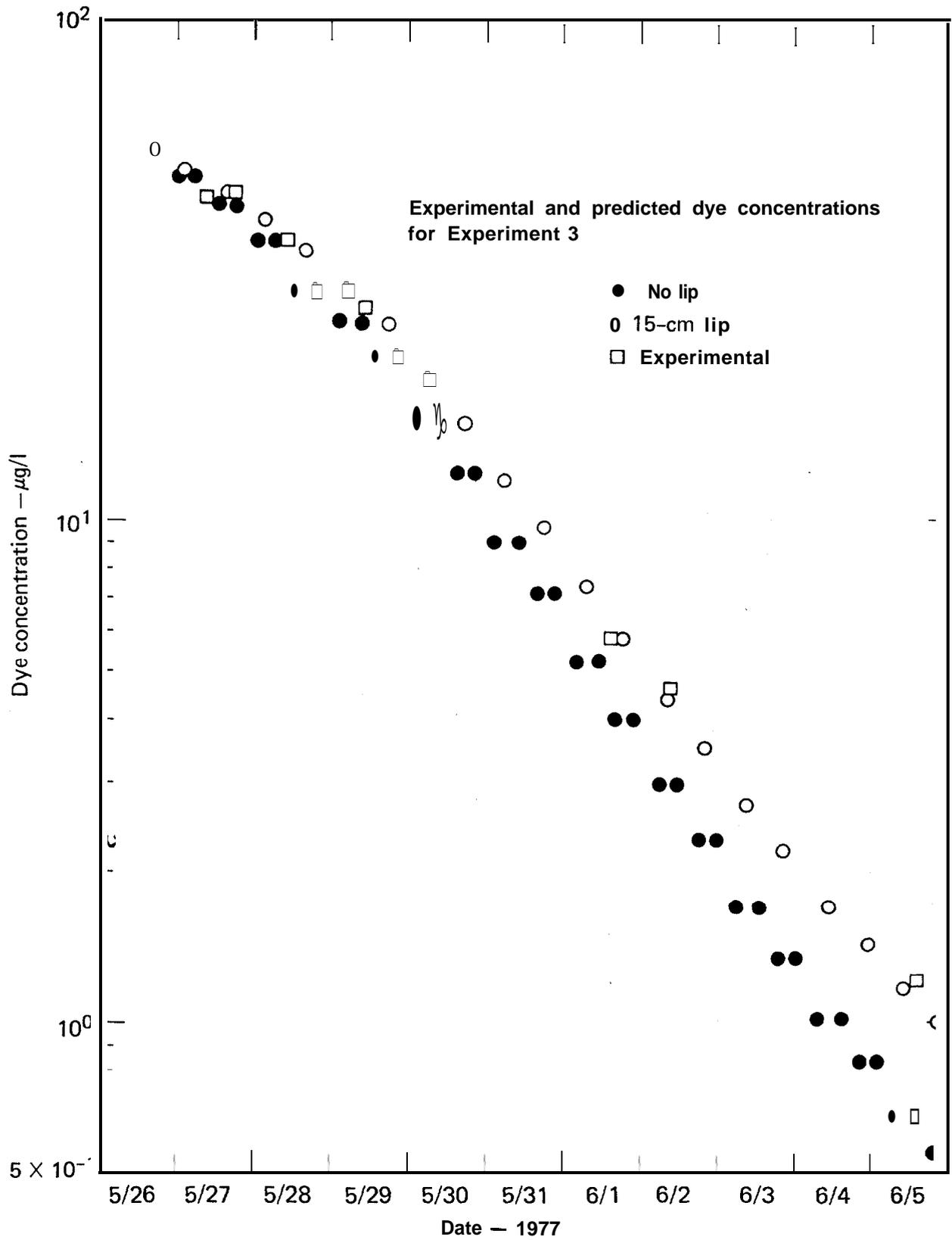
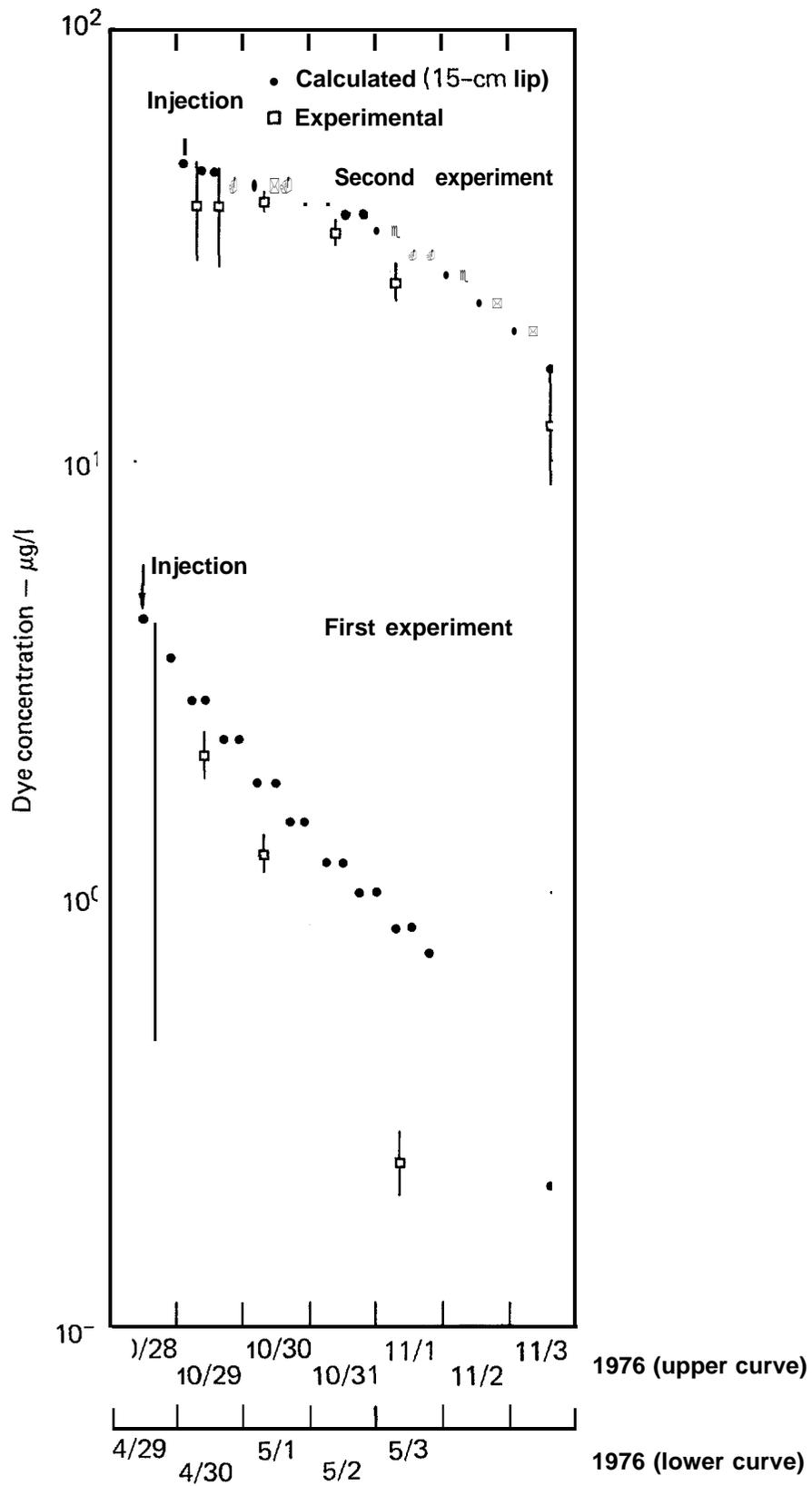Fig. 6. Experimental and predicted dye concentrations for experiment 3.

Fig. 7. Experimental and predicted dye concentrations for experiments 1 and 2.

experiment 3. The agreement is quite close for the 15-cm-lip model in both shape and absolute magnitude. It is encouraging that even the changes in slope around May 29 and less pronounced on June 5 caused by the onset of changes in tidal range (Fig. 5) are reproduced. The values plotted are the grand average values for all stations and depths at each sampling time. Figure 7 presents similar data for the first two experiments. In experiment 2, the shape is predicted reasonably well, again including a change of slope caused by tidal effects beginning on October 31, but the experimental points fall somewhat below the predicted. This is probably caused by the fact that this injection was on the surface in the center, and therefore some dye was lost before it was completely mixed. In fact, if about 200 g of dye out of 2 kg were lost in this way (a very plausible assumption), the predicted curve would be 10% lower and agreement would be much better. In experiment 1, with a surface injection of 150 g directly upwind of station 4, a loss of about 30% of the

dye before mixing would be needed to account for the observed differences. This is also a reasonable figure because at high tide there is a strong flow directly through this section of the crater. The last point from experiment 1 is just barely detectable and it is thus possible that the blank correction was too large.

Large error bars on the early samples from experiments 1 and 2 are caused by the fact that these samples were taken about 6 h after injection before complete mixing had occurred.

From the slopes of the curves in Figs. 6 and 7, a mean residence time of water in the crater can be calculated. Experiment 1 gives 1.69 days, experiment 2, 3.13 days, and experiment 3 gives 2.41 days for the last eight days and 3.36 days for the first two days. Thus, residence time is a function of tidal range, but the model could predict residence for any period with available tidal data. Without such information, an average value of 2.6 days would yield a good estimate averaged over about a month.

SUMMARY AND CONCLUSIONS

We have successfully used sulpho rhodamine B to determine the mixing rate, loss mechanism, and residence time of water in Cactus crater. Mixing is complete within 24 hours from a single point dye injection, whether surface or bottom. Water is mainly lost from the crater by overflow during periods of high tide, and most eventually flows into the lagoon through a break in the sand spit some 800 m northwest of the crater. Very little crater water either enters the island's ground water system or flows subterraneally into the lagoon.

We developed a simple model to explain our observations in terms of tidal effects: crater water is diluted by subterranean flow during a rising tide, overflows onto the reef during high tide, and subsequently subsides with no further water loss during the ebb tide. This cycle adequately explains the observed rate of dye loss and the mean residence time, which varies with the tidal range for the period in question. In the absence of detailed tidal data, an average value of 2.6 days is suggested for periods long enough to encompass both low and high range cycles.

APPENDIX: HYDROLOGICAL EFFECTS OF FILLING CACTUS CRATER

Present plans call for using the crater as a disposal site for some of the more Pu-contaminated soil on Runit. A soil-cement slurry would be deposited in the crater, possibly after first sealing the sides with hydraulic cement. The amount of soil would exceed the volume of the crater and the resulting fill would form a domed structure capped with high-strength concrete. Radionuclides released from the fill material could be lost by some version of the present overflow mechanism, or different loss mechanisms might become important depending on the stability of the fill.

If the fill mixture remained monolithic, presumably all radionuc-lides would be retained after a short period of surface leaching. However, it is probable that the material would not remain intact for a time compar-able to the half-life of ^{239}Pu. The underlying and surrounding reef structure is quite unconsolidated and may not be capable of supporting the weight of the fill for an extended time. Finally, constant wave and tidal action may in time create cracks and channels in the material itself. If this happens, the ori-ginal overflow path could be reestab-lished or new pathways into the groundwater could be formed.

If a relatively impermeable layer were to become sandwiched between two permeable ones, then during each high tide, water might be pumped from the lower to the upper stratum through cracks in the impermeable layer. The return path during the ebb tide might be quite different and this process could transport water through the crater fill material and into the island water table. The ground-water in the area immediately south-east of the crater flows generally southwest into the lagoon[3]. If the present overflow path northward were effectively blocked, this route could become the principal exit for any material leached from the crater fill. A process such as this could possibly result in higher levels of radionuclides in the Runit groundwater than presently exist.

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