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STATE OF CALIFORNIA

THE RESOURCES AGENCY

STATE WATER QUALITY CONTROL BOARD

AN INVESTIGATION ON THE FATE OF ORGANIC AND INORGANIC WASTES DISCHARGED INTO THE MARINE ENVIRONMENT AND THEIR EFFECTS ON BIOLOGICAL PRODUCTIVITY

1965

Publication No. 29

STATE OF CALIFORNIA

EDMUND G. BROWN
Governor

THE RESOURCES AGENCY

HUGO FISHER
Administrator

———

STATE WATER QUALITY CONTROL BOARD

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STATE OF CALIFORNIA

THE RESOURCES AGENCY

STATE WATER QUALITY CONTROL BOARD

AN INVESTIGATION ON THE FATE OF ORGANIC AND INORGANIC WASTES DISCHARGED INTO THE MARINE ENVIRONMENT AND THEIR EFFECTS ON BIOLOGICAL PRODUCTIVITY

1965

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—January, 1965

FOREWORD

The State Water Quality Control Board, after sponsoring in 1954 an exploratory investigation of all aspects of the submarine outfall disposal of domestic wastes, contracted for research in various specific fields where oceanographic studies were needed. Among these studies, a major project was an oceanographic and biological survey of the Southern California mainland shelf undertaken by the University of Southern California, Allan Hancock Foundation, during the period of 1956–61.

Early in 1961, the Allan Hancock Foundation proposed a cooperative research program relative to marine disposal of wastes, going beyond the previous studies conducted for the State Board. The principal aim was the investigation of the fate of organic waste and nutrient substances in the sea and their relationship to biological productivity. The project was undertaken during the fiscal years of 1961–62 through 1963–64 with the largest share of financial support by Demonstration Grants from the U. S. Public Health Service. The State Board participated in support of those portions of the program which would have the most direct and immediate applications to water pollution control problems. Dr. Leslie A. Chambers, Director of the Hancock Foundation, was Project Director. The research program was conducted under the supervision of Dr. Richard B. Tibby.

The succeeding pages present the contractor's final project report for the State Board, dated September 15, 1964. Background information is given in the Introduction of the report. The final chapter, Summary and Conclusions, covers the four aspects of waste fields in open coastal waters which were investigated.

Printing and distribution of the report as Publication No. 29 was authorized by the State Board on November 25, 1964.

The investigations reported herein were conducted under the sponsorship of the State Water Quality Control Board (formerly the State Water Pollution Control Board). The investigations and their direction were under the responsibility of the University of Southern California, Allan Hancock Foundation. The conclusions and recommendations are, therefore, those of the research contractor, and do not necessarily reflect opinions or policies of the State Water Quality Control Board.

FINAL REPORT

ON

AN INVESTIGATION ON THE FATE OF ORGANIC AND INORGANIC WASTES DISCHARGED INTO THE MARINE ENVIRONMENT AND THEIR EFFECTS ON BIOLOGICAL PRODUCTIVITY

by the

ALLAN HANCOCK FOUNDATION

UNIVERSITY OF SOUTHERN CALIFORNIA

for the

CALIFORNIA STATE WATER QUALITY CONTROL BOARD

STANDARD AGREEMENT NO. 12-17

September 15, 1964

FINAL REPORT

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STANDARD AGREEMENT NO. 12-17

September 15, 1964

February 2, 1965

Mr. Paul R. Bonderson,
Executive Officer
California State Water Quality Control Board
1416 Ninth Street, Room 855
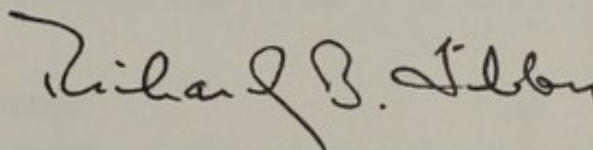Sacramento, California 95814

Dear Mr. Bonderson:

   We are pleased to submit this Research Report on selected aspects of the biological, chemical, and physical behavior of waste fields in open coastal waters, knowledge of which can be generally applied to the solution of marine waste disposal problems. The investigations were conducted under Standard Agreement No. 12-17 from the California State Water Quality Control Board, and under Demonstration Grant WPD-01-63 from the United States Public Health Service, Division of Water Supply and Pollution Control.

   The biological portion of the program was directed mainly toward establishing the effects of waste discharge on primary phytoplankton productivity. One of the unique features of the biological work, and the one which makes the results more generally applicable, was the determination of the time-sequence rather than the spatial distribution of biological and associated chemical events within an open, dispersing field. The measured effects, therefore, are independent of local differences in current systems and other such hydrographic conditions that have, in the past, imposed severe limitations on the usefulness of the studies and predictions based solely on spatially static surveys and on empirical distance-relationships. Also, it has been shown that appropriate methods for identifying a waste field and for following its subsequent trajectory are not only feasible but should be more widely adopted for field studies on biological, chemical and other changes associated with waste discharge.

   The initial success of the dye techniques in this program soon led to a greatly expanded effort in both theoretical and empirical studies on the phenomenon of eddy diffusion. For the most direct purposes of the governmental agencies which have supported the program, these diffusion studies have led in some cases to confirmation in the field of the validity of certain theoretical equations for calculating diffusion, and in other cases to new information and methods, both of which will increase the confidence with which engineering predictions can be made of the dispersal of waste fields.

   Primary productivity and eddy diffusion also are of considerable interest in their own right as fundamental processes in the sea, and it is hoped that the results of this research program are of some basic, as well as technological, significance.

Sincerely yours,

Richard B. Tibby, Ph.D.
Oceanographer

RBT:ak

ACKNOWLEDGEMENTS

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1. OBJECTIVES

The objectives of this phase of the research activities for the past three years are summarized as follows:

1. To develop equipment and devise methods to be applied to the quantitative study of the dilution and dispersion of a surface waste field in the sea.

2. To furnish dilution data for concurrent studies on the fate of organic and inorganic nutrients discharged into the sea, and their effects on plankton productivity.

3. To investigate some of the current statistical models of turbulent eddy diffusion and to substantiate the applicability of these models to the cases of instantaneous and continuous release of dye from a point source in the sea.

4. To determine the effect of wind, water column stability and sea conditions on the rate of physical dilution of a waste and on related diffusion parameters, with particular attention to the role of vertical eddy diffusion in the overall dispersion process.

5. To apply the results of the dye studies to the actual dispersion of a large scale surface waste field in the sea.

2. EQUIPMENT AND METHODS

Instrumentation

During this investigation considerable time and effort were expended on the improvement and modification of tracer detection equipment, design of an underway sampling system, and the study of the physical and chemical characteristics of rhodamine-B dye used as an external tracer. The results of this phase of the research were reported in detail in the second Annual Report by the Allan Hancock Foundation (1). A brief review of the more important aspects of this work follows.

Two G. K. Turner Model 111 fluorometers equipped with continuous-flow doors were used throughout this investigation. The fluorometers as received from the manufacturer were not suitable for immediate field use. The major problems encountered were:

1) light leaks around the flow door and through the back of the instrument.
2) deflection of the forward light path when the flow door was subjected to small normal loads. This deflection was due to the fact that the mounting bracket for the mirror assembly and cuvette holder was anchored to the door only on one end, thus normal loads on the door deflected the mirror assembly.
3) condensation on the cuvette. On several occasions condensate was observed to flow down the face of the cuvette. The presence of condensate resulted in erroneous indicated fluorescence levels, especially at high instrument sensitivity settings.
4) the location of the sensitivity control knob inside the fluorometer. This arrangement is suitable for laboratory work with the non-flow door. However, when used in the field with the continuous-flow door arrangement, it becomes an awkward and time-consuming task to change sensitivity.

Some of these problems were not serious and were easily solved. A light shield was built to house the fluorometer, thus minimizing the possibility of light leaks. Ventilation openings were provided for instrument temperature control. Condensation was minimized by forcing a continuous supply of dry air through the cuvette chamber by use of a small diaphragm pump and drying column. Deflections of the mirror assembly were reduced by anchoring both ends of the mounting bracket and securing a piece of $\frac{1}{8}$ inch flat steel bar stock diagonally across the flow door to make it more rigid. Both fluorometers were modified by addition of an external sensitivity control knob and dial located on the control panel above the cuvette chamber. By this means of external control it was possible to make rapid sensitivity changes without reaching inside the unit. This modification also extends the range of sensitivity settings to any desired value between zero and maximum instead of the 1, 3, 10 and 30 × values obtainable with the unmodified unit. Setting repeatability is provided by addition of a geared indicator dial attached to the control knob.

For field use the instrument is equipped with a pipe inlet-outlet manifold which was designed to allow continuous flow through the sampling chamber or alternately through a by-pass line. An auxiliary inlet line was provided in order that standard solutions of known tracer concentration could be passed through the fluorometer while the by-pass was in operation. This arrangement allows spot calibration checks to be made at any time during the sampling process. Figure 1 shows the modified fluorometer with light shield, air pump and drying column, as used in the field.

In order to sample continuously from a moving reference platform, it was necessary to design and construct an underway sampling device. The sampler consisted of a 4 foot section of 2 inch galvanized pipe with $\frac{1}{4}$ inch steel plate fins with adjustable flaps. A 2 inch reducer attached to a $\frac{1}{2}$ inch section of pipe is located below the body of the sampler and the open end is oriented in the direction of flow. The section of pipe leading from the inlet passes up through the main body of the unit; the end of this line is beveled in order to fit snugly inside a $\frac{1}{2}$ inch polyethylene sampling line. This design allows utilization of full impact pressure of the water medium to minimize sampling pump lift conditions during underway operation.

The sampler was designed so that it could be towed behind a moving boat. The tail fins were adjusted to provide stability and keep the sampler submerged at
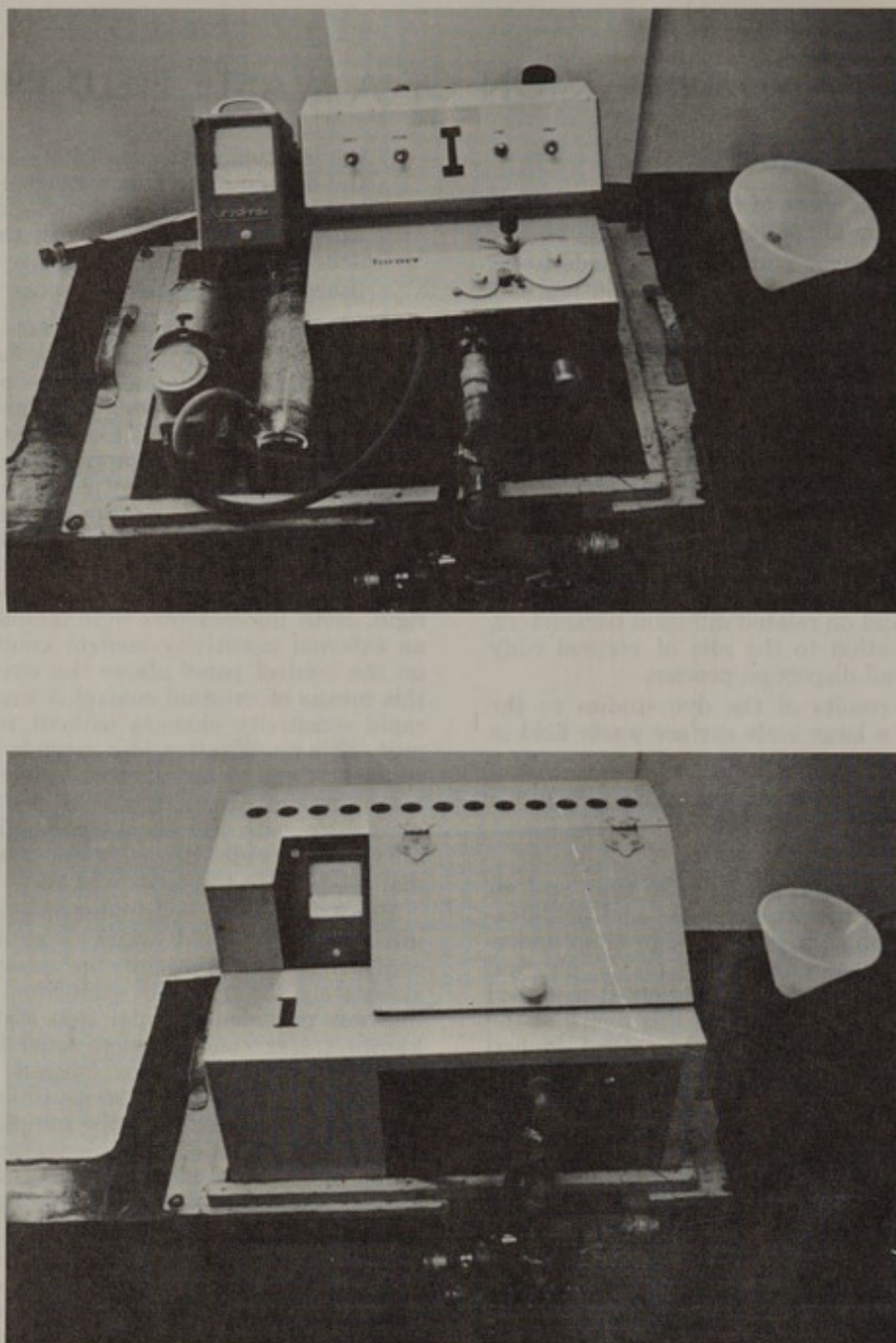
FIGURE 1

TURNER FLUOROMETER WITH PIPE
MANIFOLD AND LIGHT SHIELD

all times. A calibrated stranded wire and winch were used to lower or raise the sampler to the desired depth. A 50 foot section of polyethylene hose attached to the sampler was connected to a small positive displacement pump which in turn discharged directly into the pipe manifold attached to the fluorometer. Power for both pump and fluorometer was provided by a small 1000 watt portable generator.

The sampling equipment was assembled and mounted on an 18 ft. launch from the R.V./Velero IV, the U.S.C. marine research vessel. With this arrangement, it was possible to move personnel and equipment to any desired oceanic area. The launch was lowered for diffusion work, thus freeing the Velero IV for additional studies. The launch had the added advantage of small size and shallow draft, important factors when working in surface dye fields.

The speed of the launch was estimated by use of a Walker-type speed indicator attached to 100 feet of log-line and sinker. This device measures the total drag induced on the line and sinker when it is towed from the stern of the launch. The instrument is calibrated to read in 1/10 knot units with a maximum range of zero to ten knots. The instrument is not accurate in the sense of conventional laboratory velocity meters. Accurate speed measurement at sea is extremely difficult, particularly at low velocities. When suitably calibrated, this instrument can be used to give a reliable estimate of ship speed. The instrument was calibrated periodically by determining the time of travel over a known distance at various constant launch speeds.

The underway sampling equipment mounted on the launch ready for field use is shown in Figure 2.

Rhodamine-B Techniques

Feurestein and Selleck (2) recently published the results of an extensive series of tests designed to examine critically the physical and chemical characteristics of several tracers commonly used in surface water investigations. They discuss the effects of physical adsorption, photo-chemical decay, temperature, pH, etc., on rhodamine-B, Pontacyl Pink-B, fluorescein and orzan. These authors concluded their report by stating that Pontacyl Pink-B is the most suitable of the tracers studied for use in natural surface waters. Rhodamine-B was found to be less suitable because of the unfavorable characteristic of adsorption on suspended solids indigenous to San Francisco Bay. The magnitude of adsorption was found to be large and highly variable with the chlorosity of the surface water, the higher the chlorosity the lower the adsorption. Both tracers were found to be significantly temperature sensitive, fluorescence decreasing with increasing temperatures. pH values less than 5 or greater than 10 result in a decrease in fluorescence for rhodamine-B. No such pH effect was demonstrated with Pontacyl Pink-B. Both tracers show slight photochemical decay rates up to about 30 hours exposure time, after which significant decay rates are evident for both, rhodamine-B decaying faster than Pontacyl Pink-B. Most of the above mentioned characteristics for rhodamine-B were discussed, at least in part, by Pritchard and Carpenter (3) in their study of diffusion in Chesapeake Bay, as outlined in a previous progress report. These authors, however, did not include a study on the adsorbtion characteristics of rhodamine-B in waters with high concentrations of suspended solids.

The question that followed, then, was just how significant were the above mentioned characteristics for rhodamine-B when used in an oceanographic environment as in this investigation? The pH of the surface waters near the Orange County outfall averaged from 7.6 at the boil to 8.3 at non-boil stations. The raw rhodamine-B acetic acid mixture has a pH of approximately 3.5 and when mixed with methanol for specific gravity adjustment, the pH is approximately 4.0. The minimum pH observed from grab samples taken 30 seconds after dye release was 4.2, this value increasing to 6.5 in grab samples taken $1\frac{1}{2}$ minutes later. Therefore, it appears that pH was no problem except possibly during the first few minutes following dye release.

Temperature variations during field tests at Orange County were observed to be minimal. The maximum variation in surface water samples between boil and downstream stations was approximately 2°C. The temperature effect was also compensated for by periodic calibration of the fluorometers while following the dye patch. Before release of the dye, the instrument was zeroed by pumping local water through the unit. A standard solution was then prepared also using local water. With this standard (normally 1 ppm at the beginning of a test) the instrument sensitivity was set to give the desired dial reading, say 50 units, corresponding to the standard. This procedure was repeated at periodic intervals to check the initial standard and again when an increase in instrument sensitivity was required.

Photochemical decay, assuming the values determined by Feuerstein and Selleck apply to conditions existing in the ocean, did not appear to be of major concern in the studies conducted to date. The maximum daylight exposure time was seven hours. According to the above mentioned report, photochemical decay for rhodamine-B becomes serious after approximately 30 hours of exposure.

A more important factor to consider in studies around an existing outfall, such as Orange County, is the turbidity of the diluted waste found at or near the boil. Table 1 shows the results of a laboratory test using primary effluent from the city of Los Angeles' Hyperion Treatment Plant tagged with rhodamine-B. The undiluted effluent shows a pronounced decrease in dial reading compared to the tap water blank. At a dilution (tap water to effluent) of 10:1, the effluent mixture reading equals that of the blank. This decrease in sensitivity is probably due to the light scattering characteristics of the particulate matter contained in the effluent. The initial dilution at the Orange County Outfall, as determined by salinity measurements, ranged from 7:1 to 20:1. Therefore, on the assumption that the Hyperion and Orange County Treatment Plant effluents are similar, the light scattering effect was assumed to be minimal.

The problem of adsorbtion of rhodamine-B on suspended sediments similar to those found in San Francisco Bay is probably not of major concern in the open ocean, the reason for this being that suspended sediment concentrations are generally negligible and chlorosity is high. A problem can exist, however, if studies are conducted near existing outfalls where the effluent
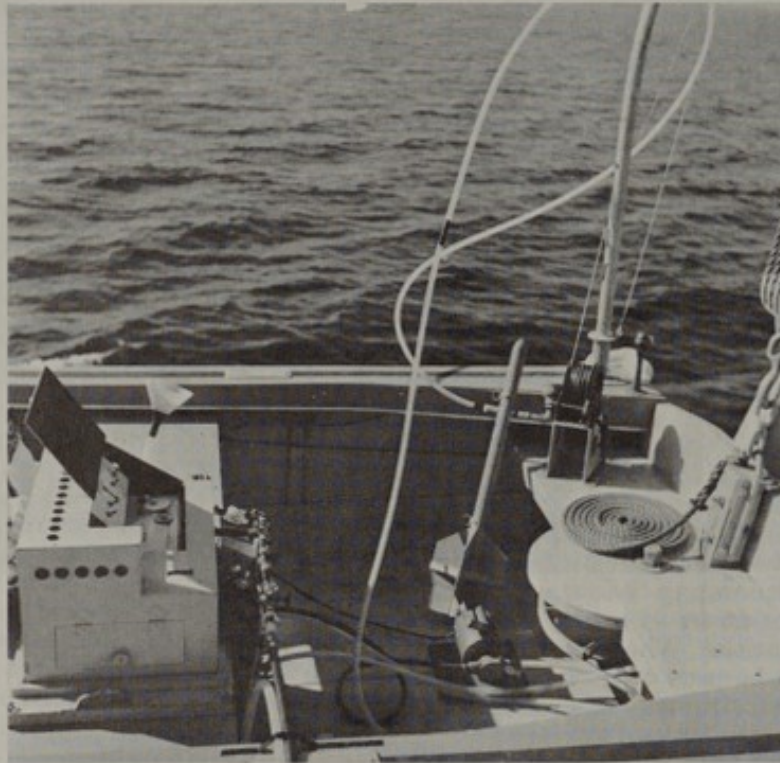
FIGURE 2

RESEARCH LAUNCH AND EQUIPMENT

TABLE 1

Hyperion Primary Effluent   Fluorometer No. 2
Suspended Solids = 90 ppm   Flow Door Assembly
Dilution with Tap Water   Filters
Temperature of Effluent   Primary: 110–832
and Water = 21°C   Secondary: 110–833
                      +110–823
                      N.D. 1%

Sample	Dilution	Dial reading	Remarks
Blank	—	64.5	1 ppm rhodamine-B
Effluent	—	57.5	1 ppm rhodamine-B well mixed sample
Tap Water and Effluent	2:1	60.5	1 ppm rhodamine-B well mixed sample
Tap Water and Effluent	3:1	62.25	1 ppm rhodamine-B well mixed sample
Tap Water and Effluent	5:1	63.5	1 ppm rhodamine-B well mixed sample
Tap Water and Effluent	10:1	64.5	1 ppm rhodamine-B well mixed sample

All readings taken immediately after addition of dye.

contains high concentrations of suspended sewage solids. Tables 2 and 3 show the results of adsorbtion studies conducted using Hyperion primary effluent. The values in Table 2 indicate the change in concentration with time for various dilutions of effluent, all containing 1 ppm of rhodamine-B. There was an initial difference in fluorescence level for the undiluted effluent which was probably due to light scattering. In the other samples there was little if any initial difference. There appeared to be a negligible decrease in fluorescence for any of the samples for the eight hour test period. The values indicated in Table 3 are for a similar test using 0.1 ppm rhodamine-B. There was again an immediate

TABLE 2

Adsorbtion Study   Fluorometer No. 2
1 ppm rhodamine-B   Non-Flow Door
Hyperion Primary Effluent   Cuvette No. 2
Suspended Solids = 90 ppm
Dilution with Tap Water

Sample	Dilution	Time	Average dial reading	Remarks
Tap Water Blank	—	1103	52	T = 22°C
		1118	51	
		1400	51	
		1923	52	
Effluent	—	1107	50	T = 21.9°C
		1122	50	Floc on bottom
		1400	50.75	Heavy floc
		1923	50	Heavy floc
Tap Water and Effluent	2:1	1111	52	T = 22°C
		1123	52.25	Floc on Bottom
		1400	51	Floc on Bottom
		1924	52.25	Floc on Bottom
Tap Water and Effluent	10:1	1116	51.5	T = 21.9°C
		1125	50.5	Fine floc on bottom
		1400	50.25	Fine floc on bottom
		1924	51.25	Fine floc on bottom

All samples agitated for 10 minutes and allowed to settle before analysis.

initial decrease of fluorescence in all samples which appeared in this case greater in the samples of higher dilution. The important point is that only in the undiluted effluent sample was there any appreciable decrease in fluorescence with time.

The concentration of suspended solids in all water samples taken at the boil during this investigation ranged from 14.6 to 81.5 ppm. Because of this low range in solids concentration and the data obtained from the laboratory tests mentioned above, it appeared reasonable to assume that physical adsorbtion was not an appreciable factor in this investigation. In order to substantiate the results of the lab tests, a series of experiments were designed to compare rhodamine-B and Pontacyl Pink-B under actual field conditions. On May 28th and 29th, 1963, 5 lb. slugs of these tracers were released just downstream from the boil at the Orange County outfall site. Pontacyl Pink, used as a control, was released during the morning hours followed by rhodamine-B in the afternoon. Figure 3 shows the results obtained when the data from both days are superposed. The least-squares regression lines are also indicated with corresponding equations. Both equations fit the data very well, having correlation coefficients of 0.98 and 0.96 for rhodamine-B and Pontacyl Pink respectively. The difference between the two curves can be attributed to many factors. If due to physical adsorbtion on suspended particles, it would have been necessary for a large quantity of rhodamine-B to have been removed initially, an occurrence that is not borne out by previous laboratory or field observations. The slopes of these curves appear to indicate that little, if any, adsorbtion took place with time. It is possible that the difference in these results can be attributed to varying oceanographic conditions existing in the vicinity of the boil at the time of release. Previous tests (as discussed later in this report) indicated that concentration vs time curves, for tests conducted in the same area during the same day, vary to an even larger degree than the curves shown in Figure 3.

Another physical characteristic of both rhodamine-B and Pontacyl Pink-B that presented a problem in field sampling was the so-called concentration "quenching"

TABLE 3

Adsorbtion Study   Fluorometer No. 2
100 ppb rhodamine-B   Non-Flow Door
Hyperion Primary Effluent   Cuvette No. 2
Suspended Solids = 58.6 ppm
Dilution with Tap Water

Sample	Dilution	Time	Average dial reading	Remarks
Tap Water Blank	—	0945	53.0	T = 21.3°C
		1143	53.0	T = 21.3°C
		1712	52.5	T = 22°C
Effluent	—	0953	51.25	T = 21.9°C
		1134	51.0	T = 21.9°C
		1716	49.5	T = 22°C
		1720	50.75	re-mixed sample
Tap Water and Effluent	2:1	0959	49.75	T = 21.5°C
		1139	49.75	T = 21.5°C
		1724	49.25	T = 22°C
		1735	49.25	re-mixed sample
Tap Water and Effluent	10:1	1003	49.5	T = 21.4°C
		1130	50.0	T = 21.4°C
		1730	49.5	T = 22°C
		1735	49.6	re-mixed sample

All samples agitated for 10 minutes and allowed to settle before analysis.
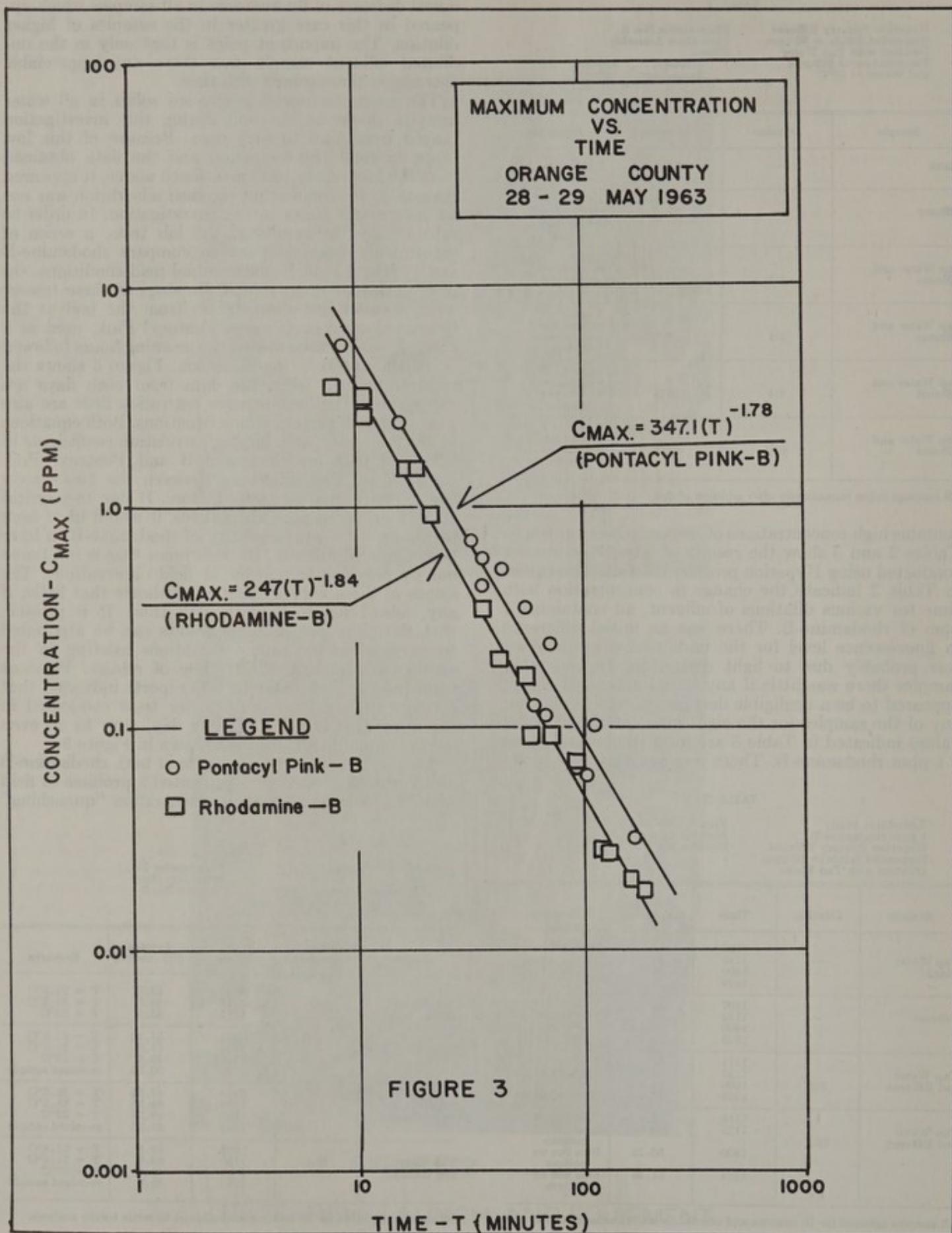
FIGURE 3

effect. When either dye is present in high concentrations it tends to absorb the ultra violet exciting light used in the fluorometer. Therefore, dye concentration is not a linear function of the instrument dial reading. Figure 4 is a typical calibration curve for rhodamine-B obtained when the instrument sensitivity was set so that 1 ppm equals 50 dial units. The severe non-linear readout characteristic is the result of the "quenching" effect.

Analysis of strip chart data from continuous-flow measurements taken at the early phases of a test run required careful interpretation. The problem was to determine which portion of the calibration curve was to be used in data reduction. Figure 5 is an illustration of the strip chart data taken continuously along the longitudinal axis of a typical dye patch. As the concentration increases the instrument senses the values indicated on the lower portion of the calibration curve in Figure 4. Near the center of the patch the concentration gradually increases to 1 ppm, and then beyond. The instrument now senses the upper region of the curve where increasing concentrations have lower apparent fluorescence levels; thus the readout indicates a drop which corresponds to the maximum concentration. The subsequent decrease in concentration is indicated by an increase in dial reading back to approximately 1 ppm., after which the instrument again senses fluorescence levels corresponding to the lower portion of the calibration curve and decreasing concentrations are indicated by decreasing dial readings. In this example the maximum concentration is actually 3 ppm. instead of an apparent maximum of 1 ppm.

It was observed that when using 5 and 10 lb. slugs of rhodamine-B dye, it took from 10 to 40 minutes before the maximum concentration in the patch was lowered to less than 1 ppm. Therefore, during the early phases of a given test, grab samples together with continuous-flow samples were taken concurrently in order to establish which portion of the calibration curve was to be used in later analysis of the data. The grab samples were analyzed at the conclusion of the test by passing diluted aliquots through the fluorometer.

3. DILUTION STUDIES

Dilution studies were conducted in order to provide back-up information for phytoplankton productivity investigations that were conducted within the sewage field. The rate of dilution was estimated both by instantaneous release of slugs of dye and by continuous release from a skiff anchored near the surface boil at the Orange County outfall site. A summary of the oceanographic conditions, empirical dilution parameters, and equations for the instantaneous release studies in both the waste field and in control areas was presented in reference (1) and is included here for further discussion (Tables 4 and 5). The results obtained from the continuous release experiments in the waste field are summarized in Tables 6 and 7.

It should be pointed out that, with one exception, the results of both the instantaneous and continuous release experiments, do not give the true rate of dilution of the entire waste field under investigation. The reason for this is the difference in size of the waste and dye fields. The rate of eddy diffusion has been shown to be a function of the scale of the turbulent eddies

participating in the diffusion phenomenon. Therefore, unless the waste and dye fields in a test area are of comparable size, the rates of diffusion and therefore of dilution will not be equivalent. The exceptional case is the experiment conducted on 17 June 1964 when the entire waste field was tagged by continuous injection of dye at the Orange County treatment plant on shore.

Regardless of these difficulties, the data presented do give a measure or indication of the rate of dilution occurring on any given day. The results of individual experiments shown in Tables 5 and 7 can be compared to determine relative rates of dilution. In this respect these data can be used to estimate and compare the influence of physical dilution on primary phytoplankton productivity within the waste field.

4. MATHEMATICAL MODELS—RELATIVE DIFFUSION

The information discussed in this section was given partial treatment in the 1962–63 Annual Report (1) and was also included in a paper (4) presented at the 1964 meeting at Monaco of the Commission Internationale pour l'Exploration Scientifique de la Mer Mediterranee (Tibby, Foxworthy, Oguri, and Fay, "The Diffusion of Wastes in Open Coastal Waters and their Effects on Primary Biological Productivity.") Some of the material is presented again at this time to serve as a basis for the discussion and conclusions which follow.

During the first few field experiments it was observed that the dye patches elongated in the direction of the surface current. This suggested that, neglecting the possible effect of a vertical velocity gradient near the surface, the process was anisotropic, i.e., diffusing at different rates in the horizontal plane. The highly positive density gradient normally found within the surface waste field from the Orange County outfall also indicated that the rate of vertical diffusion was much less than the horizontal. Under these conditions the diffusion process was considered to be of a three-dimensional anisotropic type. This assumption will be further discussed in a later section.

The three-dimensional statistical model proposed by Gifford (5) and extended by Okubo (6) to cover the case of relative diffusion in a homogeneous and stationary turbulent field was considered to be directly applicable to the case in point. This model, as discussed in reference (1), is based on the assumptions that diffusion proceeds (independently) at different rates in the horizontal and vertical planes and that the spatial distribution of diffusing substance is essentially Gaussian in all directions. The later assumption, assumed to be valid for the average concentration distribution of a large number of dye releases diffusing under similar oceanographic conditions, leads to the following equation:

$$\bar{C}(x,y,z,t) \tag{1}$$

$$= \frac{M}{\pi\sqrt{2\pi}\,[\sigma_x{}^2\sigma_y{}^2\sigma_z{}^2]^{1/2}} \exp -\left[\frac{x^2}{2\sigma_x{}^2} + \frac{y^2}{2\sigma_y{}^2} + \frac{z^2}{2\sigma_z{}^2}\right]$$

where $\bar{C}$ is the average concentration at a point x, y, z and time t, M is the amount of dye initially discharged from an instantaneous point source, and σ^2 are the

CALIBRATION CURVE
FLUOROMETER 2
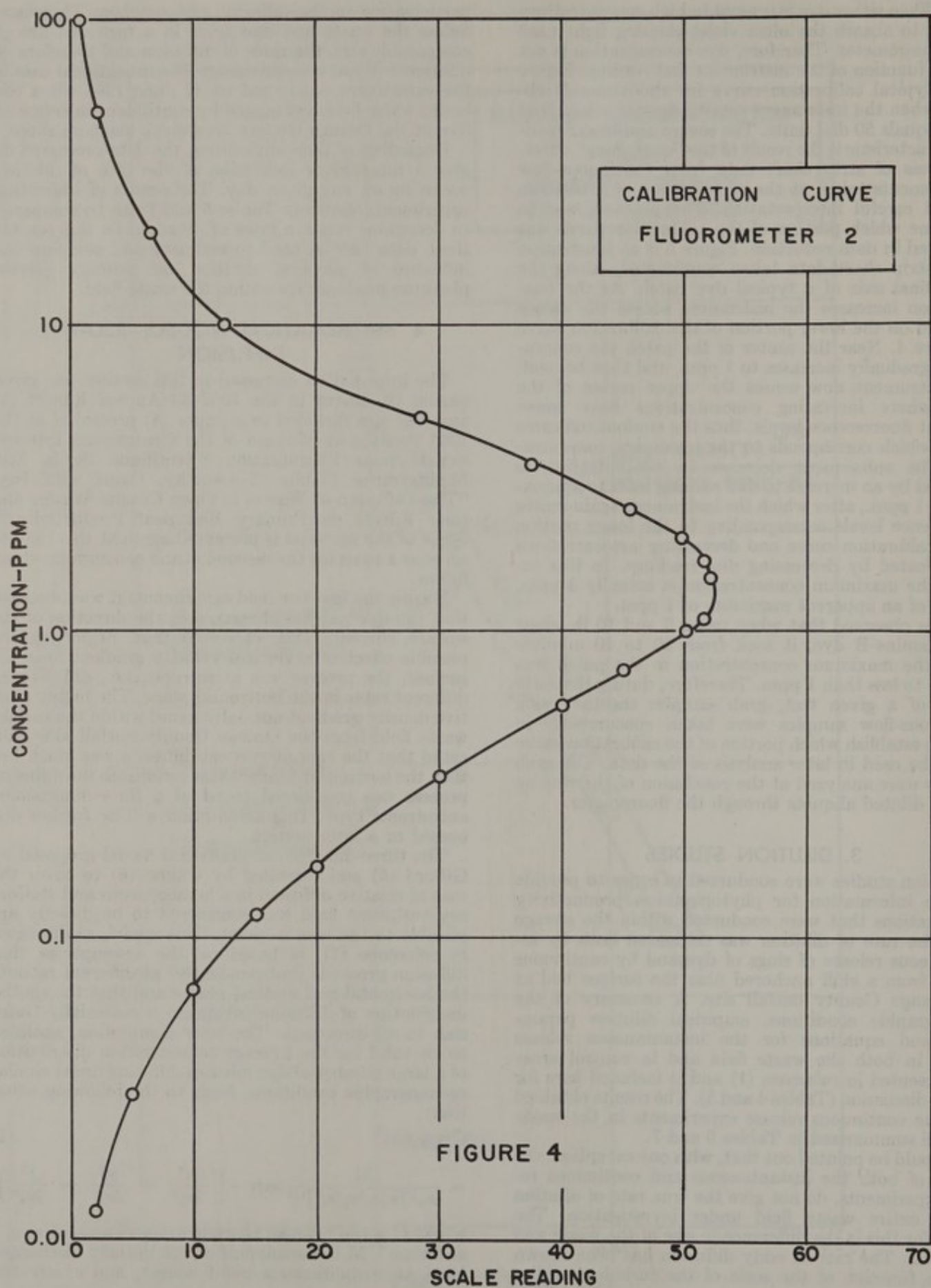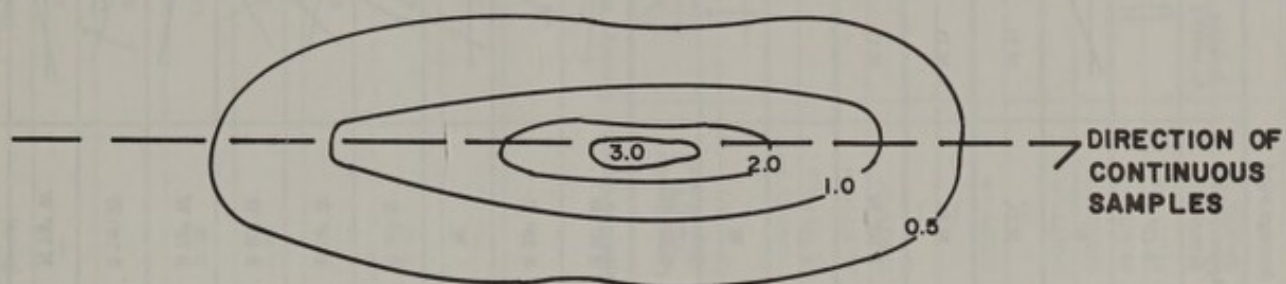
FIGURE 4

DYE PATCH
(CONCENTRATIONS IN PPM)

DIRECTION OF CONTINUOUS SAMPLES

APPARENT MAX. CONCENTRATION ≈ 1 PPM

ACTUAL MAX. CONCENTRATION ≈ 3 PPM
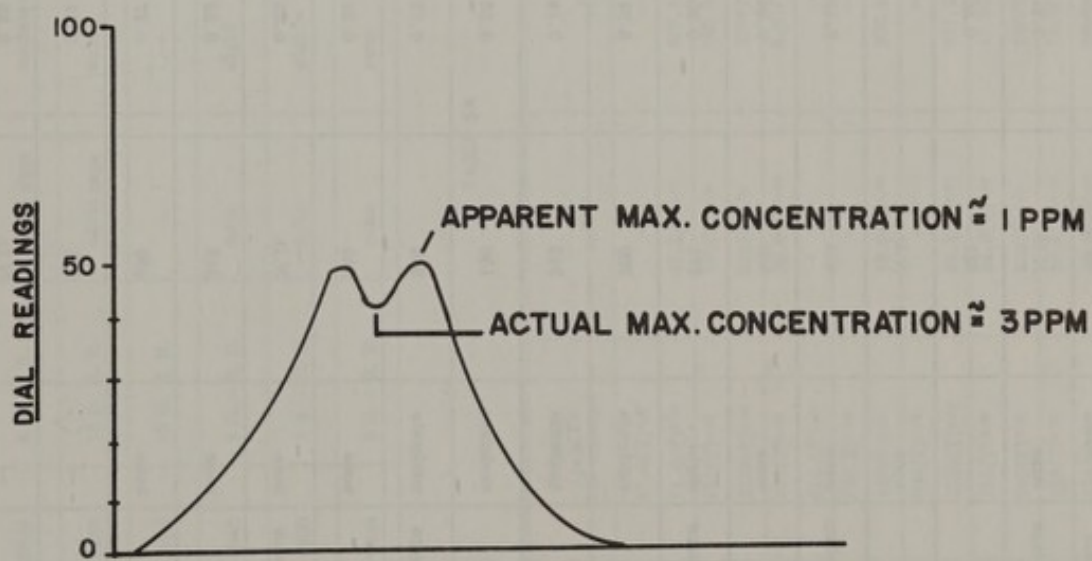
TIME

FLUOROMETER (STRIP CHART) READOUT
(NOT TO SCALE)

FIGURE 5

TABLE 4A

SUMMARY OF OCEANOGRAPHIC CONDITIONS
Dye Patch Studies—Orange County Waste Field

Number and date	Dye release time	Dye characteristics	Sea conditions		Average stability† S'	Average patch speed — U (knots)	Average wind		Relation to patch§
			Surface	Swell			W speed (knots)	Approximate direction	
1 8/17/62	1040	SG 0.7* 5 lb. rhod. B	white caps	large	N.D.‡	0.21	7.3	S 15° W	
2 10/31/62	1323	10 lb. rhod. B	—	—	337	0.50	8.6	W	
3 11/1/62	0925	5 lb. rhod. B	calm	none	N.D.	—	4.3	N.D.	N.D.
4 11/13/62	1107	5 lb. rhod. B	slight chop	none	405	0.18	8.0	N.D.	N.D.
5 11/14/62	0845	5 lb. rhod. B	calm	none	900	0.26	3.0	S 50° W	N.D.
6 11/28/62	1335	10 lb. rhod. B	white caps	slight	771	0.20	8.6	S 65° W	
7 11/29/62	0835	10 lb. rhod. B	calm	moderate	300	0.21	5.2	W	
8 11/30/62	0840	5 lb. rhod. B	calm	moderate	345	0.14	4.8	S 25° W	
9 12/19/62	0900	10 lb. rhod. B	calm	moderate	130	0.25	5.5	S 50° W	
10 3/12/63	0723	5 lb. rhod. B	white caps	moderate	846	0.22	9.6	S 25° E	
11 3/13/63	0808	5 lb. rhod. B	chop	none	246	0.26	7.6	W	
12 3/14/63	0911	5 lb. rhod. B	white caps	none	N.D.	0.26	13.2	S 30° E	
13 4/9/63	1050	5 lb. rhod. B	chop	none	348	0.52	9.3	S 75° W	
14 4/11/63	0817	5 lb. rhod. B	none	none	450	0.27	5.4	S 40° W	
15 5/29/63	1326	5 lb. rhod. B	—	—	465	0.21	9.6	S 75° W	
16 5/29/63	0953	5 lb. Pont. Pink	—	—	N.D.	0.35	7.0	S 75° W	
17 2/7/64	1349	5 lb. rhod. B	white caps	none	400	0.32	10.0	N 75° W	
18 2/9/64	0837	5 lb. rhod. B	calm	slight	1290	0.32	4.4	S 45° W	

* S.G. Specific Gravity of rhod. B, 1.02 unless otherwise noted.
† Av. Stability defined as the time average of all stabilities.
‡ N.D. No data.
§ Wind direction ——→   ; Dye patch direction ——●

TABLE 4B

SUMMARY OF OCEANOGRAPHIC CONDITIONS | Dye Patch Studies—Background Areas

	Number and date	Location	Dye release time	Dye characteristics	Sea conditions		Average stability S'	Average patch speed — $\bar{U}$ (knots)	Average wind speed — $\bar{W}$ (knots)
					Surface	Swell			
a	10/ 5/62	San Clemente	1300	5 lb.—R. B. S. G. = 1.00	calm	moderate	N. D.	—	4.0
b	11/ 2/62	San Clemente	0840	5.25 lb. R. B.	slight chop	moderate	N. D.	—	6.2
c	3/13/63	Newport Canyon	1258	10 lb. R. B.	white caps	none	157	0.28	11.2
d	4/ 9/63	Newport Canyon	1600	10 lb. R. B.	—	—	16	0.35	8.7
e	8/15/63	Redondo Canyon	0942	5 lb.—R. B.	calm	slight	743	—	4.3
f	12/15/63	Catalina	0900	5 lb.—R. B.	calm	slight	68	0.42	4.3
g	12/16/63	Catalina	0830	5 lb.—R. B.	calm	none	50	—	1.6

TABLE 5A

SUMMARY OF DIFFUSION PARAMETERS | Dye Patch Studies—Orange County Waste Field

Number and date	Concentration $C_{max}(T)$ field measure	Dilution $D_{min}(T)$ field measure	$\sigma_x(T)^2$	$\sigma_y(T)^2$	$\sigma_z(T)^2$	Concentration $C_{max}(T)$ (Equation 2)	Mass balance M' percent
1 8/17/62	$1636(T)^{-2.07}$	$47.8(T)^{2.07}$	$47.8(T)^{3.07}$	$127.1(T)^{1.19}$	$0.0014(T)^{3.19}$	—	—
2 10/31/62	$2185(T)^{-2.16}$	$71.5(T)^{2.16}$	$27.2(T)^{1.71}$	$155.9(T)^{1.06}$	$0.501(T)^{2.36}$	$10,500(T)^{-2.54}$	104
3 11/ 1/62	$82.4(T)^{-1.33}$	$951(T)^{1.33}$	$192(T)^{1.43}$	$107(T)^{1.25}$	$3.5(T)^{2.42}$	$72.2(T)^{-1.35}$	103
4 11/13/62	$33.8(T)^{-1.43}$	$2313(T)^{1.43}$	$366(T)^{1.10}$			$26.7(T)^{-1.44}$	142
5 11/14/62	$393(T)^{-1.44}$	$190(T)^{1.44}$	$20.6(T)^{1.83}$	$9.81(T)^{1.80}$	$0.81(T)^{3.45}$	$778(T)^{-2.07}$	244
6 11/28/62	$246(T)^{-1.42}$	$634.(T)^{1.42}$			$0.035(T)^{1.16}$	—	—
7 11/29/62	$475(T)^{-1.84}$	$329(T)^{1.84}$			$0.246(T)^{0.31}$	—	—
8 11/30/62	$468(T)^{-1.83}$	$167(T)^{1.83}$	$13.0(T)^{1.83}$	$200.6(T)^{3.33}$	$0.144(T)^{0.88}$	$512(T)^{-1.80}$	182
9 12/19/62	$172(T)^{-1.65}$	$909(T)^{1.65}$				—	—
10 3/12/63	$75.5(T)^{-1.43}$	$1035(T)^{1.43}$	$25.1(T)^{1.73}$	$707.4(T)^{3.46}$	$0.23(T)^{0.44}$	$245(T)^{1.41}$	69
11 3/13/63	$512(T)^{-2.36}$	$152(T)^{2.36}$	$94.5(T)^{1.59}$	$17.9(T)^{1.74}$	$0.062(T)^{1.49}$	$970(T)^{2.19}$	94
12 3/14/63	$93.0(T)^{-1.75}$	$840(T)^{1.75}$	$223(T)^{1.46}$	$138(T)^{0.87}$	$0.795(T)^{0.88}$	$63.6(T)^{-1.63}$	72
13 4/ 9/63	$427(T)^{-1.89}$	$183(T)^{1.89}$	$46.8(T)^{1.39}$	$14.6(T)^{1.63}$	$1.32(T)^{0.73}$	$331(T)^{1.48}$	69
14 4/11/63	$684(T)^{-1.89}$	$114(T)^{1.89}$	$68.8(T)^{1.48}$	$13.5(T)^{1.43}$	$0.32(T)^{0.73}$	$578(T)^{1.91}$	122
15 5/29/63	$214(T)^{-1.89}$	$365(T)^{1.89}$	$29.6(T)^{1.77}$	$31.5(T)^{1.37}$	$0.145(T)^{1.14}$	$8540(T)^{-2.49}$	88
16 5/29/63	$248(T)^{-1.67}$	$315(T)^{1.67}$	$154(T)^{1.98}$	$33.1(T)^{1.63}$	$0.40(T)^{0.73}$	$219(T)^{1.27}$	162
17 2/ 7/64	$139(T)^{-1.85}$	$630(T)^{1.85}$	$1153(T)^{1.97}$	$188.1(T)^{1.41}$	$0.0071(T)^{1.91}$	$253(T)^{2.45}$	145
18 2/ 9/64	$124(T)^{-1.82}$	$672(T)^{1.82}$	$7.58(T)^{3.34}$	$6.51(T)^{1.65}$	$166(T)^{-0.73}$	$109(T)^{1.48}$	105

TABLE 5B

SUMMARY OF DIFFUSION PARAMETERS

Dye Patch Studies—Background Areas

Number and date	Concentration $C_{max}(T)$ field measure	Dilution $D_{min}(T)$ field measure	$\sigma_x(T)$	$\sigma_y(T)$	$\sigma_z(T)$	Concentration $C_{max}(T)$ (Equation 2)	Mass balance M' percent
a	10/ 5/62	$4595(T)^{-2.54}$	$17(T)^{2.54}$	$276.8(T)^{1.07}$	$18.2(T)^{0.90}$	$0.000505(T)^{2.19}$	$6000(T)^{-2.19}$	37
b	11/ 2/62	$167(T)^{-1.91}$	$491(T)^{1.91}$	$39.0(T)^{1.47}$	$126(T)^{0.82}$	$0.12(T)^{1.53}$	$464(T)^{-1.96}$	63
c	3/13/63	$1304(T)^{-2.29}$	$120(T)^{2.29}$	$1.83(T)^{2.36}$	$3.46(T)^{1.73}$	$0.35(T)^{1.37}$	$13,300(T)^{-2.82}$	41
d	4/ 9/63	$618(T)^{-1.88}$	$253(T)^{1.88}$	$20.9(T)^{1.68}$	$135.7(T)^{0.88}$	$0.076(T)^{1.43}$	$1350(T)^{-1.88}$	42
e	8/15/63	$504(T)^{-1.84}$	$155(T)^{1.84}$	$10.6(T)^{1.87}$	$21.8(T)^{1.24}$	$1.69(T)^{0.88}$	$342(T)^{-1.80}$	78
f	12/15/63	$1380(T)^{-1.94}$	$56.6(T)^{1.94}$	$11.6(T)^{1.71}$	$77.1(T)^{0.99}$	$0.076(T)^{1.59}$	$1203(T)^{-1.35}$	43
g	12/16/63	—	—	—	—	$.00273(T)^{1.97}$	—	—

TABLE 6

SUMMARY OF OCEANOGRAPHIC CONDITIONS

Continuous Discharge Studies—Orange County Waste Field

Number and date	Dye release time	Rhod. B dye characteristics discharge rate (lb/hr)	Sea conditions Surface	Sea conditions Swell	Average stability $\bar{S}'$	Average plume speed $\bar{U}$ (knots)	$\bar{W}$ speed (knots)	Approximate direction	Relation to plume ‡
1	6/27/63	1045	S.G. 1.02* 6.35	slight chop	moderate	N.D.	0.32	6.0	S 45° W	
2	6/28/63	0905	6.5	slight chop	moderate	640	0.34	6.0	S 75° W	
3	9/11/63	0855	6.5	chop	large	470	0.40	7.4	N 80° W	
4	9/12/63	0820	6.5	chop	large	720	0.18	6.5	S 15° E	
5	11/ 9/63	0803	6.1	calm	none	610	0.15	3.5	S 75° W	
6	11/10/63	0713	6.1	calm	none	1230	0.27	1.6	S 30° W	
7	2/ 8/64	—	6.1	calm	none	375	0.14	5.6	W	
8	6/17/64	0948	2 ppm at treatment plant	chop	none	505	0.32	7.6	S 15° W	

* S.G. Specific Gravity of rhod. B, 1.02 unless otherwise noted.
† Av. Stability defined as the time average of all stability.
‡ Wind direction ——→   : Dye plume direction ——●

TABLE 7

SUMMARY OF DIFFUSION PARAMETERS

Continuous Discharge Studies—Orange County Waste Field

Number and date	Concentration $C_{max}(X)$ (ppm) field measure	$\sigma_y(x)^2$	$\sigma_z(x)^2$	Concentration $C_{max}(X)$ (ppm) (Equation 28)	Mass balance Q' percent
1	6/27/63 $298(x)^{-1.93}$	$1.64(x)^{1.38}$	$2.43 \times 10^{-3}(x)^{0.93}$	$258(x)^{-1.11}$	189
2	6/28/63 $4747(x)^{-1.42}$	$0.209(x)^{1.57}$	$*2.66 \times 10^{-3}(x)^{1.48}$	$6650(x)^{1.42}$	159
3	9/11/63 $326,200(x)^{-1.45}$	—	$2.66 \times 10^{-3}(x)^{1.48}$	—	—
4	9/12/63 $37,140(x)^{-1.44}$	$1.15 \times 10^{-2}(x)^{2.24}$	$4.78 \times 10^{-3}(x)^{1.05}$	$12,600(x)^{-1.44}$	294
5	11/ 9/63 $22,700(x)^{-1.49}$	—	—	—	—
6	11/10/63 $126(x)^{-0.92}$	$3.2 \times 10^{-3}(x)^{1.91}$	$0.405(x)^{0.51}$	$163(x)^{1.91}$	144
7	2/ 8/64 $6490(x)^{-1.42}$	$0.571(x)^{1.53}$	$1.54 \times 10^{-3}(x)^{1.36}$	$1310(x)^{1.42}$	177
8	6/17/64† ‡	‡	$7.6 \times 10^{-3}(x)^{0.93}$	‡	—

* Equation for σ_z^2 taken from data 11 Sept. 1963.
† Tag of entire sewage field.
‡ See text for equations.

average values of the variances of the concentration distribution in the coordinate directions as a function of time. Gifford also points out that no *a priori* assumption about the form of the variances is necessary to make use of equation (1), the only stipulations being those given above.

An inspection of equation (1) indicates that the maximum concentration as a function of time is given by the first term on the right, i.e., by setting $x = y = z = 0$ equation (1) becomes:

$$C_{max} = \frac{M}{\pi\sqrt{2\pi}\,[\bar{\sigma}_x{}^2\bar{\sigma}_y{}^2\bar{\sigma}_z{}^2]^{1/2}} \qquad (2)$$

Equation (2) is of special interest because it is applicable to the disposal of a patch of waste material in the sea where the decrease in maximum concentration with time is of primary interest. It is relatively easy to obtain field data for the verification of equation (2), the problem centering on determining the variances and maximum concentration within the patch as a function of dispersion time.

As already stated, the dye patches elongated with time in the direction of the surface current. In most experiments this elongation was quite marked with the overall shape resembling an ellipse or, considering the three-dimensional picture, an ellipsoid.

Equation (1) can be shown to define a series of three-dimensional ellipsoidal surfaces of equal concentration, the major and minor semi-axes being defined (Diachischin (7)) by the following equations:

$$a^2 = \ln\left(\frac{C_{max}}{C'}\right)^2 \bar{\sigma}_x{}^2 \qquad (3)$$

$$b^2 = \ln\left(\frac{C_{max}}{C'}\right)^2 \bar{\sigma}_y{}^2 \qquad (4)$$

$$c^2 = \ln\left(\frac{C_{max}}{C'}\right)^2 \bar{\sigma}_z{}^2 \qquad (5)$$

where a, b, and c are the semi-axes at any given time defining a surface with equal concentration C', and C_{max} is the maximum concentration at the center of dye mass. By repeated underway sampling along the principal axes of the patch, it was possible to determine the distribution of the corresponding dye concentrations. From these data the average values of a, b, c, C' and C_{max} were determined, and the values of the coordinate variances then estimated by use of the above equations.

Figures 6 and 7 show a series of vertical photographs taken during the initial phases of an instantaneous release experiment. Five pounds of rhodamine-B were released downstream from the boil (lower center of Figure 6). The time-variation of the size and shape of the patch can easily be seen. The patch elongated in the direction of motion, and the extent to which the shape of the patch approached that of a true ellipse should be noted.

5. SAMPLING PROCEDURES

The sampling procedure followed in all dye patch studies is summarized as follows:

1. The fluorometer was calibrated with standard solutions of tracer dye. The initial sensitivity setting was 1 ppm equal to 50 or 75 fluorometer units. The instrument was "zeroed" using water from the waste field as a blank.

2. A dye tag was initiated by release of 5 or 10 pounds of dye solution with specific gravity of approximately 1.02. The release was usually completed in less than one minute.

3. During the first few minutes following dye release, grab samples were taken at the point of apparent maximum concentration.

4. Continuous flow sampling commenced in the center of the patch to establish the depth to maximum concentration.

5. With the underway sampler set at this depth, continuous flow samples were taken periodically along the principal horizontal axis of the patch. Dye concentrations were recorded continuously on a strip chart readout attached to the fluorometer.

6. Continuous flow depth samples were taken periodically from the research launch while located in the zone of (visual) maximum concentration.

7. The fluorometer was recalibrated at approximately one hour intervals.

8. The vertical distribution of temperature and salinity was determined at various time periods by personnel on the R.V./Velero IV.

9. Aerial photographs were taken at regular time intervals to aid in subsequent data reduction and analysis.

6. EXPERIMENTAL RESULTS

Figures 8 to 10 are examples of the measured values of the concentration distribution along the principal x, y and z-axes. These data are for single crossings of the patch at various indicated average times after dye release. The observed concentration distributions have been fitted with hypothetical Gaussian curves obtained from the estimated values of the variances and measured values of C_{max}. It can be seen that the computed normal curves fit the observed data reasonably well during the early phases of diffusion. At later times the fit is not nearly as close. As described above, better results could be obtained if averages of several crossings taken at the same time could be used to establish the observed points and to estimate the magnitudes of the variances. Unfortunately, data of this type, at least for studies of relative diffusion, are almost impossible to obtain using the present sampling techniques. However, the values obtained for the variances by this method are believed to be a reasonably good estimate of the average values.

It should be mentioned that the spatial concentration distributions shown in Figures 8 to 10 are neither the best nor the poorest recorded. In some experiments the distributions were skewed to the right or left of C_{max}. In these cases the basic assumption of a Gaussian distribution breaks down. However, on the basis of the majority of test results, it appears reasonable to consider a normal distribution as a useful, if not completely accurate working rule.

Once the values of the diffusion parameters were determined, it was possible to ascertain the empirical relationships between these parameters and diffusion time. It was found that when the variances were plotted
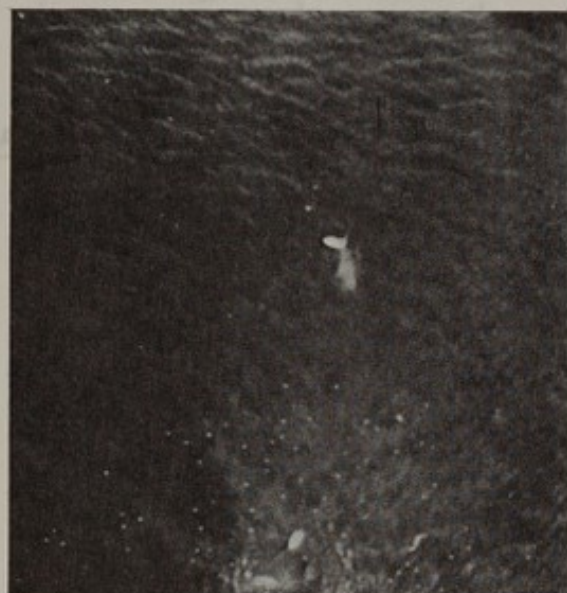
DYE PATCH

ORANGE COUNTY OUTFALL

7 FEB. 1964

T = 0.10 HOURS

$\bar{U}$ = 0.32 KNOTS

FEET

200   0   200

DYE PATCH

ORANGE COUNTY OUTFALL

7 FEB. 1964

T = 0.25 HOURS

$\bar{U}$ = 0.32 KNOTS

← $\bar{U}$

FEET

200   0   200
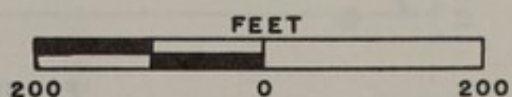
FIGURE 6

DYE PATCH

ORANGE COUNTY OUTFALL

7 FEB. 1964

T = 0.33 HOURS

Ū = 0.32 KNOTS

FEET
200   0   200
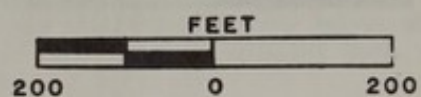
DYE PATCH

ORANGE COUNTY OUTFALL

7 FEB. 1964

T = 0.70 HOURS

Ū = 0.32 KNOTS

Ū

FEET
200   0   200

FIGURE 7

FIGURE 8

DYE DISTRIBUTION
Y-AXIS
ORANGE COUNTY OUTFALL
11 APRIL 1963

FIGURE 9

DYE DISTRIBUTION
Z - AXIS
ORANGE COUNTY OUTFALL
11 APRIL 1963

LEGEND

● Field Observation

— Normal Curve computed
with given $\sqrt{z}$ and C_{max}
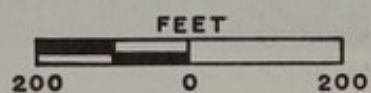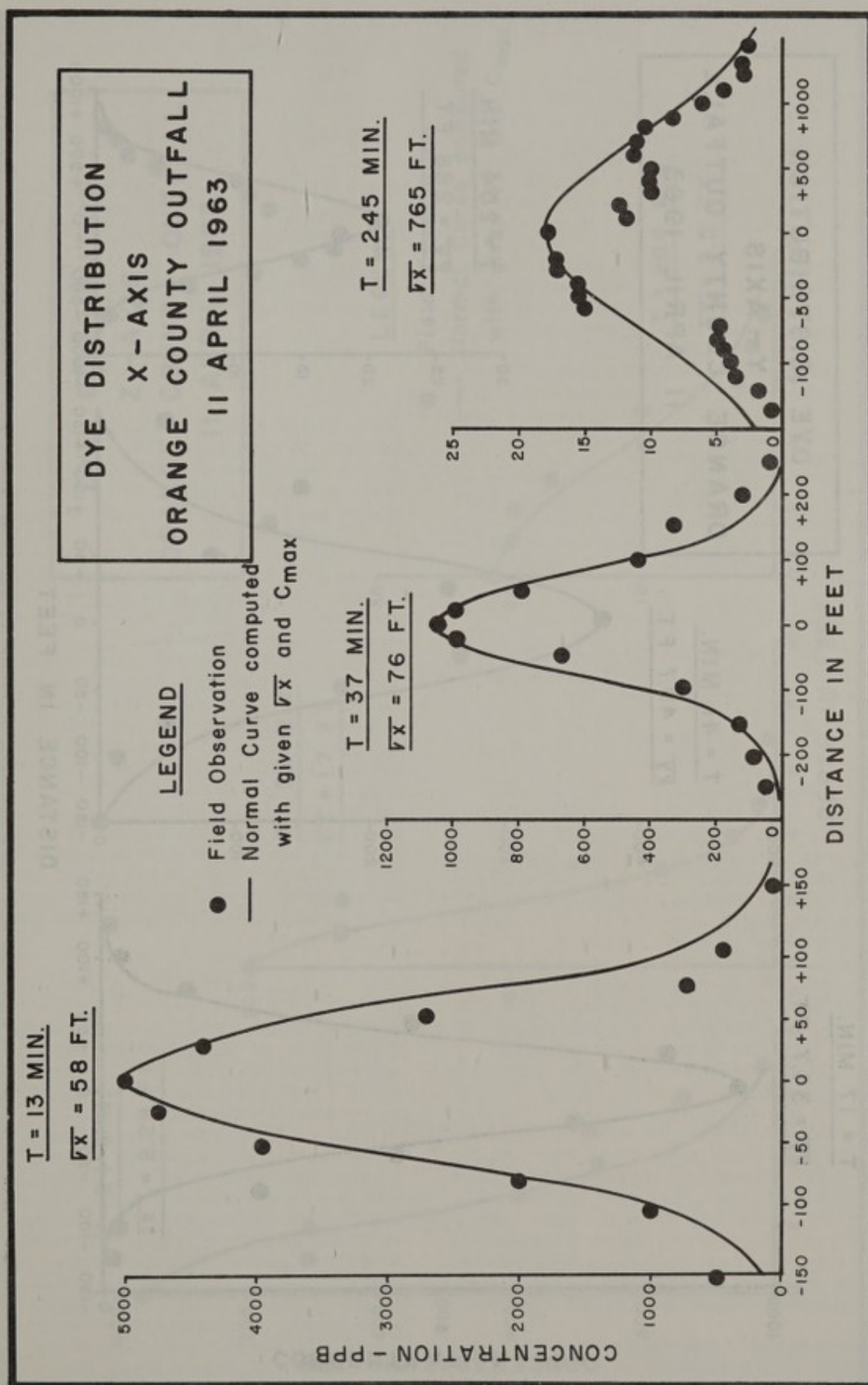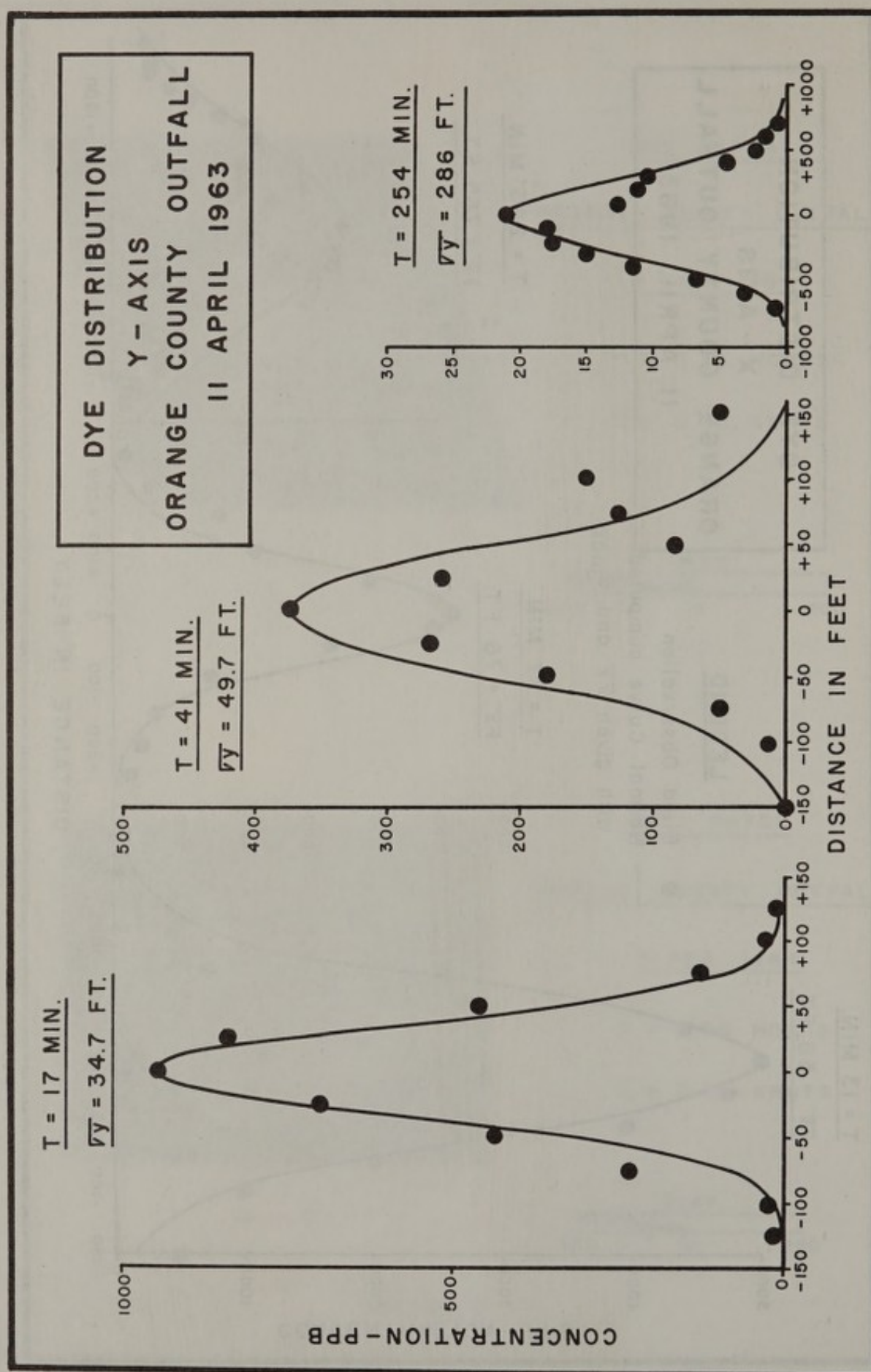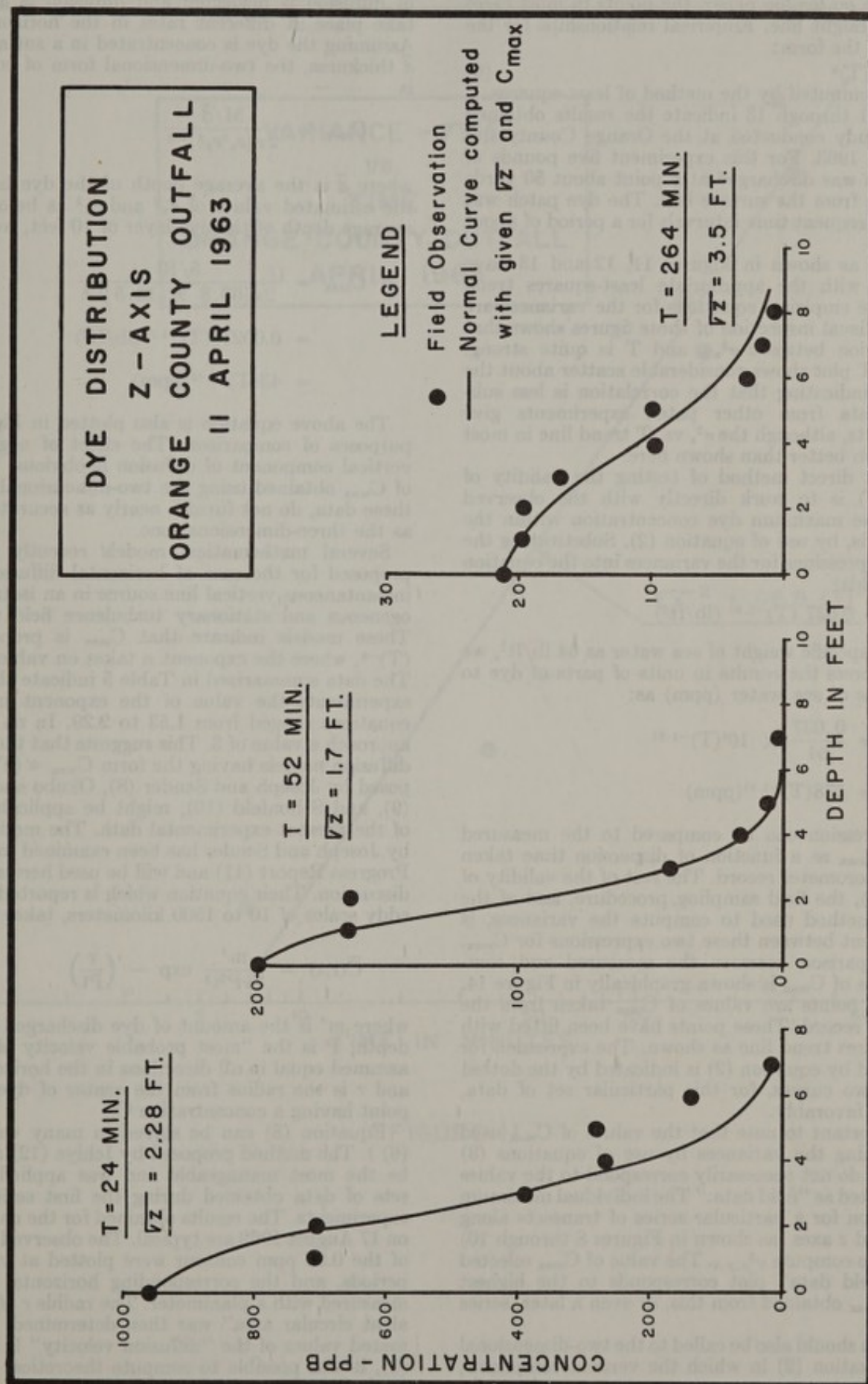
FIGURE 10

against time on log-log paper, the points in most cases defined a straight line. Empirical relationships for the variances of the form:

$$\bar{\sigma}^2 = k(T)^n \qquad (6)$$

were then computed by the method of least-squares.

Figures 11 through 13 indicate the results obtained from the study conducted at the Orange County site on 11 April 1963. For this experiment five pounds of dye solution was discharged at a point about 50 yards downstream from the surface boil. The dye patch was sampled at frequent time intervals for a period of about 6 hours.

The data as shown in Figures 11, 12 and 13 have been fitted with the appropriate least-squares trend lines and the empirical equations for the variances are indicated. Visual inspection of these figures shows that the correlation between $\sigma^2_{x,y}$ and T is quite strong. The σ^2_z vs. T plot shows considerable scatter about the trend line, indicating that the correlation is less substantial. Data from other patch experiments give similar results, although the σ^2_z vs. T trend line in most cases is much better than shown here.

The most direct method of testing the validity of equation (1) is to work directly with the observed values of the maximum dye concentration within the patch, that is, by use of equation (2). Substituting the empirical expressions for the variances into the equation for C_{max} yields:

$$C_{max} = 0.037 \, (T)^{-1.91} \, (lb/ft^3)$$

Taking the specific weight of sea water as 64 lb/ft³, we can also express the results in units of parts of dye to million parts of sea water (ppm) as:

$$C_{max} = \frac{0.037}{64} \times 10^6 (T)^{-1.91}$$

$$= 578(T)^{-1.91}(ppm)$$

This expression can be compared to the measured values of C_{max} as a function of dispersion time taken from the fluorometer record. The test of the validity of equation (2), the field sampling procedure, and of the analytical method used to compute the variances, is the agreement between these two expressions for C_{max}.

The comparison between the measured and computed values of C_{max} is shown graphically in Figure 14. The circled points are values of C_{max} taken from the fluorometer record. These points have been fitted with a least-squares trend line as shown. The expression for C_{max} derived by equation (2) is indicated by the dotted line. The two curves, for this particular set of data, agree quite favorably.

It is important to note that the values of C_{max} used in determining the variances by use of equations (3) through (5) do not necessarily correspond to the values of C_{max} plotted as "field data." The individual maximum concentration for a particular series of transects along the x, y, and z axes (as shown in Figures 8 through 10) were used to compute $\sigma^2_{x,y,z}$. The value of C_{max} selected for the "field data" plot corresponds to the highest value of C_{max} obtained from this, or even a later, series of samples.

Attention should also be called to the two-dimensional form of equation (2) in which the vertical component of diffusion is neglected and diffusion is assumed to take place at different rates in the horizontal plane. Assuming the dye is concentrated in a surface layer of $\bar{d}$ thickness, the two-dimensional form of equation (2) is

$$C_{max} = \frac{M/\bar{d}}{2\pi [\bar{\sigma}_x^2 \bar{\sigma}_y^2]^{1/2}} \qquad (2a)$$

where $\bar{d}$ is the average depth of the dye layer. Using the estimated values of $\bar{\sigma}_x^2$ and $\bar{\sigma}_y^2$ as before, and an average depth of the dye layer of 10 feet, we obtain:

$$C_{max} = \frac{5/10}{2\pi [68.8 \times 13.5]^{1/2}}$$

$$= 0.00275(T)^{-1.55}(lb/ft^3)$$

$$= 43(T)^{-1.55}(ppm)$$

The above equation is also plotted in Figure 14 for purposes of comparison. The effect of neglecting the vertical component of diffusion is obvious. The values of C_{max} obtained using the two-dimensional model, for these data, do not furnish nearly as accurate estimates as the three-dimensional one.

Several mathematical models recently have been proposed for the case of horizontal diffusion from an instantaneous vertical line source in an isotropic, homogeneous and stationary turbulence field in the sea. These models indicate that C_{max} is proportional to $(T)^{-n}$, where the exponent n takes on values of 2 or 3. The data summarized in Table 5 indicate that in these experiments the value of the exponent in the C_{max} equations ranged from 1.53 to 2.29. In no case did n approach a value of 3. This suggests that the horizontal diffusion models having the form $C_{max} \propto (T)^{-2}$, as proposed by Joseph and Sender (8), Okubo and Pritchard (9), and Schonfeld (10), might be applicable to some of the present experimental data. The model proposed by Joseph and Sender has been examined in a previous Progress Report (11) and will be used here as a basis of discussion. Their equation which is reportedly valid for eddy scales of 10 to 1500 kilometers, takes the form

$$\bar{C}(r,t) = \frac{m'}{2\pi P^2 t^2} \exp - \left(\frac{r}{Pt}\right) \qquad (8)$$

where m' is the amount of dye discharged per foot of depth, P is the "most probable velocity of diffusion" assumed equal in all directions in the horizontal plane, and r is the radius from the center of dye mass to a point having a concentration C.

Equation (8) can be solved in many ways (Okubo (6)). The method proposed by Ichiye (12) appeared to be the most manageable and was applied to several sets of data obtained during the first series of patch experiments. The results obtained for the data collected on 17 August 1962 are typical. The observed dimensions of the 0.05 ppm contour were plotted at various time periods, and the corresponding horizontal areas were measured with a planimeter. The radius r of an "equivalent circular area" was then determined. Using estimated values of the "diffusion velocity" P in equation (8), it was possible to compute theoretical values of r

FIGURE II

VARIANCE — $\overline{V_y}^2$
vs.
TIME
ORANGE COUNTY OUTFALL
II APRIL 1963

$\overline{V_y}^2 = 13.5\ (T)^{1.62}$

VARIANCE — $\overline{V_y}^2$ (FT^2 x 10^3)

TIME IN MINUTES

FIGURE 12

VARIANCE — $\overline{Vz}^2$
VS.
TIME
ORANGE COUNTY OUTFALL
II APRIL 1964
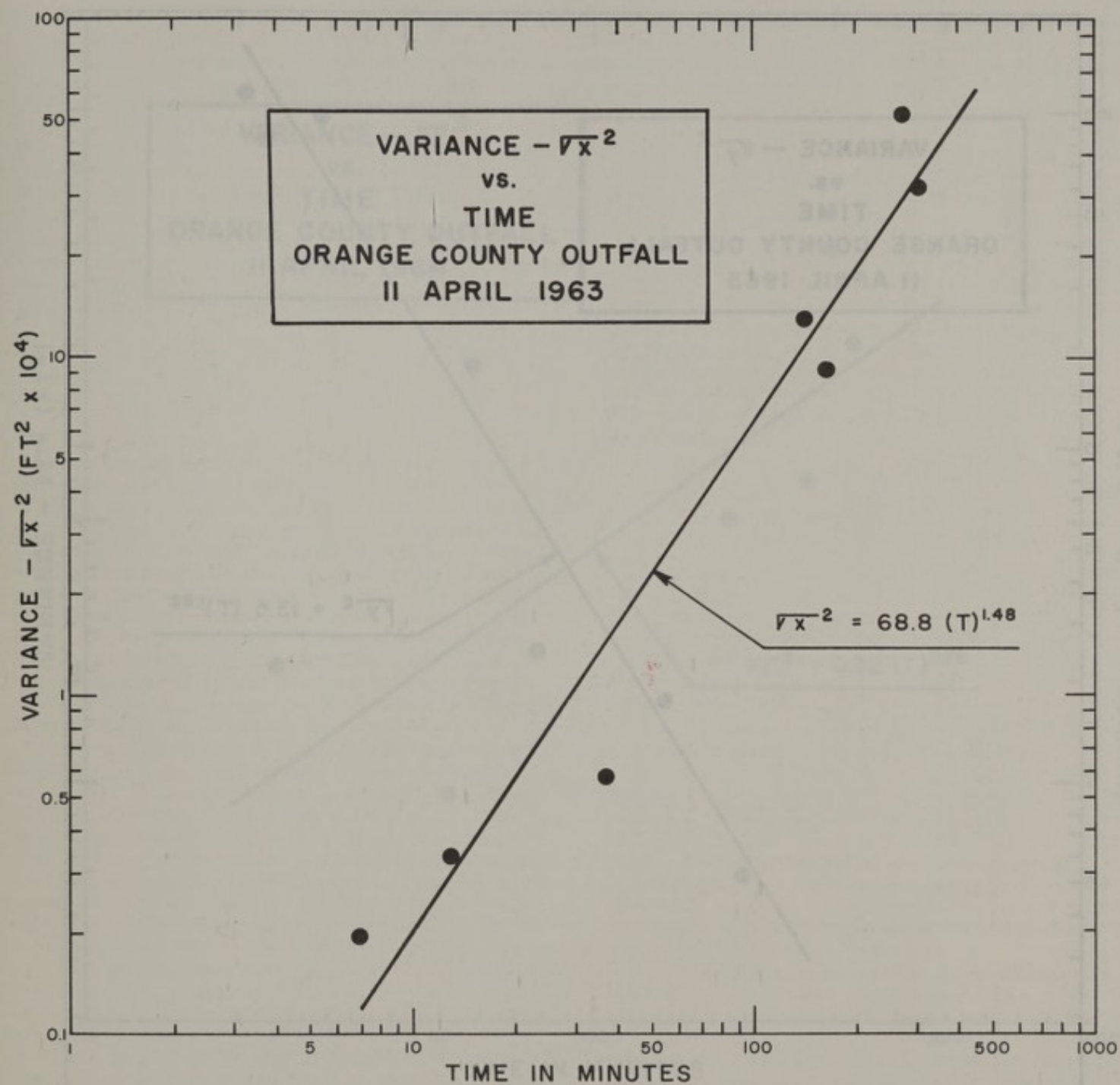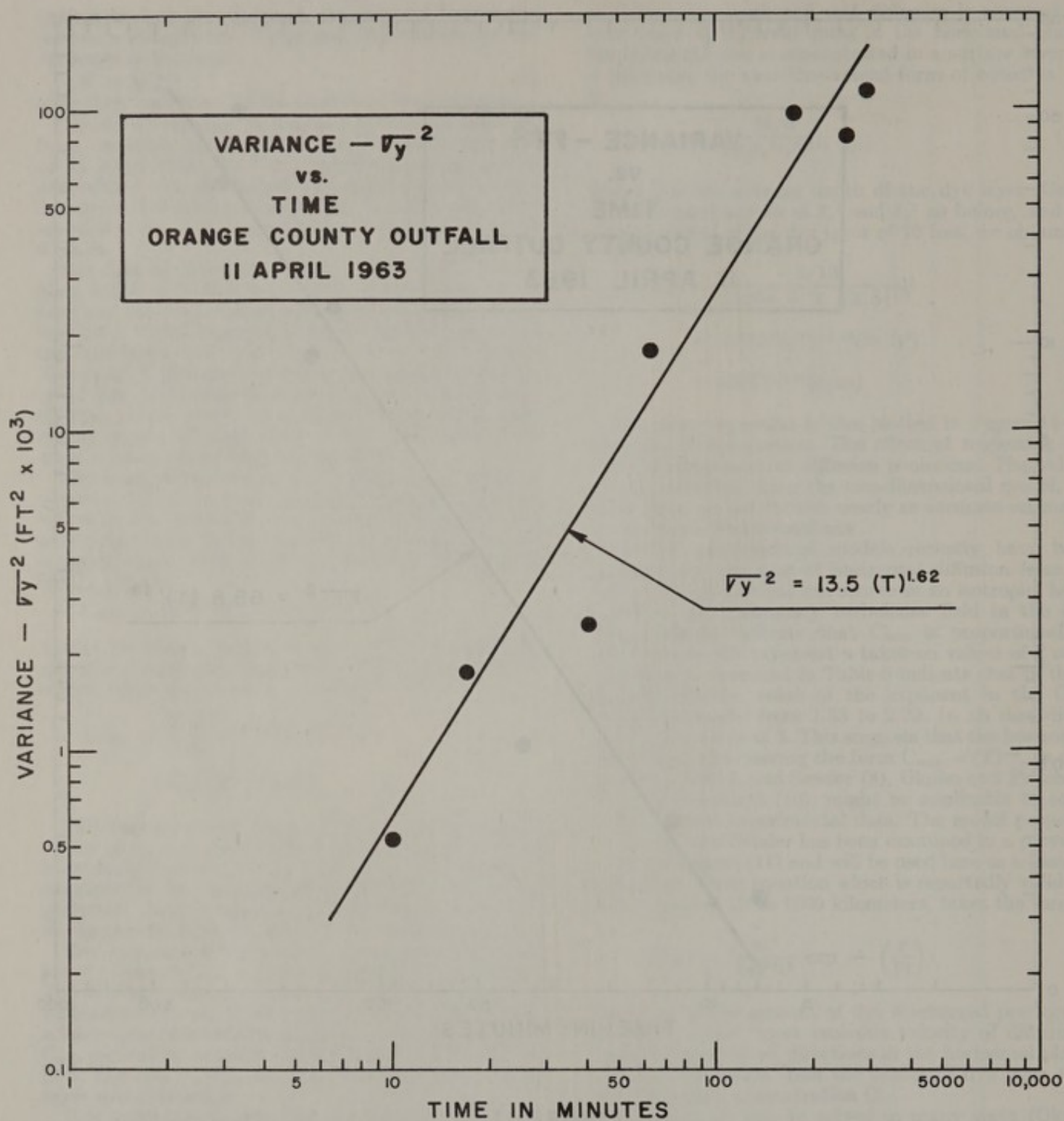
$\overline{Vz}^2 = 0.32\,(T)^{0.72}$
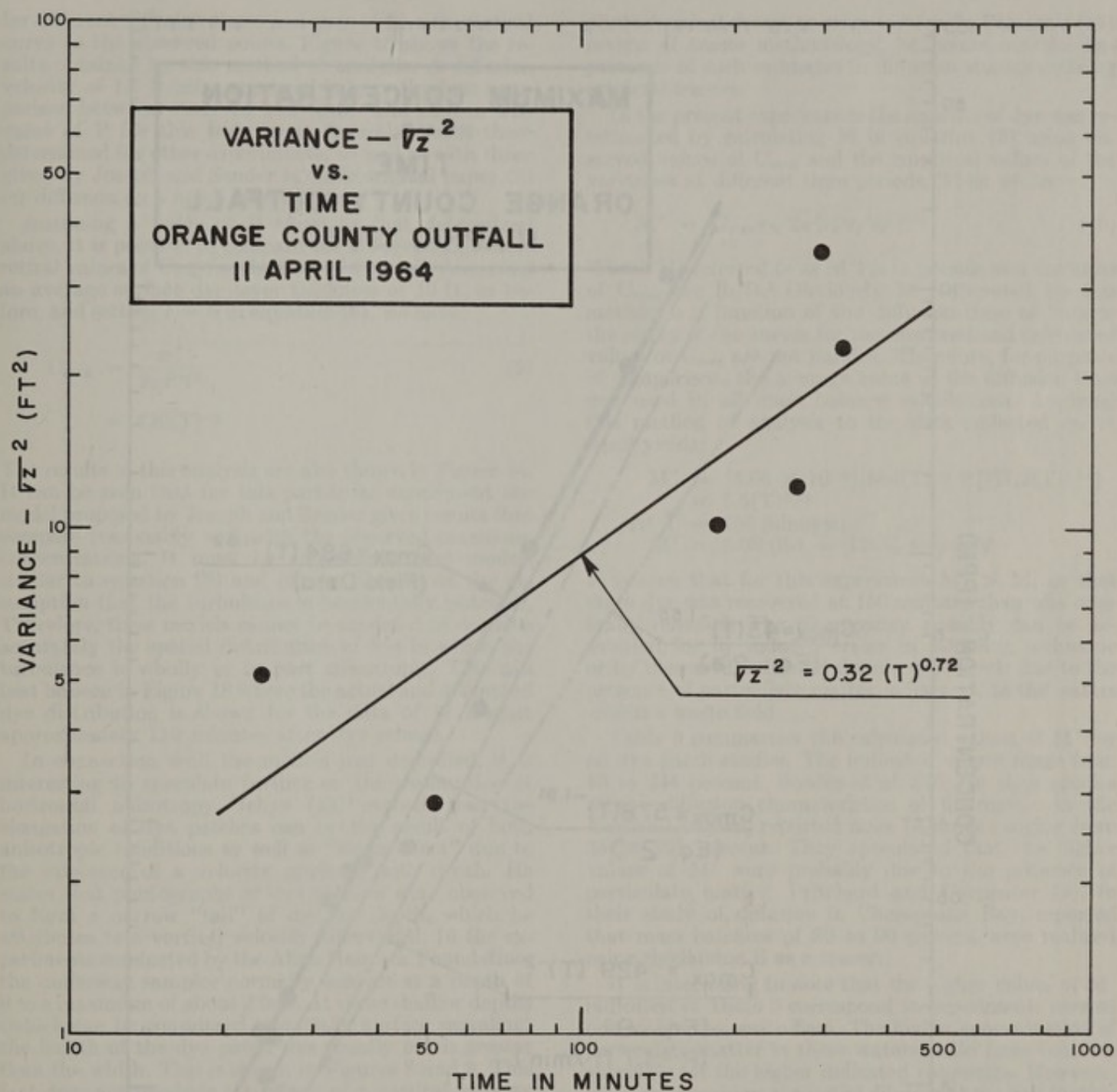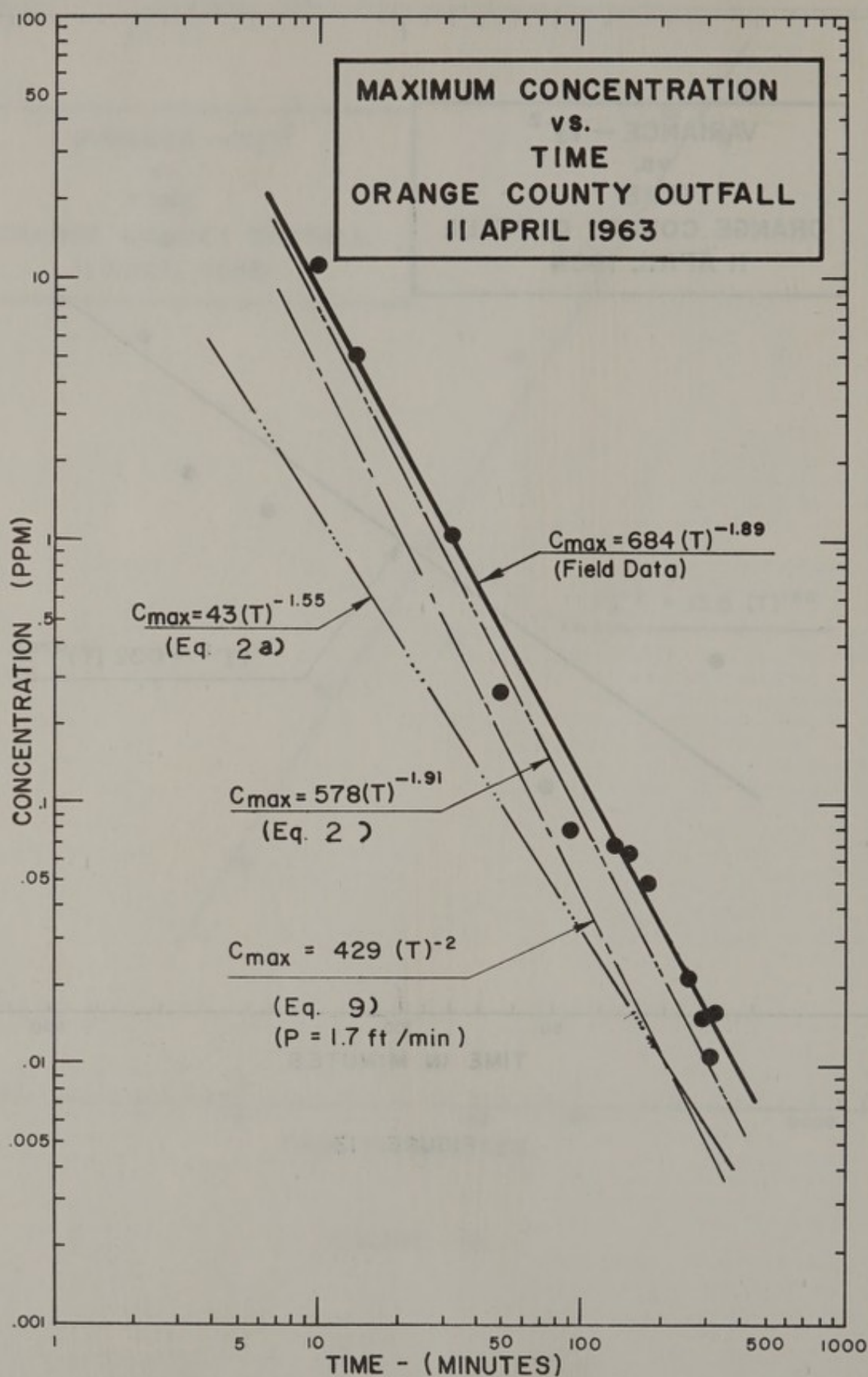
FIGURE 13

FIGURE 14

for different diffusion times and thus to fit a theoretical curve to the observed points. Figure 15 shows the results obtained by this method of analysis. A diffusion velocity of 1.7 ft/min. appeared to give the best comparison between observed and theoretical curves. The value of P for this test agrees favorably with those determined for other experiments, as well as with those given by Joseph and Sender in their original paper (8) for diffusion on a much larger scale.

Assuming a value of P equal to that determined above, it is possible to compare the observed and theoretical values of C_{max} for the data of 11 April. Assuming an average surface dye layer thickness of 10 ft. as before, and setting r = 0 in equation (8), we have:

$$C_{max} = \frac{m'}{2\pi P^2 t^2} \qquad (9)$$

$$= 429(T)^{-2}$$

The results of this analysis are also shown in Figure 14. It can be seen that for this particular experiment the model proposed by Joseph and Sender gives results that compare reasonably well with the observed maximum concentrations. It must be emphasized that models similar to equation (8) and (9) are derived on the assumption that the turbulence is horizontally isotropic. Therefore, these models cannot be expected to describe accurately the spatial distribution of dye in which the turbulence is wholly or in part anisotropic. This can best be seen in Figure 16 where the actual and estimated dye distribution is shown for the data of 17 August approximately 110 minutes after dye release.

In connection with the models just described, it is interesting to speculate further on the assumption of horizontal anisotropy. Ichye (13) reports that the elongation of dye patches can be the result of both anisotropic conditions as well as "shear effect" due to the existence of a velocity gradient with depth. He states that photographs of dye patches were observed to form a narrow "tail" of dye, at depth, which he attributes to a vertical velocity differential. In the experiments conducted by the Allan Hancock Foundation, the underway sampler normally was set at a depth of 0 to a maximum of about 2 feet. At those shallow depths (which can be considered essentially surface sampling) the length of the dye patch was usually much greater than the width. This is shown in Figures 8 and 9. This fact does not preclude the effects of a vertical velocity gradient in the thin upper layers of the water surface, but at least gives some substance to the assumption of horizontal anisotropy. If shear is important, its effect is included in the measured values of $\sigma^2_{x,y}$ shown in Table 5. Field measurements and analytical techniques devised to separate the shear effect from true anisotropy must be left for future study.

7. MASS BALANCE ANALYSIS

In any study of relative diffusion it is necessary periodically to re-estimate the amount of dye remaining within a patch. An analysis of this type is termed a "mass or materials balance." Depending on the accuracy of the calculations, a mass balance may indicate the amount of dye lost through physical adsorption, photochemical decay, or other factors. In Pearson's (14) review of tracer methodology, he points out the importance of such estimates in diffusion studies utilizing artificial tracers.

In the present experiments the amount of dye was re-estimated by calculating M in equation (2) using observed values of C_{max} and the empirical values of the variances at different time periods. Thus we have:

$$M' = C_{max}\pi\sqrt{2\pi}\,[\bar{\sigma}_x^2\bar{\sigma}_y^2\bar{\sigma}_z^2]^{1/2} \qquad (10)$$

Where M (referred to as M') is in pounds and the units of C_{max} are lb/ft.³ Obviously M' computed by this method is a function of the diffusion time as long as the slopes of the curves for the observed and calculated values of C_{max} are not parallel. Therefore, for purposes of comparison, the average value of the diffusion time was used in all mass balance calculations. Applying this method of analysis to the data collected on 11 April yields:

$$M' = [4.66 \times 10^{-4}][684(T)^{-1.89}][17.2(T)^{1.91}]$$
$$= 5.5(T)^{0.02}$$
$$\text{At } \overline{T} = 150 \text{ minutes:}$$
$$M' = 6.08 \text{ (lb)} = 122\% \text{ recovery}$$

It is seen that for this experiment M' > M, or that more dye was recovered at 150 minutes than was originally released. The discrepancy possibly can be accounted for by induced errors in sampling technique or by increased indicated fluorescence levels due to the presence of particulate matter indigenous to the waters within a waste field.

Table 5 summarizes the calculated values of M' for all dye patch studies. The indicated values range from 40 to 244 percent. Bowles et al. (15), in their studies of the diffusion characteristics of fluorescein in the English Channel, reported mass balances ranging from 35 to 304 percent. They speculated that the higher values of M' were probably due to the presence of particulate matter. Pritchard and Carpenter (3), in their study of diffusion in Chesapeake Bay, reported that mass balances of 80 to 90 percent were realized using rhodamine B as a tracer.

It is interesting to note that the higher values of M' indicated in Table 5 correspond to experiments carried out within the waste field. The higher concentration of particulate matter in these waters could have been responsible for the higher indicated recoveries. However, when one considers the initial dilution at the boil (values for these experiments ranged from 7/1 to 20/1.) plus the rapid dilution as the field moves downstream, it is not likely that particulate matter was a serious problem. This is confirmed by transparency measurements taken in the field.

The values of M' for experiments conducted in the background sites outside the waste field ranged from 37 to 78 percent. These waters were characterized by relatively low natural turbidity. In all but one of these experiments the stabilities were much lower than that observed in the waste field at Orange County. The rate of vertical diffusion, with one exception, was observed to be much greater in these areas. Deeper dye penetration made vertical sampling more difficult, and it is possible that the observed data were less accurate for

FIGURE 15

0.05 PPM CONTOUR
AT
T = 110 MINUTES
ORANGE COUNTY
17 AUGUST 1962

0.05 PPM CONTOUR

≈960 FT.

75 FT.

EQUIVALENT AREA

r = 146 FT.

100 FT.
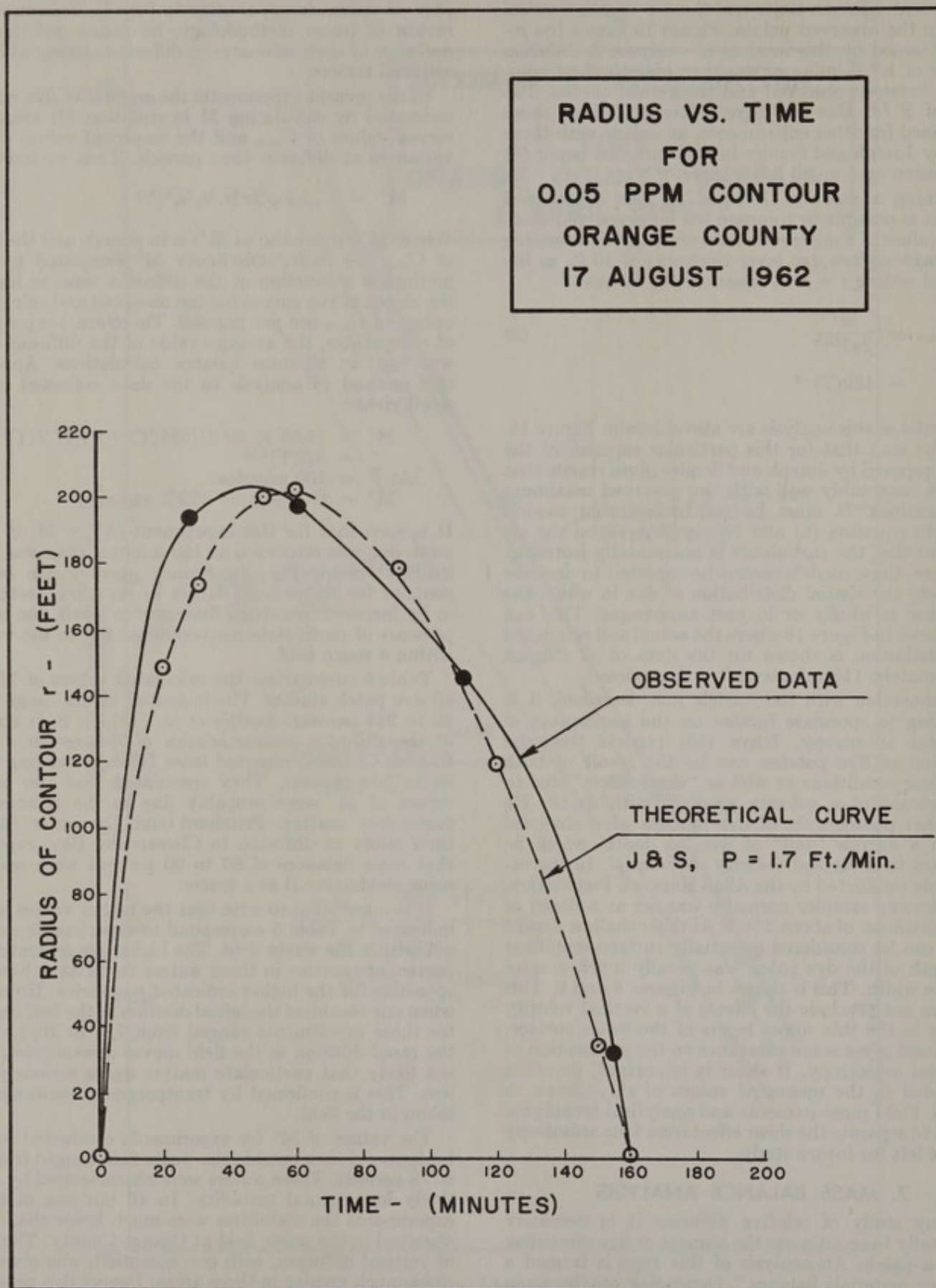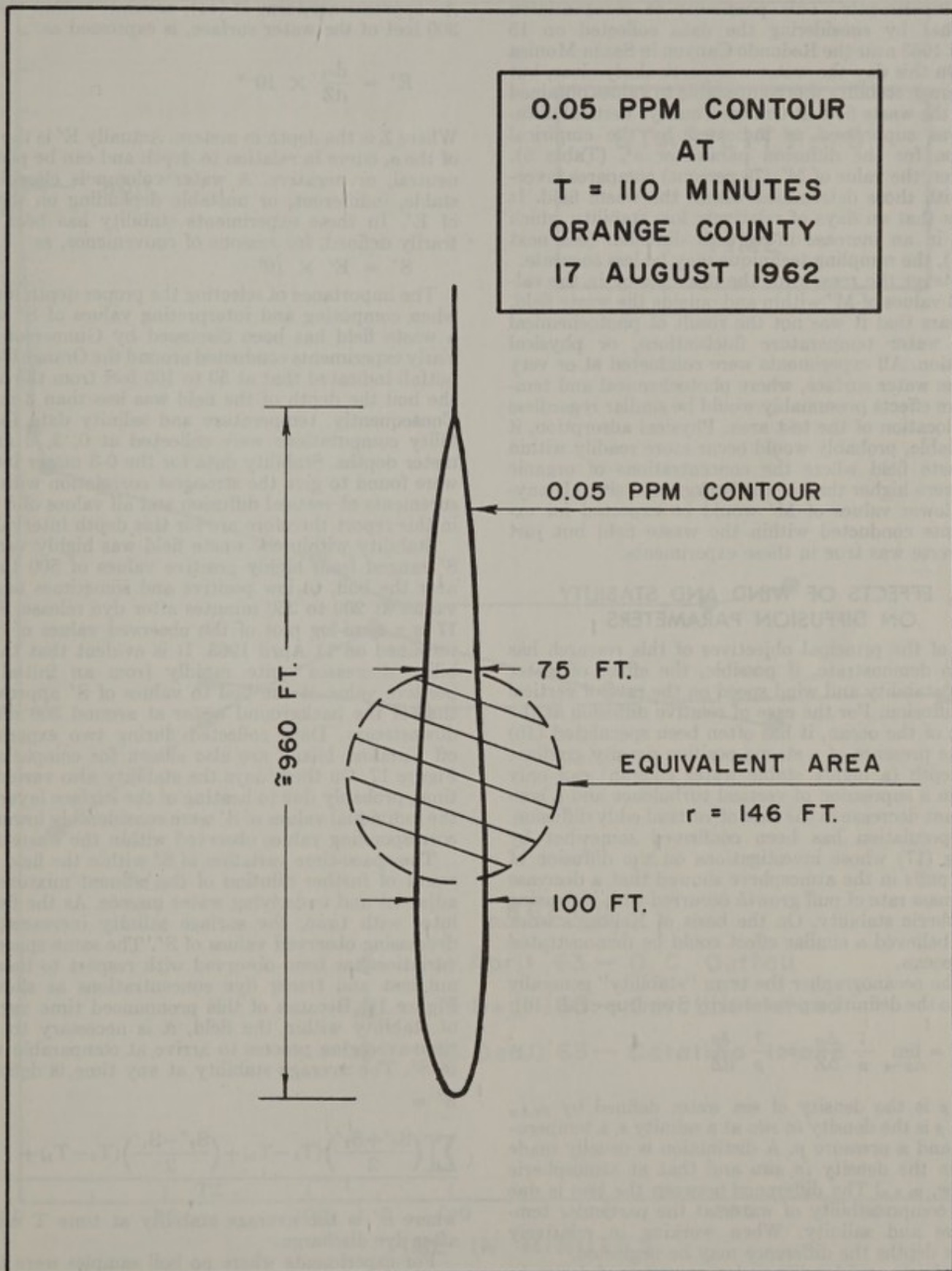
FIGURE 16

these experiments. This possibility is substantiated somewhat by considering the data collected on 15 August 1963 near the Redondo Canyon in Santa Monica Bay. On this day the water was particularly clear, but the average stability was comparable to values obtained within the waste field at Orange County. Vertical diffusion was suppressed as indicated by the empirical equation for the diffusion parameter σ_z^2 (Table 5). However, the value of M' (78 percent) compares favorably with those determined within the waste field. It appears that on days of relatively low stability which results in an increase in vertical diffusion (see next section), the sampling technique may be less accurate.

Whatever the reason for the discrepancy in the calculated values of M' within and outside the waste field, it appears that it was not the result of photochemical decay, water temperature fluctuations, or physical adsorption. All experiments were conducted at or very near the water surface, where photochemical and temperature effects presumably would be similar regardless of the location of the test area. Physical adsorption, if appreciable, probably would occur more readily within the waste field where the concentrations of organic solids were higher than at the background sites. If anything, lower values of M' would be expected for experiments conducted within the waste field but just the reverse was true in these experiments.

8. EFFECTS OF WIND AND STABILITY ON DIFFUSION PARAMETERS

One of the principal objectives of this research has been to demonstrate, if possible, the effect of water column stability and wind speed on the rate of vertical eddy diffusion. For the case of relative diffusion at the surface of the ocean, it has often been speculated (16) that the presence of a strong positive density gradient with depth (a highly stable water column) can only result in a supression of vertical turbulence and a concomitant decrease in the rate of vertical eddy diffusion. This speculation has been confirmed somewhat by Kellogg (17) whose investigations on the diffusion of smoke puffs in the atmosphere showed that a decrease in the mass rate of puff growth occurred with increasing atmospheric stability. On the basis of Kellogg's work it was believed a similar effect could be demonstrated in the ocean.

To the oceanographer the term "stability" generally refers to the definition presented by Sverdrup et al. (16):

$$E = \lim_{\triangle z \to 0} \frac{1}{\rho} \frac{\triangle\rho}{\triangle Z} = \frac{1}{\rho} \frac{\delta\rho}{dZ} \qquad (11)$$

where ρ is the density of sea water defined by $\rho_{s,\theta,p}$ that is, ρ is the density *in situ* at a salinity s, a temperature θ and a pressure p. A distinction is usually made between the density *in situ* and that at atmospheric pressure, $\rho_{s,\theta,0}$. The difference between the two is due to the compressibility of water at the particular temperature and salinity. When working in relatively shallow depths the difference may be neglected.

In order to avoid writing a large number of decimals, the density $(\rho_{s,\theta,0})$ is normally expressed by the symbol sigma-t, defined by:

$$\sigma_t = (\rho_{s,\theta,0} - 1)\, 10^3 \qquad (12)$$

An approximate form of (11), accurate within the first 300 feet of the water surface, is expressed as:

$$E' = \frac{d\sigma_t}{dZ} \times 10^{-3} \qquad (13)$$

Where Z is the depth in meters. Actually E' is the slope of the σ_t curve in relation to depth and can be positive, neutral, or negative. A water column is classified as stable, indifferent, or unstable depending on the sign of E'. In these experiments stability has been arbitrarily defined, for reasons of convenience, as

$$S' = E' \times 10^7$$

The importance of selecting the proper depth interval when computing and interpreting values of S' within a waste field has been discussed by Gunnerson (18). Early experiments conducted around the Orange County outfall indicated that at 50 to 100 feet from the axis of the boil the depth of the field was less than 3 meters. Consequently, temperature and salinity data for stability computations were collected at 0, 3, 6 and 12 meter depths. Stability data for the 0-3 meter interval were found to give the strongest correlation with measurements of vertical diffusion and all values of S' used in this report therefore are for this depth interval.

Stability within the waste field was highly variable. S' ranged from highly positive values of 500 to 5800 near the boil, to low positive and sometimes negative values at 200 to 250 minutes after dye release. Figure 17 is a semi-log plot of the observed values of S' determined on 11 April 1963. It is evident that the stability decreases quite rapidly from an initial high positive value at the boil to values of S' approaching that of the background water at around 300 minutes downstream. Data collected during two experiments off Catalina Island are also shown for comparison in Figure 17. On these days the stability also varied with time, probably due to heating of the surface layers, but the individual values of S' were considerably lower than corresponding values observed within the waste field.

The space-time variation of S' within the field is the result of further dilution of the effluent mixture with adjacent and underlying water masses. As the field dilutes with time, the surface salinity increases, thus decreasing observed values of S'. The same space-time variation has been observed with respect to inorganic nutrient and tracer dye concentrations as shown in Figure 18. Because of this pronounced time variation of stability within the field, it is necessary to use a time-averaging process to arrive at comparable values of S'. The average stability at any time is defined as

$$\bar{S}' = \frac{\sum\left[\left(\dfrac{S_0'+S_1'}{2}\right)(T_1-T_0)+\left(\dfrac{S_2'-S_1'}{2}\right)(T_2-T_1)+ \ldots\right]}{\sum T}$$

where $\bar{S}'$ is the average stability at time T minutes after dye discharge.

For experiments where no boil samples were taken, the average of all observed boil stabilities (4500) was arbitrarily used. The computed average values of S' for all experiments at or about 200 minutes after dye release are indicated in Tables 4 and 6.
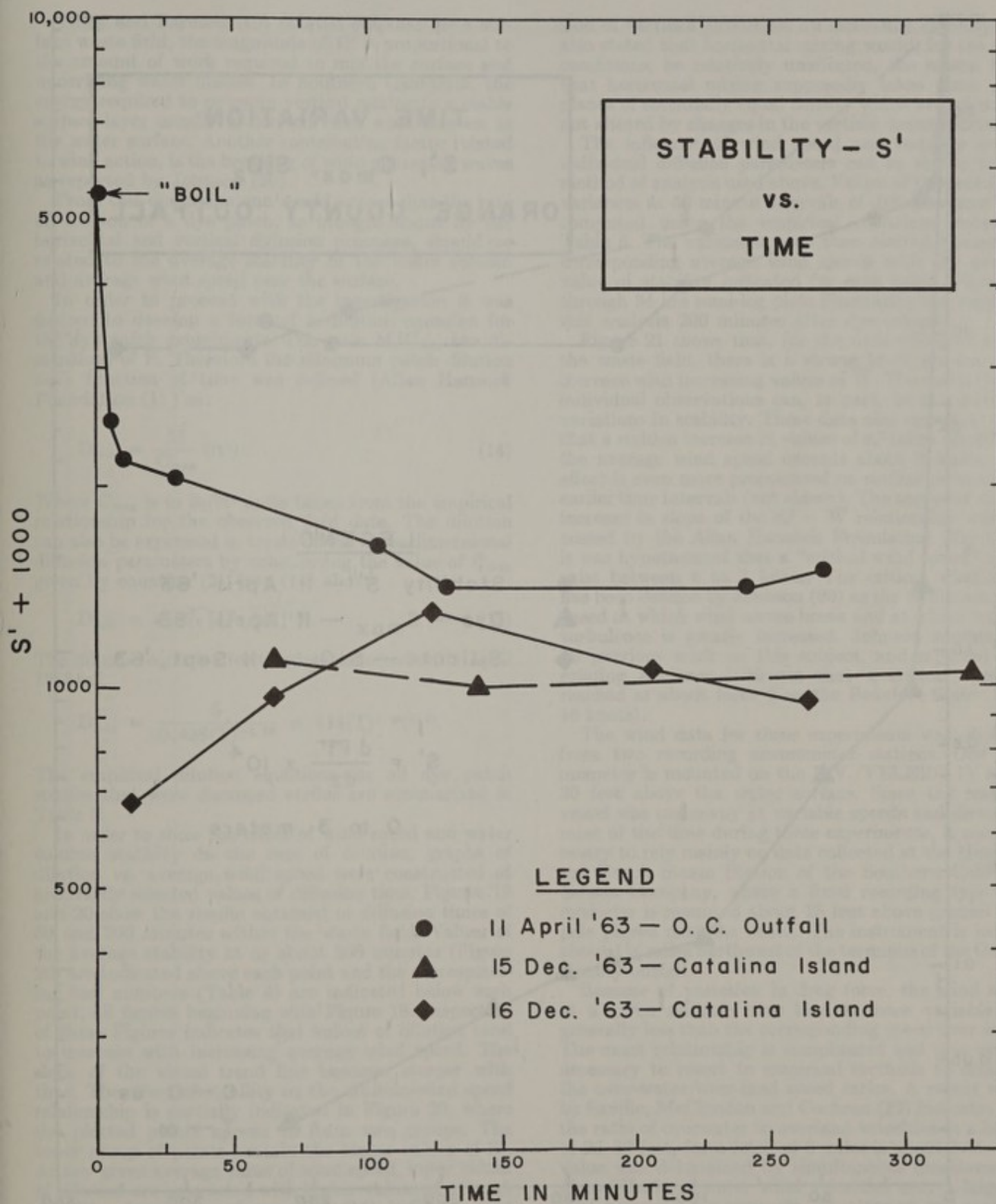
FIGURE 17
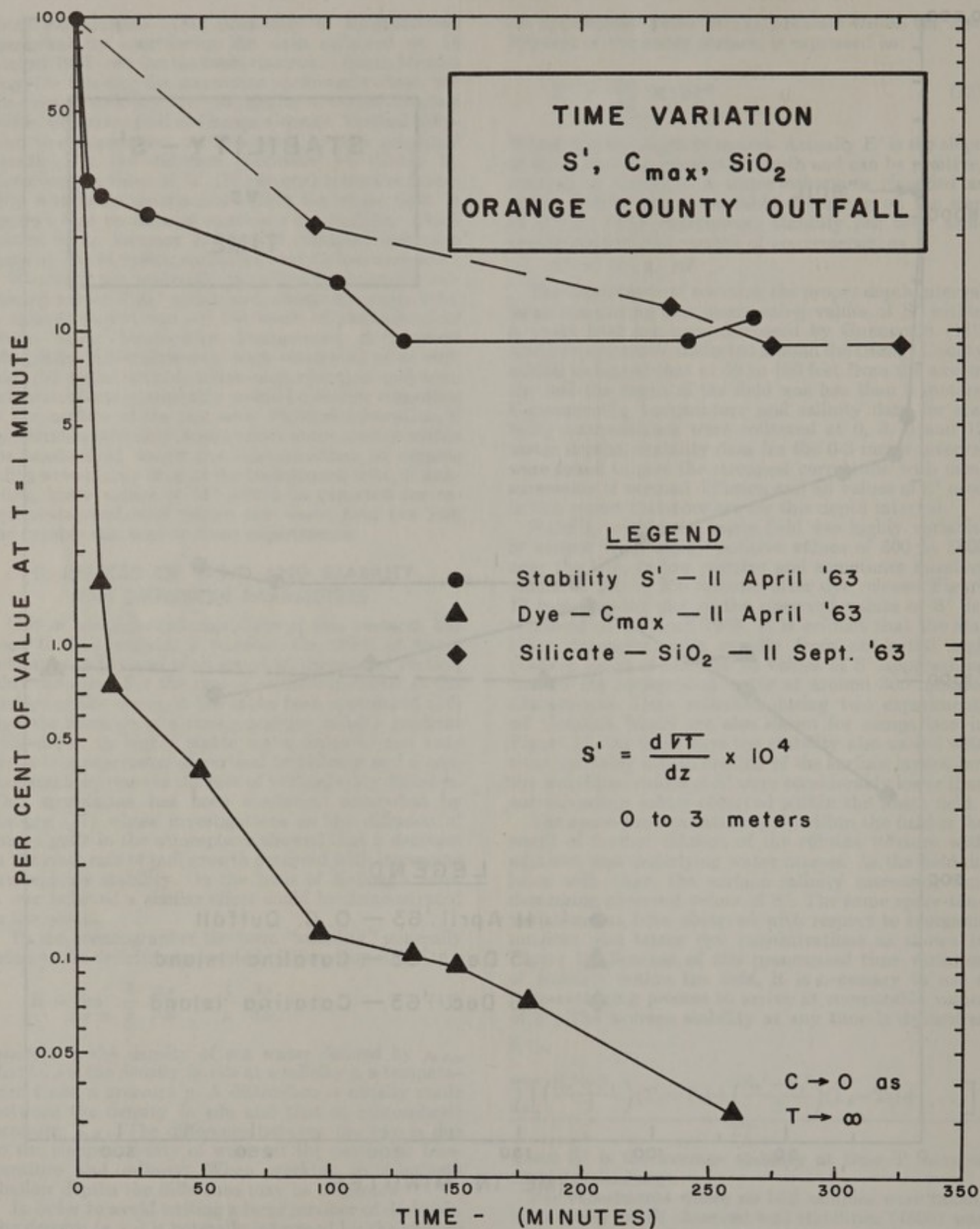
FIGURE 18

Tibby and Barnard (19) pointed out that for a surface waste field, the magnitude of E′ is proportional to the amount of work required to mix the surface and underlying water masses. In Southern California, the energy required to promote vertical mixing in a stable surface layer usually is derived from wind stresses at the water surface. Another contributing factor related to wind action, is the breaking of wind-generated waves as reported by Johnson (20).

From this discussion one would expect that the rate of dilution of a dye patch, as brought about by the horizontal and vertical diffusion processes, should be related to the average stability of the water column and average wind speed near the surface.

In order to proceed with the investigation it was desired to develop a form of a dilution equation for the dye patch experiments. The ratio M/C_{max} has dimensions of l^3. Therefore the minimum patch dilution as a function of time was defined (Allan Hancock Foundation (1)) as:

$$D_{min} = \frac{M}{C_{max}} \text{ (ft}^3) \qquad (14)$$

Where C_{max} is in lb/ft^3 units taken from the empirical relationship for the observed field data. The dilution can also be expressed in terms of the three-dimensional diffusion parameters by substituting the value of C_{max} given by equation (2), into (14) above

$$D_{min} = \pi\sqrt{2\pi}[\bar{\sigma}_x{}^2\bar{\sigma}_y{}^2\bar{\sigma}_z{}^2]^{1/2} \qquad (15)$$

The dilution equation for the data collected on 11 April 1963 is:

$$D_{min} = \frac{5}{0.438(T)^{-1.89}} = 114(T)^{1.89}(ft^3)$$

The empirical dilution equations for all dye patch studies that were discussed earlier are summarized in Table 5.

In order to show the effect of wind speed and water column stability on the rate of dilution, graphs of dilution vs. average wind speed were constructed at arbitrarily selected values of diffusion time. Figures 19 and 20 show the results obtained at diffusion times of 50 and 200 minutes within the waste field. Values of the average stability at or about 200 minutes (Figure 20) are indicated above each point and the corresponding test numbers (Table 4) are indicated below each point, all figures beginning with Figure 18. Inspection of these Figures indicates that values of dilution tend to increase with increasing average wind speed. The slope of the visual trend line becomes steeper with time. The effect of stability on the dilution-wind speed relationship is partially indicated in Figure 20, where the plotted points appear to form two groups. The lower group of points contain the higher values of S′. At any given average value of wind speed, lower values of dilution are associated with higher values of average stability. Inspection of equation (15) indicates that this effect is controlled by the relationship between S′ and the vertical diffusion parameter $\bar{\sigma}_z{}^2$, provided the horizontal parameters are unaffected by stability. Sverdrup et al. (16) not only speculated on the supres-

sion of vertical turbulence by increasing stability, but also stated that horizontal mixing would, for the same conditions, be relatively unaffected, the reason being that horizontal mixing supposedly takes place along planes of essentially equal density which are, of course, not altered by changes in the vertical density structure.

The influence of wind speed and stability on the individual diffusion parameters can be shown by the method of analysis used above. Values of the coordinate variances at 50 minute intervals of diffusion time were computed using the empirical equations shown in Table 5. The variances were then plotted against the corresponding average wind speeds with the average value of stability indicated for each point. Figure 21 through 24 are semi-log plots illustrating the results of this analysis 200 minutes after dye release.

Figure 21 shows that, for the data collected within the waste field, there is a strong tendency for $\bar{\sigma}_z{}^2$ to increase with increasing values of $\bar{W}$. The scatter in the individual observations can, in part, be attributed to variations in stability. These data also appear to show that a sudden increase in values of $\bar{\sigma}_z{}^2$ takes place when the average wind speed exceeds about 8 knots. This effect is even more pronounced on similar plots for the earlier time intervals (not shown). The apparent sudden increase in slope of the $\bar{\sigma}_z{}^2 - \bar{W}$ relationship was discussed by the Allan Hancock Foundation (21) where it was hypothesized that a "critical wind speed" might exist between 6 to 7 knots. The critical wind speed has been defined by Johnson (20) as the minimum wind speed at which wind waves break and at which vertical turbulence is greatly increased. Johnson summarized all previous work on this subject, and reported that existing evidence indicates that a critical speed is reached at about force 4 on the Beaufort Scale (11 to 16 knots).

The wind data for these experiments was obtained from two recording anemometer stations. One anemometer is mounted on the R.V./VELERO IV about 30 feet above the water surface. Since the research vessel was underway at variable speeds and directions most of the time during these experiments, it was necessary to rely mainly on data collected at the Huntington Beach Steam Station of the Southern California Edison Company, where a fixed recording type anemometer is mounted about 25 feet above ground on a pole placed near the beach. The instrument is located about 1½ miles northwest of the terminus of the Orange County outfall.

Because of variation in drag force, the wind speed at a given altitude over land is more variable and generally less than the corresponding speed over water. The exact relationship is complicated and it is usually necessary to resort to empirical methods to establish the over-water/over-land speed ratios. A recent study by Saville, McClendon and Cochran (22) indicates that the ratio of overwater to overland velocities at a height of 25–30 feet, for a fetch of 8 miles is about 1.31. This value was determined by simultaneous measurements of overland-overwater wind velocities near a large inland water supply reservoir. An attempt was made to establish a similar relationship for the Orange County test area. Airspeed recordings for the same period from both anemometer stations were compared. These data, collected on 14 different days, cover the period from

T = 50 MINUTES

DILUTION
VS.
AVERAGE WIND SPEED
ORANGE COUNTY OUTFALL
1962 - 1964

DILUTION (FT³ X 10⁵)

WIND SPEED - $\overline{W}$ (KNOTS)
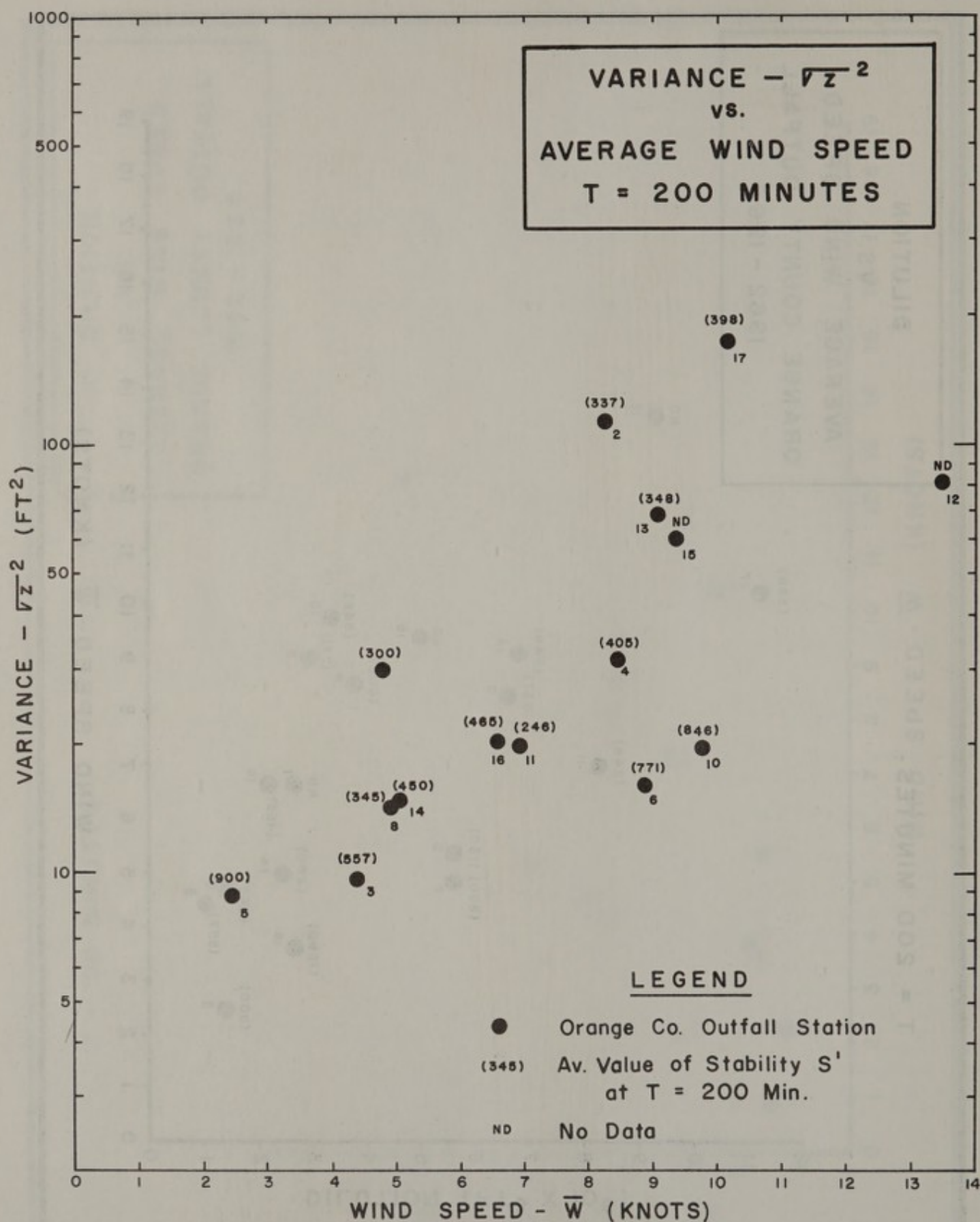
FIGURE 19

FIGURE 20

FIGURE 21

FIGURE 22

FIGURE 23

VARIANCE — $\overline{\sigma_y}^2$
vs.
AVERAGE WIND SPEED
T = 200 MINUTES

LEGEND

● Orange County Station
◆ Background Station
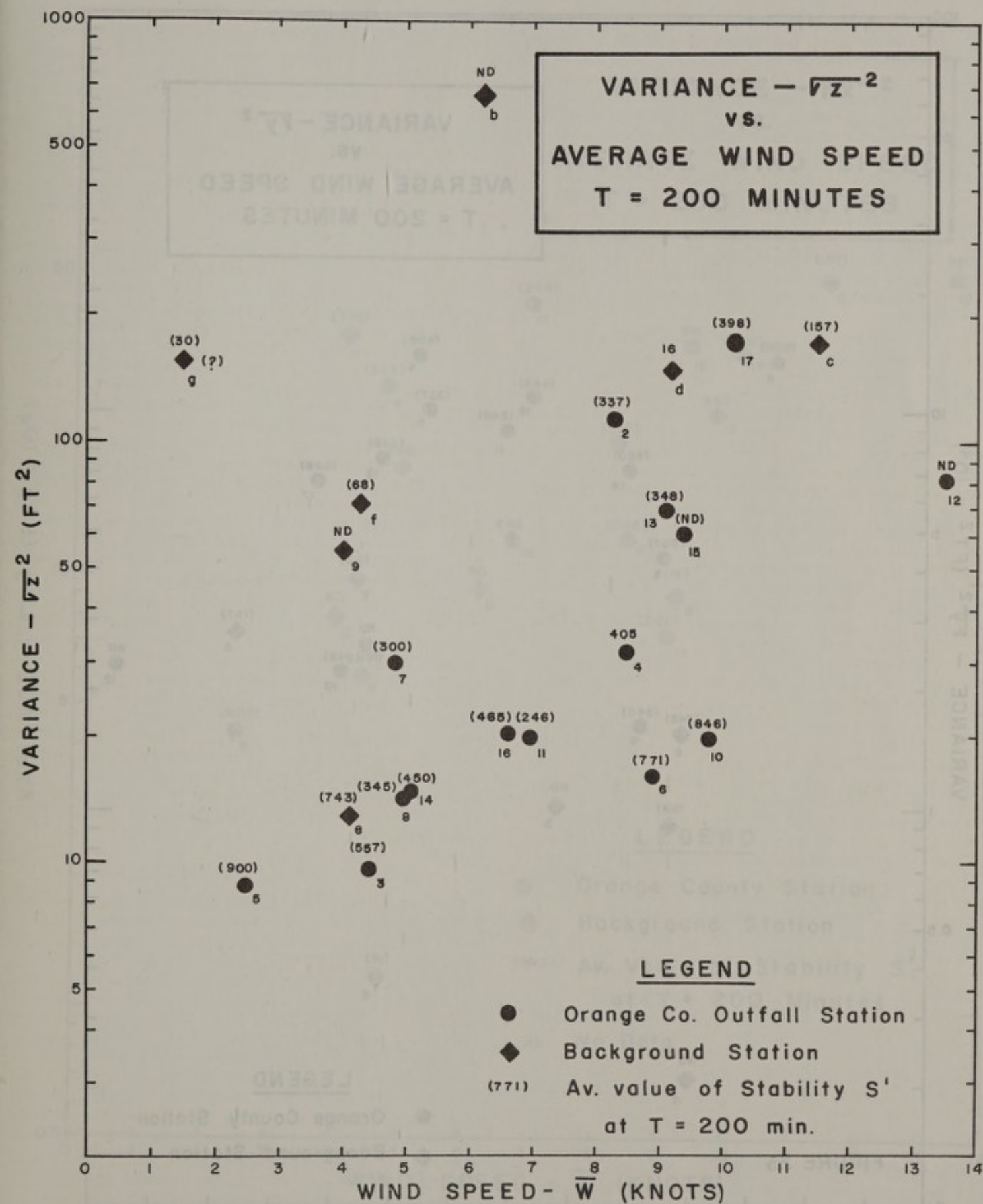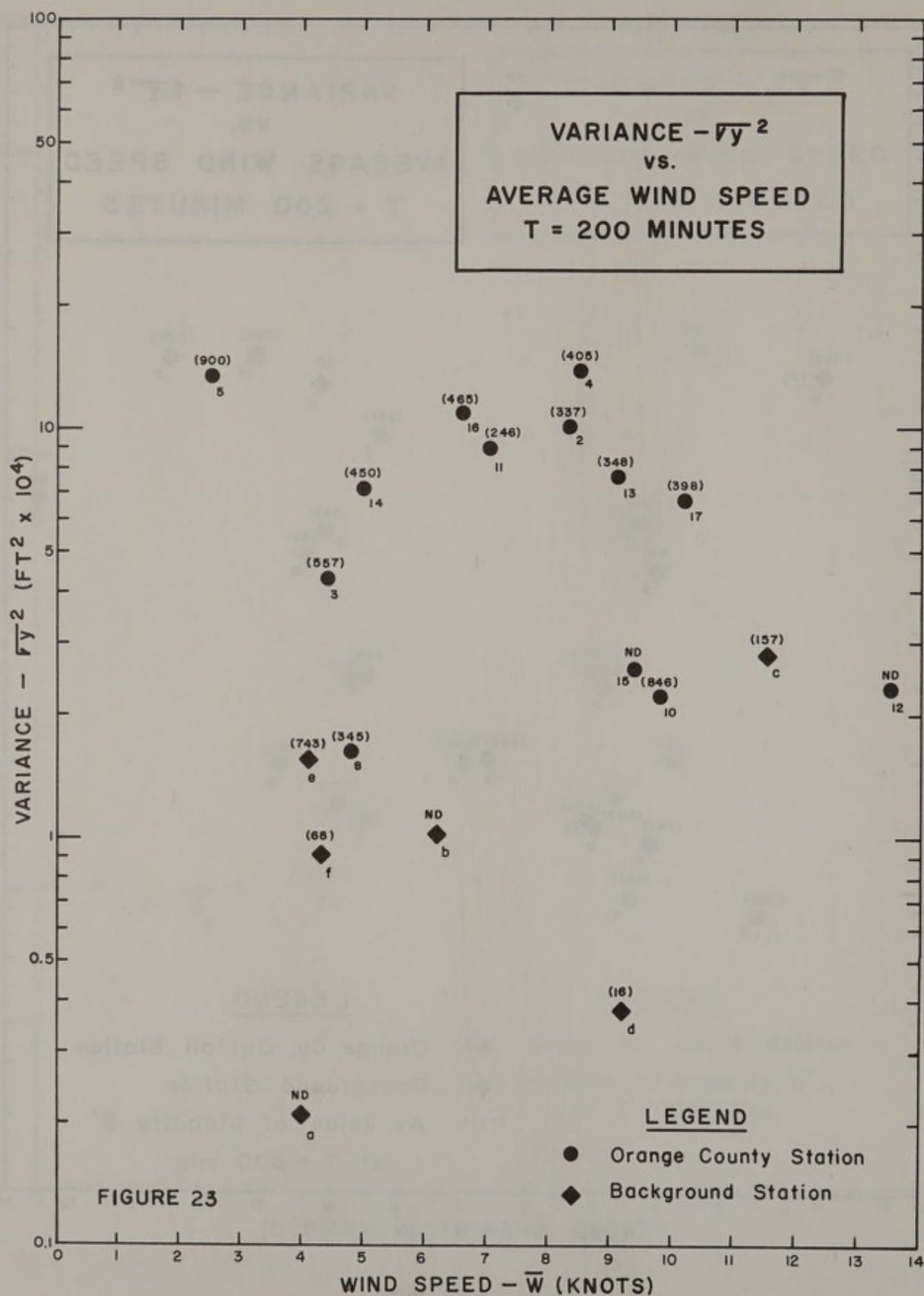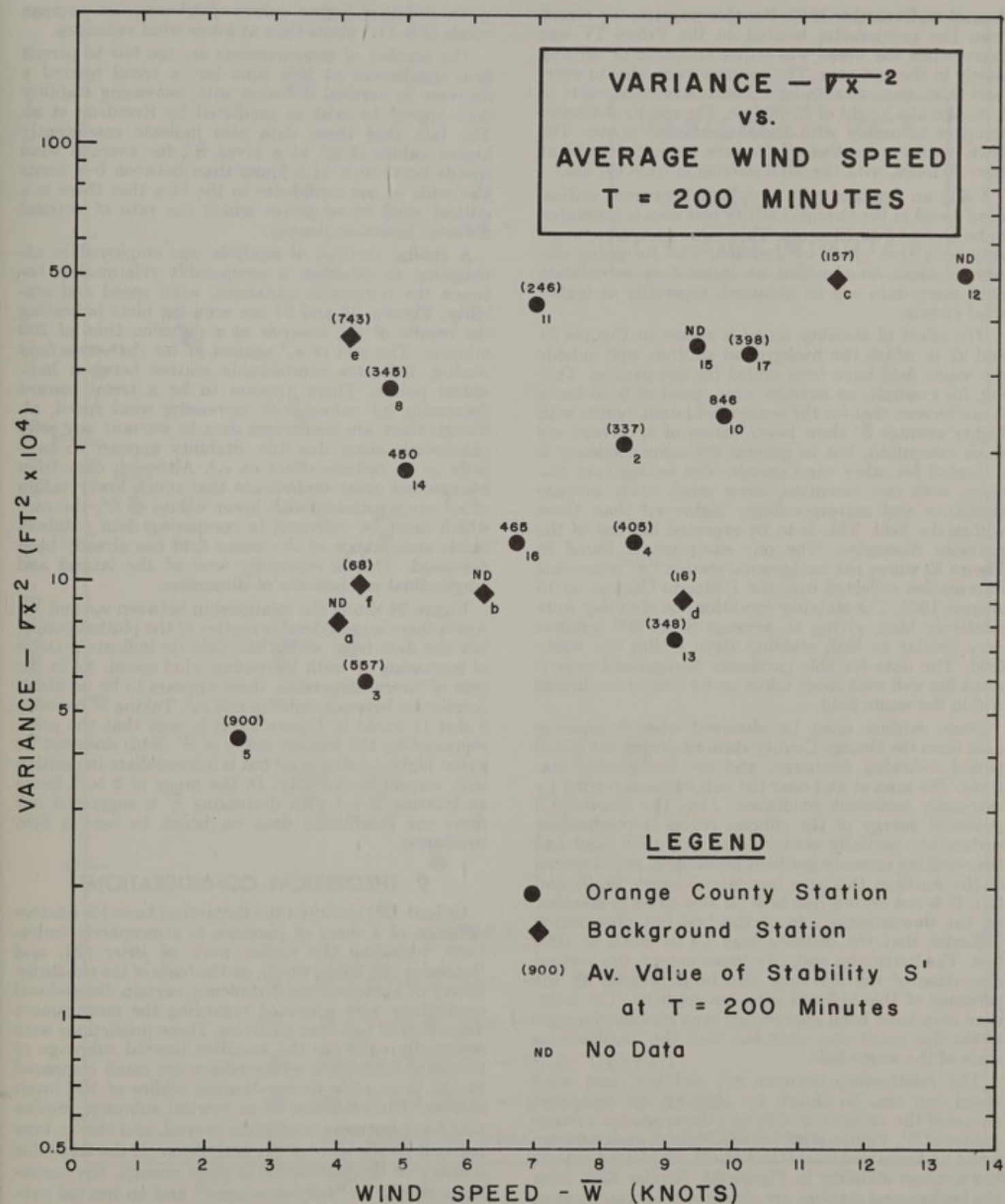
FIGURE 24

August to December 1962. For this purpose, the record from the anemometer located on the Velero IV was taken when the vessel was either anchored or drifting slowly in the test area. The average overwater to overland ratio was found to be 1.3 with a median value of 1.18, also at a height of 25–30 fe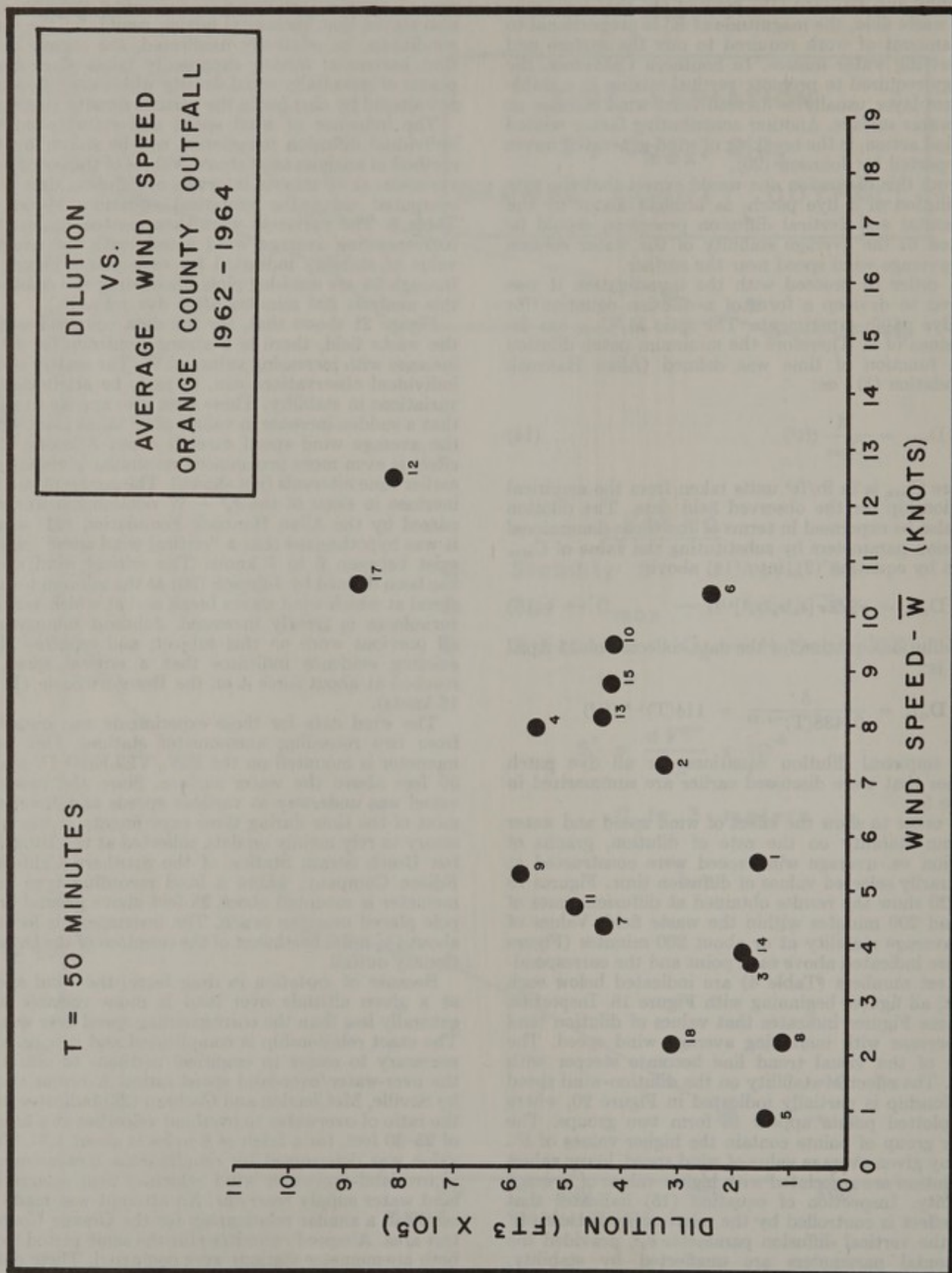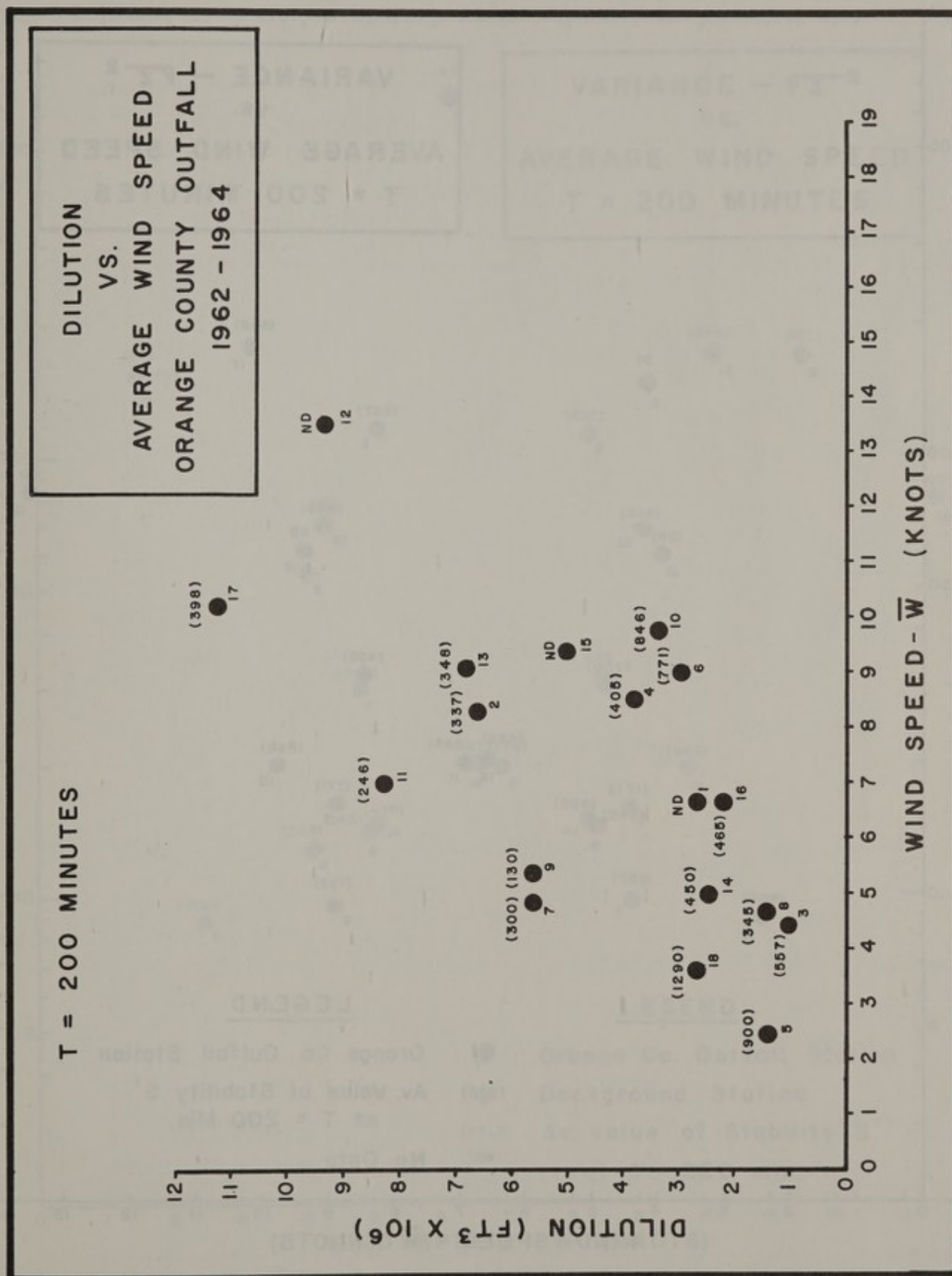et. The results obviously compare favorably with those mentioned above. The fetch distances for these data were estimated to be at least 20 miles, with the wind moving in from the sea.

Using an average ratio of 1.3, the apparent critical wind speed in the Orange County test area is estimated to be around 9 to 12 knots. This value compares favorably with that given by Johnson. The foregoing discussion must be classified as interesting speculation until more data can be obtained, especially at higher wind speeds.

The effect of stability on $\bar{\sigma}_z{}^2$ is shown in Figures 21 and 22 in which the background stations well outside the waste field have been added for comparison. Taking, for example, an average wind speed of 8–10 knots it can be seen that for the sewage field data, points with higher average $\bar{S}'$ show lower values of $\bar{\sigma}_z{}^2$. There are some exceptions, but in general the same tendency is indicated for other wind speeds. The background stations, with one exception, show much lower average stabilities and correspondingly higher $\sigma_z{}^2$ than those within the field. This is to be expected in view of the previous discussion. The one exception is found in Figure 22 where the background station "e" represents information collected over the Redondo Canyon on 15 August 1963. The stability conditions on that day were relatively high, giving an average $\bar{S}'$ at 200 minutes very similar to high stability days within the waste field. The data for this particular background experiment fits well with those taken under similar conditions within the waste field.

Some caution must be observed when comparing data from the Orange County stations during the initial period following discharge, and the background stations. The area at and near the boil is characterized by extremely turbulent conditions. Also, the kinetic and potential energy of the effluent jet as it reaches the surface are partially converted to hydraulic head and the resulting pressure gradient promotes a radial spread of the waste in this area (see later Figures 26, 27 and 28). It is not known just how far this effect is manifest on the downstream side of the boil but observation indicates that the distance may be as much as 1000 feet. The horizontal and, to a lesser extent, the vertical dispersion of the dye may also be influenced by the presence of this induced pressure gradient. The influence may have been appreciable even though the scale of the dye patch was much less than the simultaneous scale of the waste field.

The relationship between $\bar{\sigma}_z{}^2$, stability, and wind speed can also be shown by plotting the computed values of the variance at different times against average values of S'. Values of $\bar{\sigma}_z{}^2$ for wind speeds ranging from 8 to 11.5 knots and from 0 to 8 knots are plotted against the average stability in Figure 25. Similar data from the background stations are also shown for comparison. The Figure indicates that within both ranges of wind speed, there is a tendency for $\bar{\sigma}_z{}^2$ to decrease with increasing stability. The plot also indicates that for any

given stability, higher values of $\bar{\sigma}_z{}^2$ occur at average winds of 8–11.5 knots than at lower wind velocities.

The number of measurements are too few to permit firm conclusions at this time but a trend toward a decrease in vertical diffusion with increasing stability does appear to exist as predicted by Sverdrup et al. The fact that these data also indicate consistently higher values of $\bar{\sigma}_z{}^2$ at a given $\bar{S}'$, for average wind speeds between 8–11.5 knots than between 0–8 knots also adds to our confidence in the idea that there is a critical wind speed above which the rate of vertical diffusion increases sharply.

A similar method of analysis was employed in attempting to establish a comparable relationship between the horizontal variances, wind speed and stability. Figures 23 and 24 are semi-log plots indicating the results of the analysis at a diffusion time of 200 minutes. The plot of $\sigma_y{}^2$ against $\overline{W}$ for the waste field studies, indicates considerable scatter between individual points. There appears to be a trend toward decreasing $\sigma_y{}^2$ values with increasing wind speed, although there are insufficient data to warrant any solid conclusions along this line. Stability appears to have little or no definite effect on $\sigma_y{}^2$. Although data from background areas do indicate that much lower values of $\sigma_y{}^2$ are associated with lower values of $\bar{S}'$, the care which must be exercised in comparing data obtained inside and outside of the waste field has already been discussed. This is especially true of the lateral and longitudinal components of dispersion.

Figure 24 shows the relationship between $\sigma_x{}^2$ and $\overline{W}$. Again there is considerable scatter of the plotted points, but the data from within the field do indicate a trend of increasing $\sigma_x{}^2$ with increasing wind speed. As in the case of lateral dispersion, there appears to be no direct correlation between stability and $\sigma_x{}^2$. Taking $\overline{W}$ between 8 and 11 knots in Figure 24, it is seen that the point representing the highest value of $\bar{S}'$ (846) does not lie at the highest value of $\sigma_x{}^2$ but is intermediate in position with respect to stability. In the range of 2 to 8 knots an increase in $\sigma_x{}^2$ with decreasing $\bar{S}'$ is suggested but there are insufficient data on which to base a firm conclusion.

9. THEORETICAL CONSIDERATIONS

Gifford (23) reviewed the theoretical basis for relative diffusion of a cloud of particles in atmospheric turbulence, including the earlier work of Brier (24) and Batchelor (27, 29) in which, on the basis of the similarity theory of homogeneous turbulence, certain dimensional predictions were proposed regarding the mean-square dispersion of two fluid particles. These predictions were reportedly valid for the so-called inertial subrange of turbulent eddy sizes where eddies are small compared to the large scale energy-bearing eddies of the mean motion. The existence of an inertial subrange implies that local isotropic conditions prevail, and this in turn depends on the state of the turbulence. If the Reynolds number of the turbulence is large enough, the turbulence should be "fully-developed" and an inertial subrange will exist. Okubo (9) reported that in most oceanic areas the Reynolds number of turbulence is sufficiently high to meet this requirement.

VARIANCE — $\overline{Vz}^2$
vs.
STABILITY — S'
T = 200 MINUTES

LEGEND

● $\overline{W}$ = 8 - 11.5 Kts. — O. C. Outfall

⬤ $\overline{W}$ = 8 - 11.5 Kts. — Control Station

◆ $\overline{W}$ = 0 - 8 Kts. — O. C. Outfall

◆ $\overline{W}$ = 0 - 8 Kts. — Control Station

(8.9) Av. value of wind speed at T = 200 min.

FIGURE 25

CONTINUOUS   DISCHARGE

ORANGE   COUNTY   OUTFALL

27   JUNE   1963

T = 4.5   HOURS

$\bar{U}$ = 0.32 KNOTS

COAST   LINE
APPROX. 1.2 MILE

EDGE OF DYE
PLUME
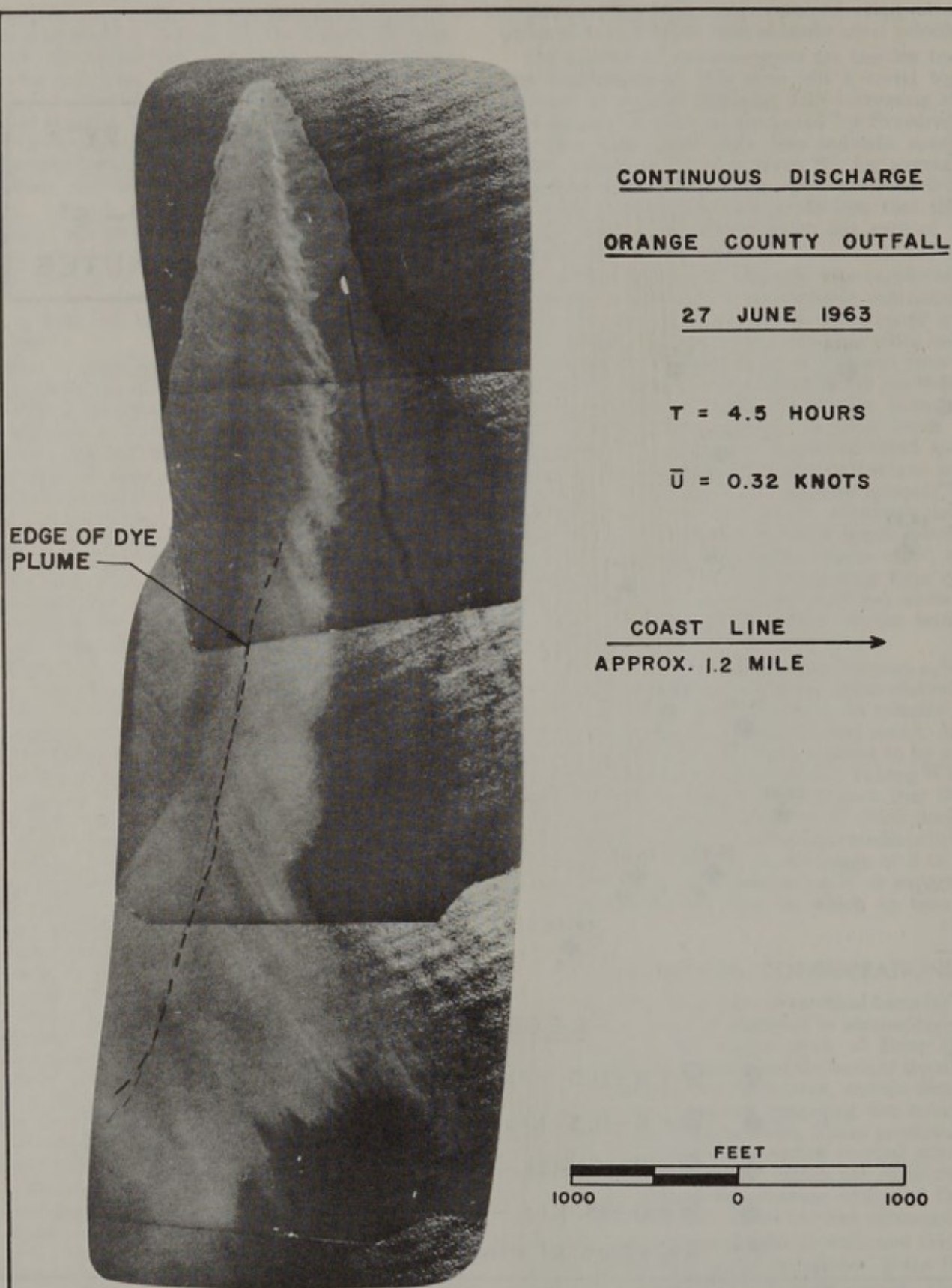
FEET

1000   0   1000
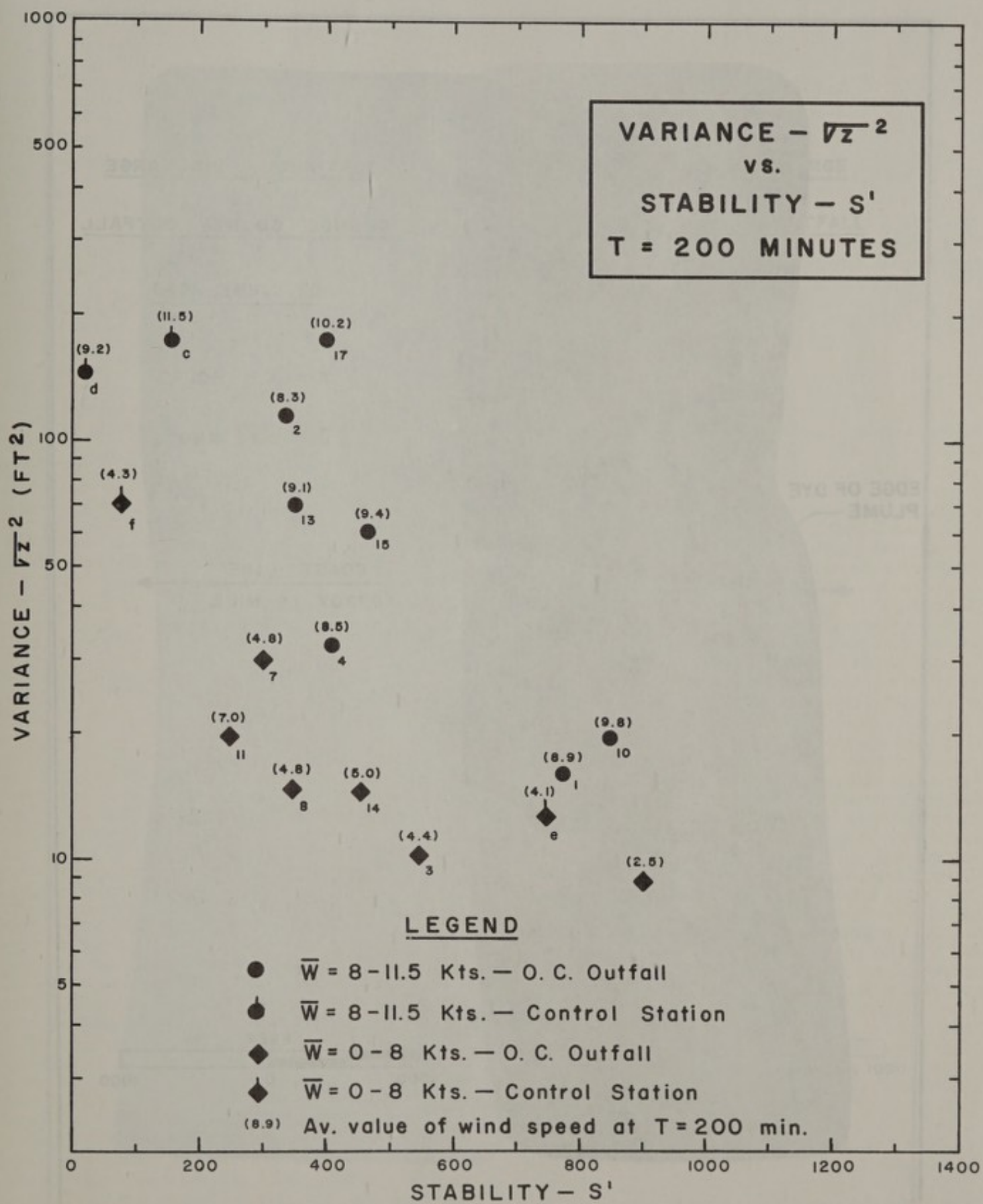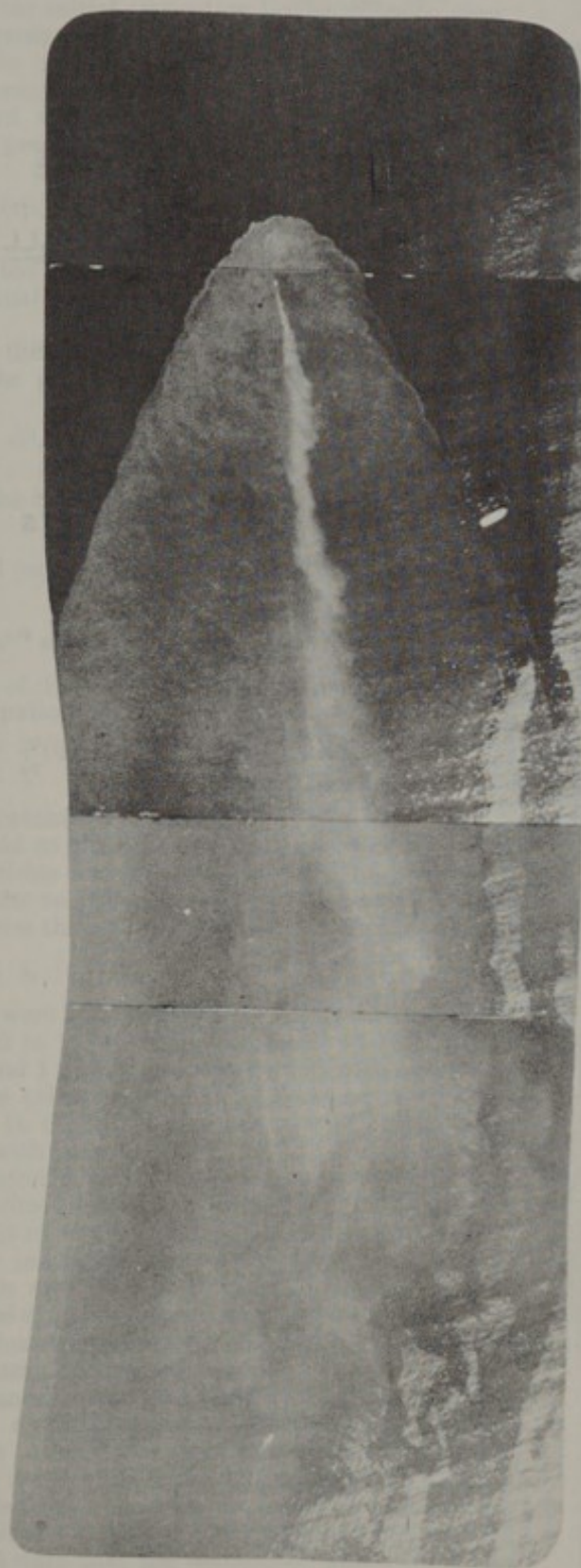
FIGURE 26

CONTINUOUS DISCHARGE

ORANGE COUNTY OUTFALL

28 JUNE 1963

T = 1.75 HOURS

$\bar{U}$ = 0.34 KNOTS

COAST LINE
APPROX. 1.2 MILE

FEET

1000   0   1000

FIGURE 27

CONTINUOUS DISCHARGE

ORANGE COUNTY OUTFALL

28 JUNE 1963

T = 3.0 HOURS

$\bar{U}$ = 0.32 KNOTS

COAST LINE
APPROX. 1.2 MILE

FEET
1000   0   1000
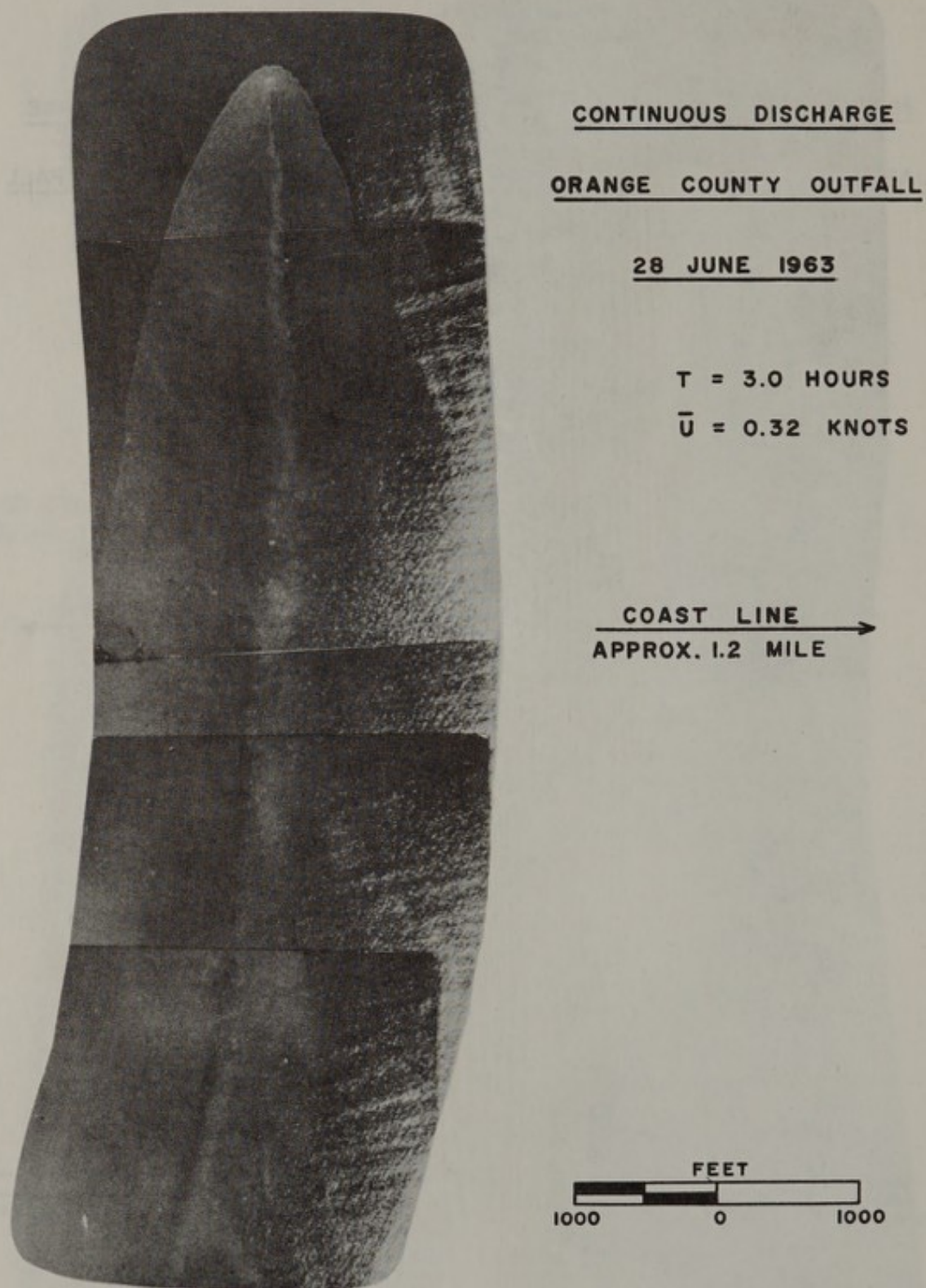
FIGURE 28

Batchelor (25) pointed out that when the distance between two diffusing particles lies in the inertial sub-range, the rate of change of the particle-separation depends on the initial separation l_0, the diffusion time, and the parameters of the turbulence (the eddy viscosity and the rate of energy dissipation per unit mass, ϵ.). If the lower limit of the inertial subrange in which the effects of viscosity are felt is small, Batchelor's dimensional predictions yield:

$$\frac{d\xi^2}{dt} \propto (\epsilon\xi_0)^{2/3}t, \text{ (for "small" t)} \tag{16}$$

where ξ^2 is the mean-square dispersion at time t in a given coordinate direction (the projection of l on the ξ axis).

When the diffusion time is large enough, the relative motion of the particles no longer depends on ξ_0, and

$$\frac{d\xi^2}{dt} \propto \epsilon t^2, \ (t_1 \ll t) \tag{17}$$

where t_1 is the time beyond which the initial separation has no affect on $\frac{d\xi^2}{dt}$ and is given by:

$$t_1 = l_0^{2/3} \epsilon^{1/3} \tag{18}$$

Integration of (16) and (17) for a constant rate of energy dissipation yields

$$\xi^2(t) - \xi^2(o) \propto t^2 \tag{16a}$$
$$\xi^2(t) \propto t^3 \tag{17a}$$

It is important to note, as Batchelor (25) further indicates, that as the diffusion time becomes very long the two particles wander independently, and the components of the relative dispersion of the two particles reduce to twice that of a single particle. In other words:

$$\xi^2(t) \propto t, \ (t \longrightarrow \infty) \tag{19}$$

Thus, if we were able to determine $\xi^2(t)$ for dispersion times from 0 to ∞ we would expect ξ^2 to vary with t to the 2, 3 and 1 power, providing an inertial sub-range of eddy sizes exists and the rate of energy dissipation is constant. In the latter case the rate of change of ξ^2 is constant with time.

These relationships for the relative mean dispersion of two particles were later extended by Batchelor (27) to include the case of a cloud of many particles. Gifford (23) further indicated that equations similar to (16) and (17) can also be shown to apply to the case of average cloud dispersion over a large number of identical trials and thus the equations should be applicable to relative diffusion of dye patches.

The variances computed from the present experiments were assumed to be proportional to the true mean-square values. The fact that three-dimensional isotropy did not prevail in these experiments is evident from observed differences in the rates of vertical and horizontal diffusion. As discussed previously, it was not known for certain that the turbulence was truly anisotropic in the horizontal plane. The problem that arises in this respect is one of separating the effects of dispersion due to wind action and vertical velocity variation from that due to turbulent diffusion. If we can

assume these effects to be manifested in longitudinal dispersion only, it is possible to check the validity of Batchelor's predictions by analysis of the lateral variance as a function of time.

Figure 12 shows a typical relationship between the variance and diffusion time. It is seen that σ_y^2 is proportional to the time to a power less than 2. The trend of the plotted points do not indicate any apparent tendency toward an increase in slope at the larger values of time. It is possible that the experiment was not carried out long enough to show such a trend. However, an estimate of the time t_1 as given by equation (18) can aid in the analysis. Assuming the initial radius of the dye patch (≈ 6 ft.) to be proportional to the initial particle-separation in Batchelor's predictions, and that a reasonable estimate of the constant rate of energy dissipation in the ocean is from 0.002 to 0.08 cm²/sec³ (Okubo, (9)) we have:

$$t_1 = \frac{(r)^{2/3}}{(\epsilon)^{1/3}} \approx 4.3 \text{ to } 1.3 \text{ minutes}$$

If these estimates are at all accurate, we can assume the time period during which (16) and (16a) apply is very small. Therefore, σ_y^2 would be expected to vary with diffusion time to a power ranging from 3 to 1.

These data appear to indicate that the extent of the inertial subrange was limited to very small eddy scales in this particular oceanic area. It is possible that the state of turbulence in the area around the Orange County outfall is not "fully-developed" due to such complicating factors as the proximity of the shoreline, the shallow (50 ft.) depth, or the highly stable condition of the water column. Another important factor is the effect of the turbulent energy added by the presence of the boil. As Batchelor (26) pointed out, the range of eddy sizes over which the similarity hypotheses applies must be free of external influences, the basis behind the similarity theory being that a state of equilibrium of the smaller eddies must exist. This implies that the only source of energy for this range is that transferred from the larger eddies. If additional energy is fed into the range of small eddies, equilibrium may not obtain and the similarity theory may not apply. Even if the energy added by the effluent jet at the boil is of minor importance, it is still possible that the rate of energy dissipation within the field was not constant. As described earlier, the wind velocities varied considerably during individual test runs. Normally the wind speeds increased steadily from the early morning to late afternoon hours. The effect of a variable rate of energy dissipation on the rate of mean particle-separation can be seen by inspection of equations (16) and (17).

The data summarized in Table 5 indicate that similar results were obtained for all tests conducted within the waste field. Additional "control" experiments were conducted in coastal areas characterized by greater depth, and the absence of an effluent boil, and in most cases lower wind speeds. The results of these experiments are labeled c through f as shown in Table 5. The analysis of the data for σ_y^2 yielded results similar to those obtained for the experiments in the waste field. The empirical expressions for σ_y^2 show that the maximum exponent on t was 2.36, all other values being less than 2.

10. DIFFUSION COEFFICIENTS

It is possible to express the results of the diffusion analysis, at least in the x and y directions, in terms of apparent coefficients of diffusion. Thus, according to Okubo (6):

$$K_{x,y} = \tfrac{1}{2} \frac{d(\bar{\sigma}_{x,y}{}^2)}{dt} \qquad (19)$$

It can be shown from the equations given in the previous section, that the so-called "4/3 law" of eddy diffusion is analogous to equation (17a), i.e., differentiating (17) we have:

$$K = \tfrac{1}{2} \frac{d(\text{const } \epsilon t^2)}{dt} = \text{const } \epsilon t^2 \qquad (20)$$

providing ϵ is not a function of t.
Eliminating t between (19) and (20) yields:

$$K = \text{const.} \, (\epsilon)^{1/3} \, (\sigma)^{4/3} \qquad (21)$$

Assuming the effective eddy scale l of the phenomenon to be proportional to σ, we have

$$K = \text{const.} \, (\epsilon)^{1/3} \, (l)^{4/3} \qquad (22)$$

which, for a constant rate of energy dissipation ϵ, is the "4/3 relationship."

When diffusion is controlled by larger and larger eddies than those found in the inertial subrange, the exponent on l decreases to zero, K becoming constant when the largest eddies characteristic of a given area control the diffusion process. The results of the dye patch studies appear to indicate that the "4/3 law" of eddy diffusion does not apply in the nearshore areas investigated in these experiments.

Values of the average horizontal coefficients for each experiment were computed by use of equation (19), the empirical equations for the coordinate variances, and the average diffusion time. The corresponding average eddy scales were also computed by assuming $l \approx 4\sigma_{av}$. The computed values of K_x ranged from 2.5 to 135 ft²/sec for average eddy scales of 650 and 3700 ft. respectively. The corresponding values of K_y ranged from 0.2 to 7.4 ft²/sec for scales of 200 to 1000 ft.

It is doubtful that the same procedure can be used to estimate the average vertical coefficients in the surface layers because of the influence of stability on vertical diffusion. The data in Table 5 shows that on several days $\sigma_z{}^2$ was observed to be proportional to the diffusion time to a power less than one. The preceding discussion indicates that in this case K_z would become smaller with time, which is contrary to theory. Regardless of these difficulties average values of K_z were computed for the sake of comparison, and were found to range from 0.40 to 14.0 $\times$ 10⁻³ ft²/sec.

B. DILUTION AND DISPERSAL UNDER CONDITIONS OF CONTINUOUS RELEASE: DYE PLUME STUDIES

One of the main objectives of this research has been to study eddy diffusion of a surface waste field resulting from the continuous discharge of material from submarine outfalls. The equations for diffusion from a continuous fixed source can be obtained by integration (with respect to distance) of the equations for relative diffusion of a patch of material. Thus, information gathered on the horizontal and vertical diffusion of a dye patch in terms of the variances of the concentration distribution, can be used to predict or estimate the material distribution given by so-called steady plume models. However, this approach is limited (Okubo (9)). Such complicating factors as the effects of local boundaries and the non-homogeneous, non-stationary and anisotropic properties of a particular turbulent field must be given consideration.

For these and other reasons it was considered advisable to conduct a number of field studies involving the continuous release of tracer dye from a fixed point. The studies were all conducted within the waste field at Orange County.

1. FIELD METHODS AND SAMPLING TECHNIQUES

The usual procedure followed in these experiments was to first pre-mix a known quantity of rhodamine-B dye with methanol for specific gravity adjustment. The dye solution was mixed in a 55-gallon drum mounted in a small skiff. Sea water was added to produce approximately 45 gallons of final tracer solution. A small, calibrated positive-displacement pump with electric motor and variable speed drive was used to discharge dye at a constant rate. Power for the pump was furnished by a small portable generator. The skiff was anchored close to the boil by use of two bow and two stern anchors. Proper anchoring procedure was important to minimize movement of the skiff and initial distortion of the dye plume.

The typical sampling procedure employed during the continuous release experiments was similar to that used for the dye patch experiments with the following modifications:

1. The dye pump was turned on and the discharge calibrated by volumetric measurement.
2. It was assumed that steady state conditions were established within one to two hours after the experiment was begun.
3. The sampler was set at the depth of maximum dye concentration and repeated passes were made up the central axis of the dye plume.
4. Sampling across the plume axis was accomplished by making successive passes at known distances downstream from the skiff. Distances were estimated by use of a calibrated log-line velocity indicator and stop-watch.

5. Vertical samples were taken periodically at known distances along the center line of the plume.

Figures 26, 27, and 28 show a series of composite photographs taken during the experiments conducted on 27 and 28 June 1963. These Figures show the waste and dye fields as they appeared during two typical continuous release experiments and will be continually referred to in the discussion which follows.

2. MATHEMATICAL MODELS

Several statistical models have been proposed which describe the distribution of material in a steady state plume emanating from a fixed point source. The majority of these models are based on the assumption that the turbulence field is isotropic, homogeneous, and stationary, and that the plume model is assembled by the superposition of an infinite number of overlapping Gaussian patches of material as shown in Figure 29a. If diffusion in the direction of the mean current is neglected, the steady plume can then be considered to be of the "disk-element" type proposed by Frenkiel (30), and shown in Figure 29b.

Gifford (31) pointed out that a real plume presents a more complicated appearance than that shown in Figure 29. He indicates that the motion of the individual plume elements consists of two parts: spreading within individual elements, and meandering of the center of the element. Spreading is thought to result from turbulent eddies of sizes equal to or smaller than the plume element itself. The meandering is caused by large scale eddies which have no direct effect on diffusion taking place within the patch. Figure 30 depicts the "fluctuating plume" models as visualized by Gifford. The problem involved in attempting to predict the mean material concentration at any point with respect to the fixed axes, is obvious. Gifford does, however, propose a series of two-dimensional models that take into account the effects of both spreading and meandering of the plume. These models are based on an assumed Gaussian distribution within individual patch elements as well as an assumed Gaussian form for the frequency function associated with the variability of the cloud center about the fixed axis. The instantaneous plume concentration is given by:

$$C(x,y,z) = \frac{Q}{2\pi\bar{\sigma}^2 \bar{U}} \exp - \left[\frac{(y - D_y)^2 + (z - D_z)^2}{2\bar{\sigma}_y{}^2} \right] \quad (23)$$

where Q is the continuous steady rate of discharge of material from a point source, $\bar{U}$ is the mean current velocity, and $\bar{\sigma}^2$ is the average variance of the material distribution within the individual disk elements. $\bar{\sigma}^2$ as a function of dispersion time (or distance) was discussed in a previous section on relative diffusion. The disk
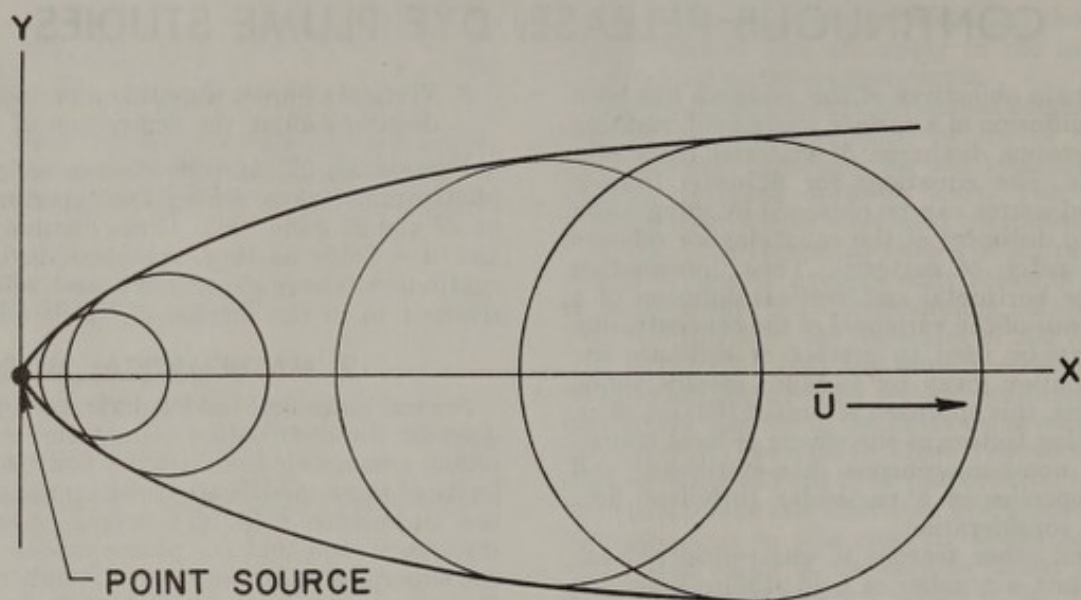
FIGURE 29a. STEADY PLUME FORMED BY SERIES OF OVERLAPPING "GAUSSIAN" PATCHES
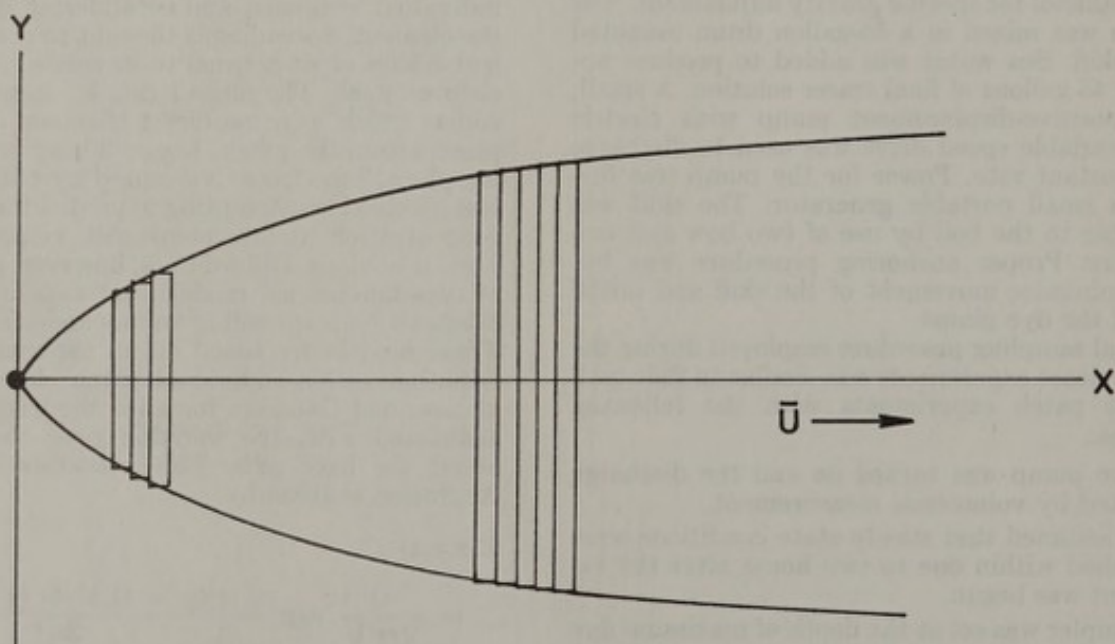
FIGURE 29b. STEADY PLUME FORMED BY SUPERPOSITION OF OVERLAPPING "GAUSSIAN" DISK ELEMENTS
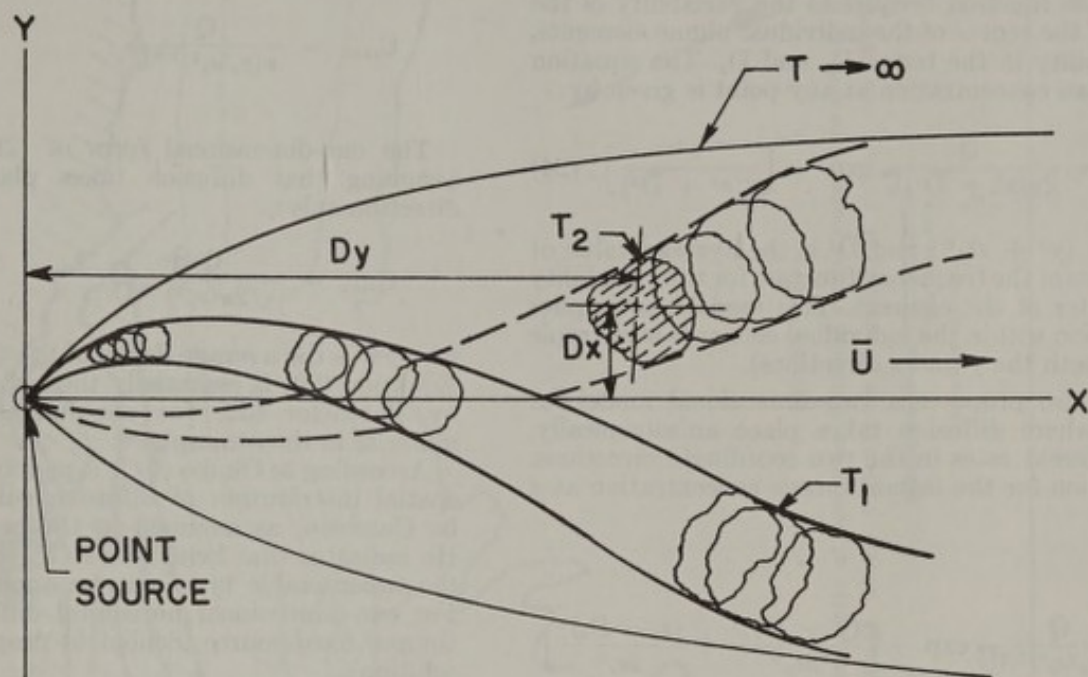
FIGURE 30 a "FLUCTUATING PLUME" MODEL COMPOSED
OF OVERLAPPING "GAUSSIAN" PATCHES
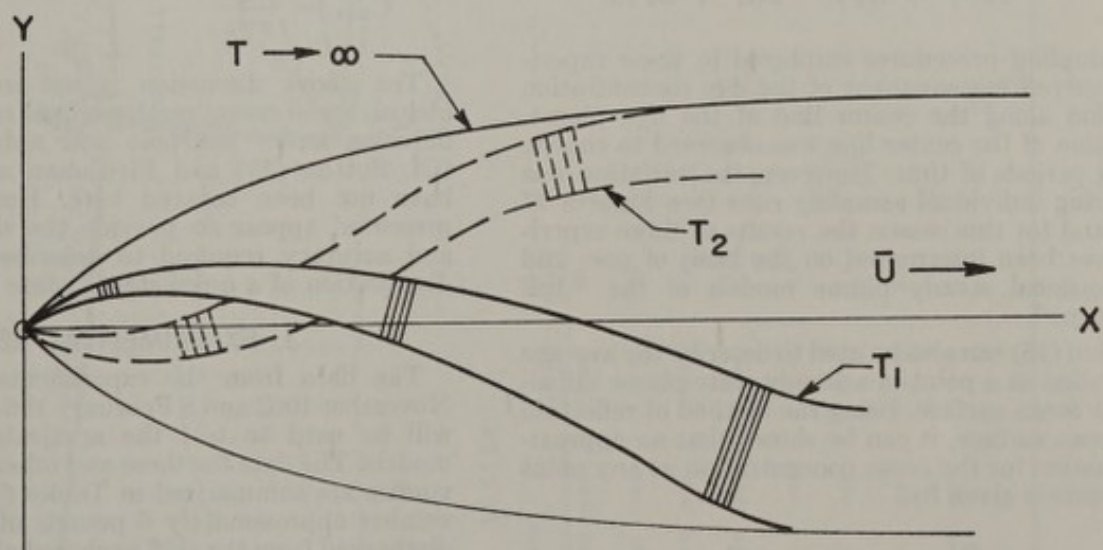
FIGURE 30 b "FLUCTUATING PLUME" MODEL COMPOSED
OF OVERLAPPING "GAUSSIAN" DISK-ELEMENTS

element assumption, as indicated above, amounts to neglecting diffusion in the direction of motion. The concentration C at any point and time is considered to be a random function because of the variability of the position of the center of the individual plume elements, i.e., variability in the terms D_y and D_z. The equation for the mean concentration at any point is given by:

$$\bar{C}(x,y,z) = \frac{Q}{2\pi(\bar{\sigma}^2 + \bar{D}^2)U} \exp - \left[\frac{r^2}{2(\bar{\sigma}^2 + \bar{D}^2)}\right] \quad (24)$$

where $r = (y^2 + z^2)^{1/2}$ and $\bar{D}^2$ is the average value of the variance of the frequency function for the variability of the center of the element. This model also implies that diffusion within the individual elements is isotropic (equal in both the y and z directions).

Gifford also proposes a two-dimensional model for the case where diffusion takes place anisotropically, i.e., at different rates in the two coordinate directions. The equation for the instantaneous concentration at a point is:

$$C(x,y,z)$$
$$= \frac{Q}{2\pi(\sigma_y^2\sigma_z^2)^{1/2}U} \exp - \left[\frac{(y - D_y)^2}{2\sigma_y^2} + \frac{(z - D_z)^2}{2\sigma_z^2}\right]$$
$$(25)$$

The mean value of the concentration at a point is given by

$$\bar{C}(x,y,z) = \frac{Q}{2\pi(\sigma_y^2 + D_y^2)^{1/2}(\sigma_z^2 + D_z^2)^{1/2}U} \exp$$
$$- \left[\frac{y^2}{2(\sigma_y^2 + D_y^2)} + \frac{z^2}{2(\sigma_z^2 + D_z^2)}\right] \quad (26)$$

The sampling procedures employed in these experiments involved measurement of the dye concentration distribution along the center line of the dye plume. The position of the center line was observed to change over long periods of time. However, the variation was small during individual sampling runs (see Figures 27 and 28) and for this reason the results of these experiments have been interpreted on the basis of one- and two-dimensional steady plume models of the "disk element type".

Equation (25) can also be used to describe the average concentration at a point in a steady state plume diffusing at the ocean surface. Using the method of reflection at the ocean surface, it can be shown that an approximate equation for the mean concentration at any point in the plume is given by

$$\bar{C}(x,y,z) = \frac{Q}{\pi(\sigma_y^2\sigma_z^2)^{1/2}U} \exp - \left[\frac{y^2}{2\sigma_y^2} + \frac{z^2}{2\sigma_z^2}\right] \quad (27)$$

Where the variances are a function of diffusion time or distance from the source, i.e., by making the substitution $t = x/U$, the variances can be expressed approximately as functions of distance.

The maximum theoretical concentration as a function of distance x can be obtained from (27) by setting $y = z =$ zero and:

$$C_{max} = \frac{Q}{\pi(\sigma_y^2\sigma_z^2)^{1/2}U} \quad (28)$$

The one-dimensional form of (28) is obtained by assuming that diffusion takes place in the lateral direction only:

$$C_{max} = \frac{Q/\bar{d}}{\sqrt{2\pi}(\sigma_y^2)^{1/2}U} \quad (29)$$

where $\bar{d}$ is the average depth of the diffusing substance. Equation (29) is essentially the same as that proposed by Batchelor (32) for one-dimensional diffusion of material in the atmosphere.

According to Okubo (9) it is possible that the average spatial distribution of diffusing substance might not be Gaussian, as assumed in the preceding equations. He indicates that Schönfeld's (10) general equation of the superposable type may be applicable in this case. For one-dimensional horizontal diffusion from a continuous fixed source, Schönfeld proposes the following solution:

$$\bar{C}(x,y) = \frac{Q/\bar{U}}{\pi} \frac{w(x/\bar{U})}{w^2(x/\bar{U})^2 + y^2} \quad (30)$$

where "w" is the mean diffusion velocity (assumed constant) and where the dispersion time t has been replaced by its equivalent x/U. The maximum theoretical concentration along the center line of the steady plume is obtained by setting $y =$ zero in (30),

$$C_{max} = \frac{Q}{\pi wx} \quad (31)$$

The above discussion is not intended to be all-inclusive and many mathematical models proposed for diffusion under isotropic and anisotropic conditions (Cf. Sutton (33) and Fleishman and Frenkiel (34)) have not been covered here. However, the models presented appear to provide the degree of flexibility and accuracy required to describe the concentration distribution of a quasi-steady state dye plume.

3. EXPERIMENTAL RESULTS

The data from the experiments conducted on 10 November 1963 and 8 February 1964 at Orange County will be used to test the applicability of the above models. The data for these and other continuous release studies are summarized in Tables 6 and 7. On 10 November approximately 6 pounds of dye per hour was discharged from the skiff anchored about 500 feet downstream from the boil. The resulting dye plume resembled those shown in Figures 27 and 28. The dye and waste fields moved approximately parallel to the coast line in a southeasterly direction as shown in Figure 31. The average current velocity obtained by periodic radar fixes on the leading edge of the plume (corrected for diffusion effects) was 0.27 knots. The average wind speed re-

FIGURE 31

Cruise tracks of continuous discharge studies made in the area of the
Orange County Outfall from August 1962 through July 1964

NO.	DATE	$\bar{U}$ (Knots)	$\bar{W}$ (Knots)
1	27 JUNE 1963	0.32	9.4
2	28 JUNE 1963	0.34	6.0
3	11 SEPT. 1963	0.40	7.4
4	12 SEPT. 1963	0.18	6.5
5	9 NOV. 1963	0.15	3.5
6	10 NOV. 1963	0.27	1.6
7	6 FEB. 1964	0.14	5.6
8	17 JUNE 1964	0.36	7.6

LEGEND
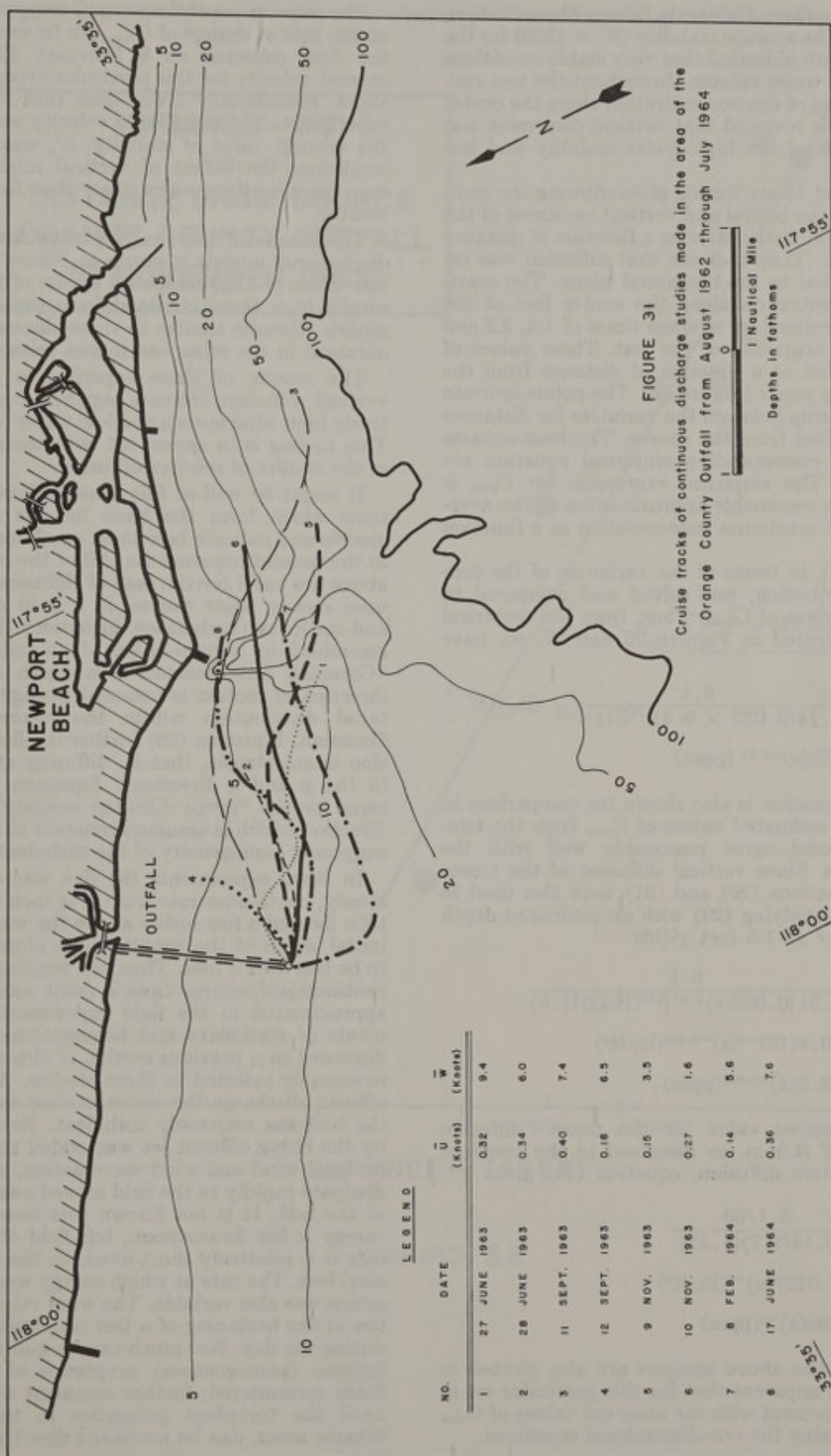
corded at the Southern California Edison Shore Station, was 1.6 knots. The average stability (S' = 1230) for the 0 to 3 meter depth indicated that very stable conditions prevailed in the water column throughout the test run. Vertical sampling of dye concentration along the center line of the plume revealed that vertical dispersion was small, the result of the high water stability and low wind speed.

Figures 32 and 33 are log-log plots showing the computed values of the lateral and vertical variances of the dye concentration distribution as a function of distance from the source. They indicate that diffusion was essentially restricted to the horizontal plane. The maximum dye concentration along the center line of the plume was determined for average times of 1.4, 2.2 and 3.2 hours after beginning of the test. These values of C_{max} were plotted as a function of distance from the source on log-log paper (Figure 34). The points indicate a linear relationship between the variables for distances of 500 to 5000 feet from the source. The least-squares trend line and corresponding empirical equation are also indicated. The empirical expression for C_{max} is assumed to be a reasonable approximation of the average value of the maximum concentration as a function of distance.

Equation (28), in terms of the variances of the concentration distribution, was solved and compared to the observed values of C_{max}. Thus, from the empirical expressions indicated in Figures 26 and 27, we have from (28):

$$C_{max} = \frac{6.1}{3.14(0.032 \times 0.4)^{1/2}U(x)^{1.01}} \quad (lb/ft^3)$$

$$= 165(x)^{-1.01} \quad (ppm)$$

The above equation is also shown for comparison in Figure 34. The estimated values of C_{max} from the two-dimensional model agree reasonably well with the observed values. Since vertical diffusion of the tracer was minor, equations (29) and (31) were also used to estimate C_{max}. Applying (29) with an estimated depth of the dye layer at 1.5 feet yields

$$C_{max} = \frac{6.1}{2.51[0.032(x)^{1.81}]^{1/2}(1642)(1.5)}$$

$$= 53.4(10)^{-4}(x)^{-0.905}(lb/ft^3)$$

$$= 83.5(x)^{-0.905}(ppm)$$

Using an estimated value for the mean "diffusion velocity" of 1.7 ft/min, as discussed in the previous section on relative diffusion, equation (31) gives

$$C_{max} = \frac{6.1/60}{3.14(1.7)(1.5)x}$$

$$= 0.0127(x)^{-1}(lb/ft^3)$$

$$= 198(x)^{-1}(ppm)$$

The results of the above analysis are also plotted in Figure 34. It is apparent that for this particular set of data better agreement with the observed values of C_{max} was obtained using the one-dimensional equations.

The importance of the vertical component of diffusion on the rate of change of C_{max} can be seen by analysis of the data collected on 8 February 1964. The mean current velocity for this particular experiment was 0.14 knots, considerably lower than that for the previous experiment. The mean wind velocity was 5.6 knots and the average value of stability, S', was 375. For these conditions the extent of vertical mixing (Figure 35) was significantly greater than that found on 10 November.

The results of the analysis using the one- and two-dimensional models is shown in Figure 36. In this case the values of C_{max} computed by use of (28) gave better results than those obtained from the one-dimensional models. Results similar to those discussed above were obtained in the other continuous release experiments.

The results of these experiments point out that vertical diffusion becomes significant on days of relatively high wind speeds and low water column stability. This finding is in agreement with the results obtained in the studies of relative diffusion.

It might be well at this time to discuss the assumptions which form the basis for the above diffusion models and indicate how these conditions were satisfied in the present experiments. All of the models discussed above are valid for the case of diffusion from a continuous steady point source, in a field of homogeneous and stationary turbulence. Equations (28) and (29) are assembled by superposition of an infinite number of "Gaussian disk elements", in which diffusion in the direction of motion is assumed negligible and the material distribution within the element is assumed Gaussian. Equation (28) further implies that the diffusion is anisotropic, that is, diffusing at different rates in the y and z directions. Equation (31) includes a term for the "mean diffusion velocity" in the lateral direction which is assumed constant in space, thus presupposing homogeneity of the turbulent field.

In these experiments the dye was discharged at a steady, continuous rate from a ⅛ inch diameter plastic tube located a few inches above the water surface. The initial width of the resulting dye plume was observed to be less than a foot. Thus, the requirements of steady continuous discharge from a point source were closely approximated in the field experiments. The requirements of stationary and homogeneous turbulence, as discussed in a previous section of this report, were not necessarily satisfied in these studies. At times of high effluent discharge the water surface in the vicinity of the boil was extremely turbulent. Energy contributed by the rising effluent jet was added to that generated by local wind and wind wave action, and appeared to dissipate rapidly as the field moved away from the area of the boil. It is not known just how far this added energy is felt downstream, but field observations indicate it is relatively short-lived, on the order of a thousand feet. The rate at which energy was added by wind action was also variable. The wind velocity was usually low at the beginning of a test run, building up steadily during the day. Not much can be said about the translational (homogeneous) properties of the turbulence fields encountered; further comment will have to wait until the turbulent properties in this, and similar oceanic areas, can be measured directly.

FIGURE 32

$$\sqrt{z}^{2} = 0.4 (X)^{0.21}$$

VARIANCE $-\sqrt{z}^{2}$
vs.
DISTANCE FROM SOURCE
ORANGE COUNTY OUTFALL
10 NOVEMBER 1964

FIGURE 33

MAXIMUM CONCENTRATION
vs.
DISTANCE FROM SOURCE
ORANGE COUNTY OUTFALL
10 NOVEMBER 1964

$C_{max} = 126\,(X)^{-0.98}$
(Field Data)

$C_{max} = 165\,(X)^{-1.01}$
(Eq. 28)

$C_{max} = 83.5\,(X)^{-.905}$
(Eq. 29)

$C_{max} = 198\,(X)^{-1}$
(Eq. 31)
(W = 1.7 ft./min.)

LEGEND
▲ = 1.4 Hours
■ = 2.2 Hours
● = 3.2 Hours

CONCENTRATION (PPM)

DISTANCE -   (FEET)
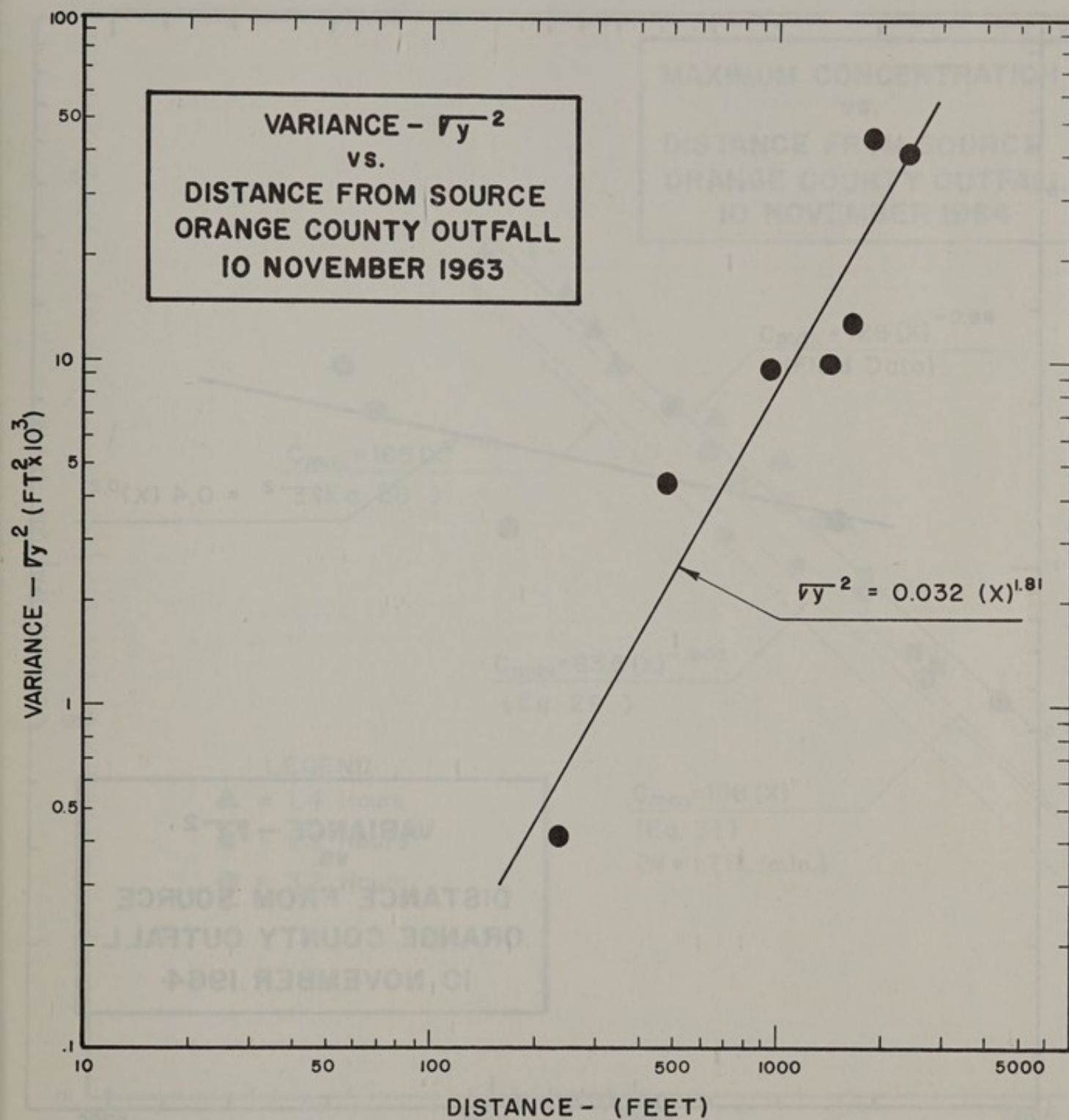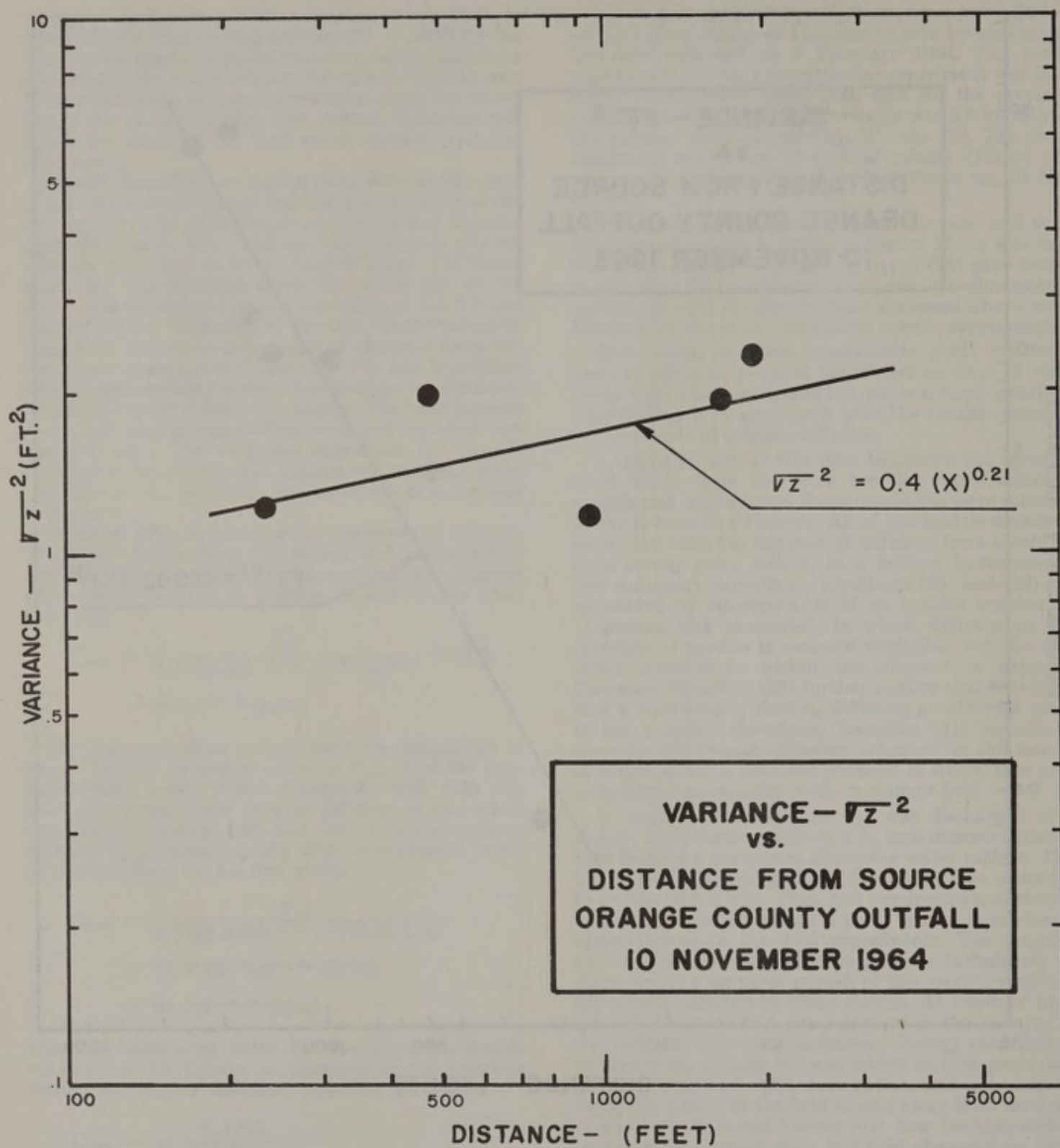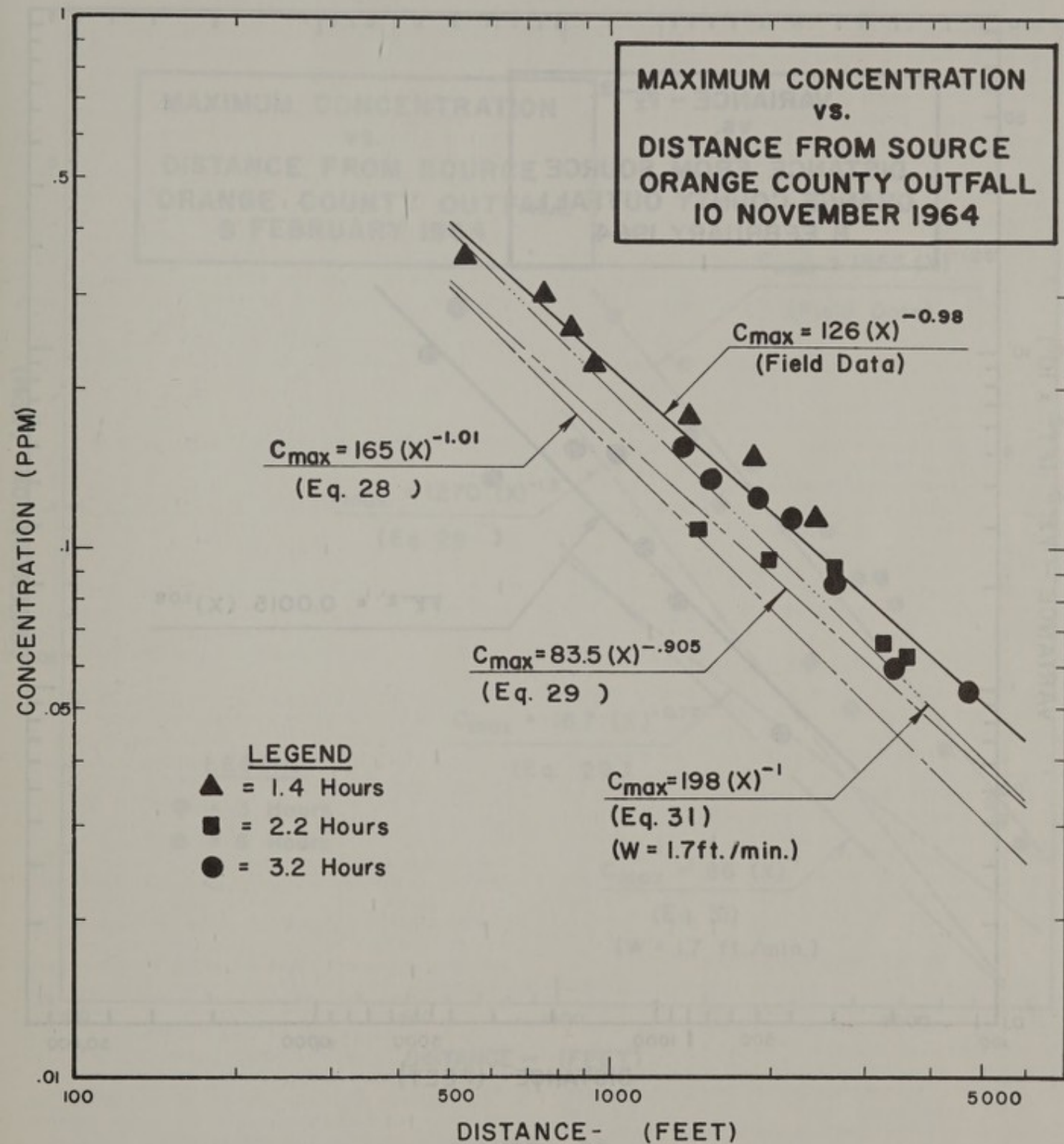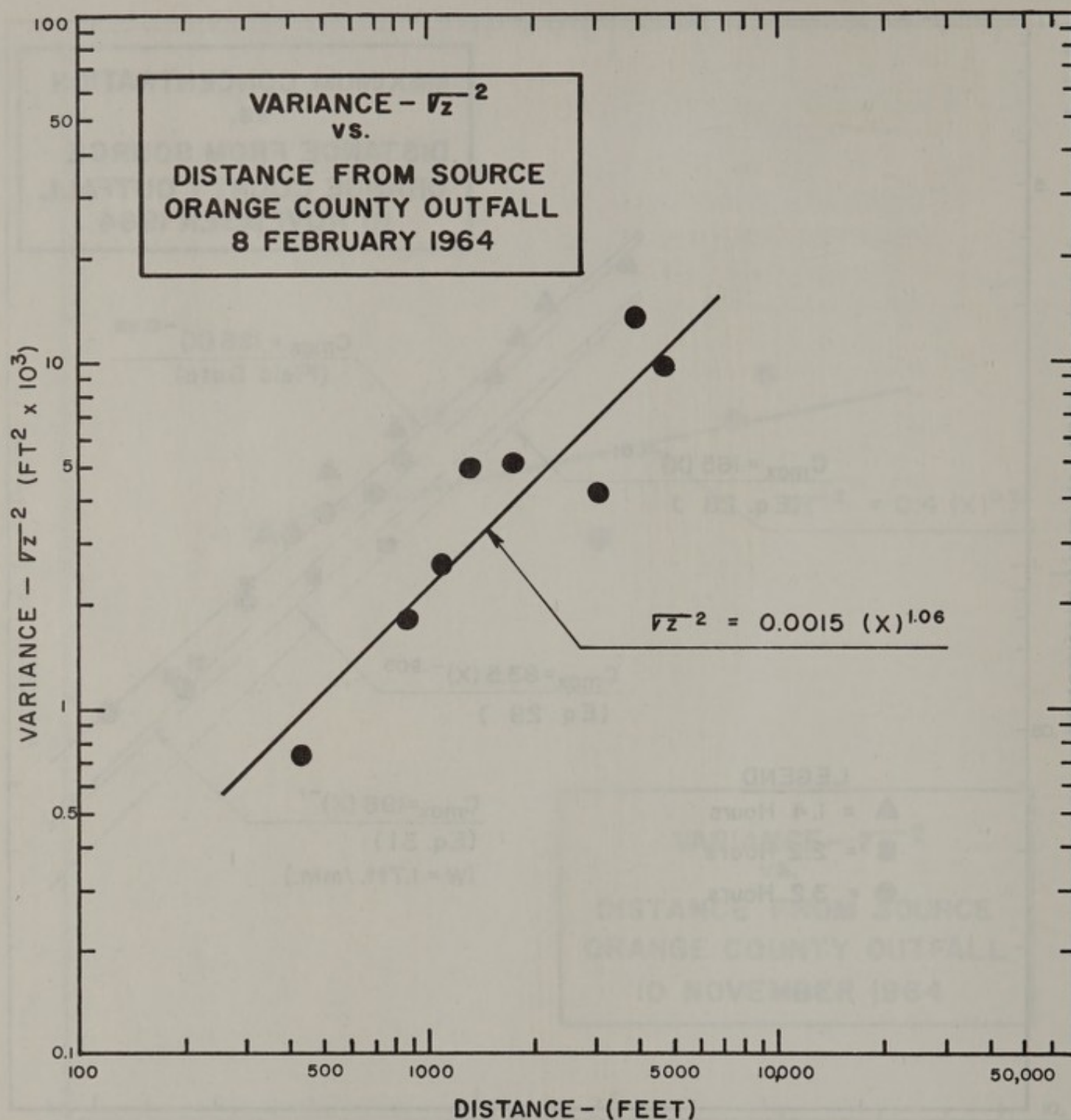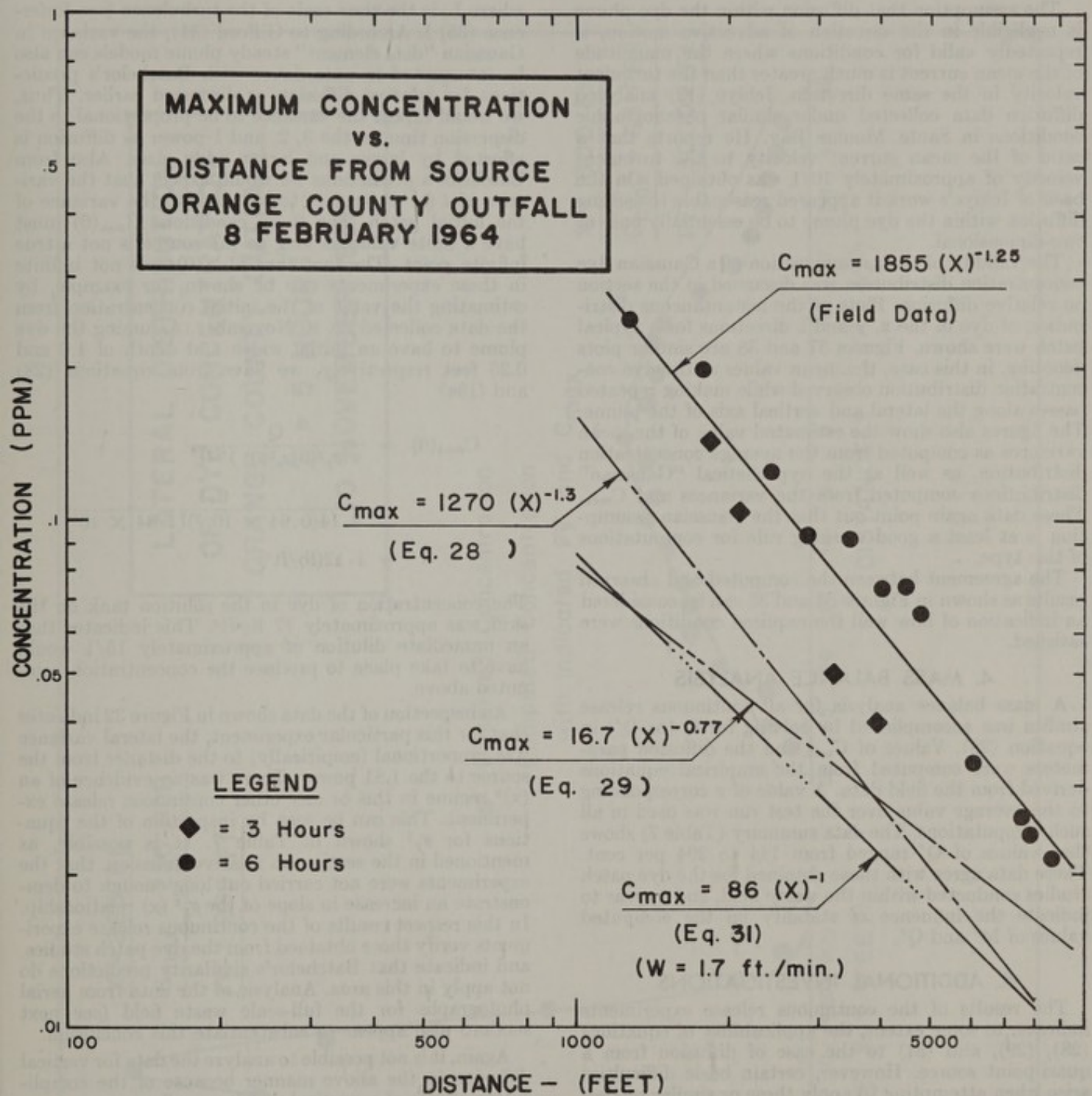
FIGURE 34

FIGURE 35

FIGURE 36

The assumption that diffusion within the dye plume is negligible in the direction of advective motion, is reportedly valid for conditions where the magnitude of the mean current is much greater than the turbulent velocity in the same direction. Ichiye (12) analyzed diffusion data collected under similar oceanographic conditions in Santa Monica Bay. He reports that a ratio of the mean current velocity to the turbulent velocity of approximately 10/1 was obtained. On the basis of Ichiye's work it appeared reasonable to assume diffusion within the dye plume to be essentially one- or two-dimensional.

The validity of the presupposition of a Gaussian dye concentration distribution was discussed in the section on relative diffusion. Plots of the instantaneous distribution of dye in the x, y and z directions for a typical patch were shown. Figures 37 and 38 are similar plots denoting, in this case, the mean values of the dye concentration distribution observed while making repeated passes along the lateral and vertical axis of the plume. The figures also show the estimated value of the mean variances as computed from the average concentration distribution, as well as the hypothetical "Gaussian" distributions computed from the variances and C_{max}. These data again point out that the Gaussian assumption is at least a good working rule for computations of this type.

The agreement between the computed and observed results as shown in Figures 34 and 36 can be considered an indication of how well the required conditions were satisfied.

4. MASS BALANCE ANALYSIS

A mass balance analysis for all continuous release studies was accomplished by solving for Q (or Q') in equation (28). Values of C_{max} and the diffusion parameters were computed from the empirical equations derived from the field data. A value of x corresponding to the average value over the test run was used in all such computations. The data summary (Table 7) shows that values of Q' ranged from 144 to 294 per cent. These data agree with those obtained for the dye patch studies conducted within the waste field, and appear to indicate the influence of stability on the computed values of M' and Q'.

5. ADDITIONAL INVESTIGATIONS

The results of the continuous release experiments indicate, to some extent, the applicability of equations (28), (29), and (31) to the case of diffusion from a quasi-point source. However, certain basic difficulties arise when attempting to apply these or similar models to diffusion of a large scale surface field in the sea. For example, point source models of the Gaussian type break down at small diffusion times (or distances), that is

$$\sigma^2 \longrightarrow 0, \text{ and } C_{max}(0) \longrightarrow \infty \text{ as } t \text{ (or } x) \longrightarrow 0$$

The variances in the "disk-element" plume models can be interpreted in light of Taylor's (35) theory of diffusion by continuous movements (one-particle type analysis). According to this theory:

$$\sigma^2 \propto t, \text{ as } t \longrightarrow \infty \tag{32}$$

$$\sigma^2 \propto t^2, \text{ for } t \ll L_t \tag{33}$$

where L_t is the time scale of the turbulence (see Reference (35)). According to Gifford (31), the variance in Gaussian "disk element" steady plume models can also be interpreted in accordance with Batchelor's predictions for relative diffusion as discussed earlier. Thus, we would expect the variance to be proportional to the dispersion time to the 3, 2, and 1 power as diffusion is affected by larger and larger eddy sizes. Also from Batchelor's predictions we would expect that the variance at t (or x) = zero to be equal to the variance of the initial patch. For these conditions $C_{max}(0)$ must have a finite value as long as the source is not a true infinite point. The fact that $C_{max}(0)$ was not infinite in these experiments can be shown, for example, by estimating the value of the initial concentration from the data collected on 10 November. Assuming the dye plume to have an initial width and depth of 1.0 and 0.25 feet respectively, we have from equations (28) and (16a)

$$C_{max}(0) = \frac{Q}{\pi (\bar{\sigma}_y^2(0) \bar{\sigma}_z^2(0))^{1/2} U}$$

$$\approx \frac{6.1}{3.14(0.94 \times 10^{-3})(1.84 \times 10^3)}$$

$$\approx 1.12 (\text{lb/ft}^3)$$

The concentration of dye in the solution tank on the skiff was approximately 17 lb/ft³. This indicates that an immediate dilution of approximately 15/1 would have to take place to produce the concentration computed above.

An inspection of the data shown in Figure 32 indicates that for this particular experiment, the lateral variance was proportional (empirically) to the distance from the source to the 1.81 power. There was no evidence of an $(x)^3$ regime in this or any other continuous release experiment. This can be seen by inspection of the equations for $\bar{\sigma}_y^2$ shown in Table 7. It is possible, as mentioned in the section on relative diffusion, that the experiments were not carried out long enough to demonstrate an increase in slope of the $\bar{\sigma}_y^2$ (x) relationship. In this respect results of the continuous release experiments verify those obtained from the dye patch studies, and indicate that Batchelor's similarity predictions do not apply in this area. Analysis of the data from aerial photographs for the full-scale waste field (see next section) also appear to substantiate this conclusion.

Again, it is not possible to analyze the data for vertical diffusion in the above manner because of the complicating effects of a vertical density gradient.

Photographs shown in Figures 27 and 28 indicate that near the boil the shape of the waste field was essentially parabolic. This implies that $\bar{\sigma}_y^2 \propto x$, as given earlier by equation (32) for the case of large diffusion times. Assuming the waste material to be Gaussian in its distribution (as will be discussed later), it was possible to estimate the $\bar{\sigma}_y^2$ (x) relationship from the photographs for 27 June. The analysis revealed that $\bar{\sigma}_y^2 \propto (x)^{1.03}$, for distances to 6000 feet from the boil. A plot of $\bar{\sigma}_y^2 - \bar{\sigma}_y^2$ (0) indicated little change in the exponent on x for distances greater than about 100 feet. These results, although approximate, also indicated that

LATERAL DISTRIBUTION
OF DYE CONCENTRATION
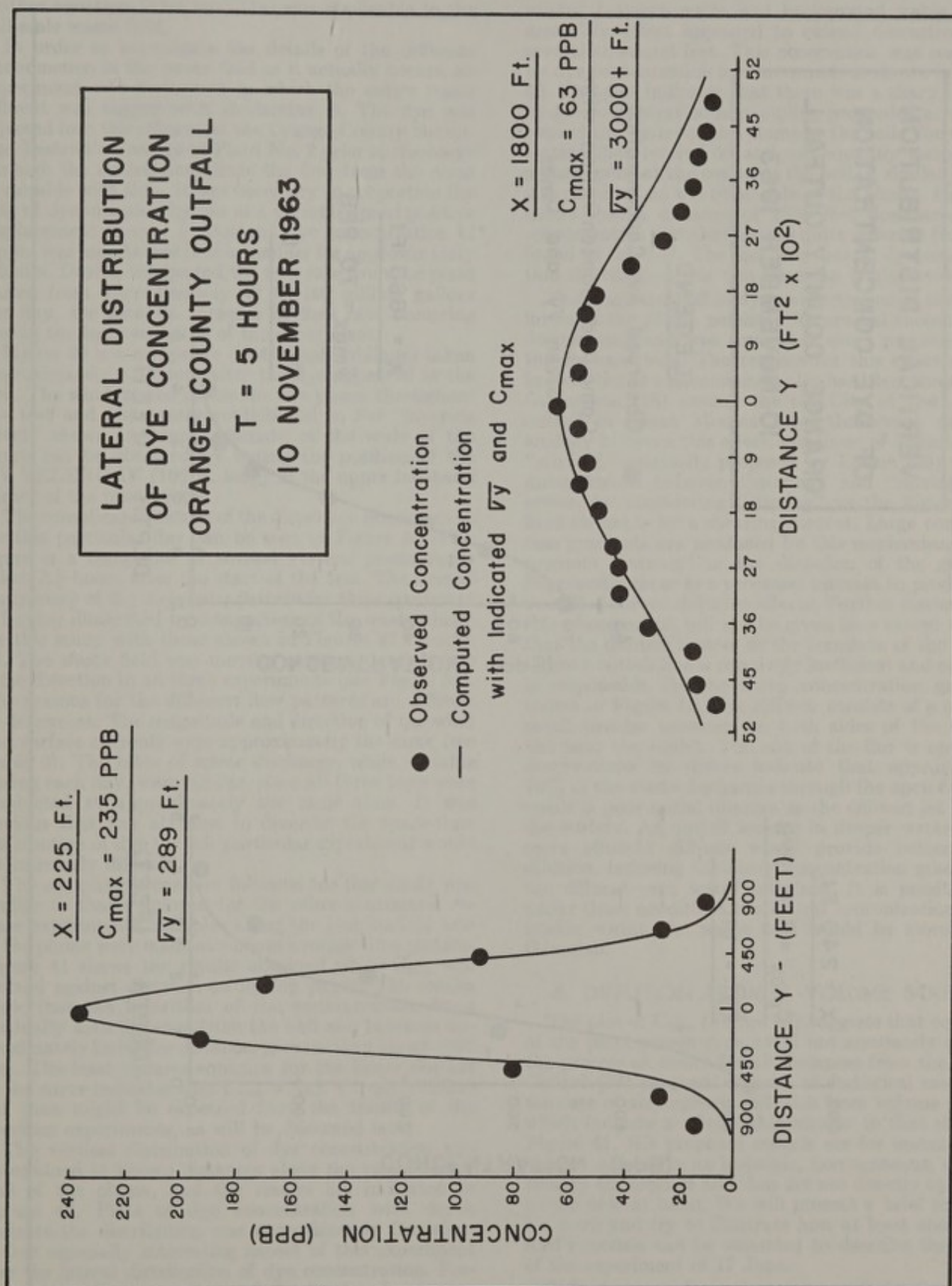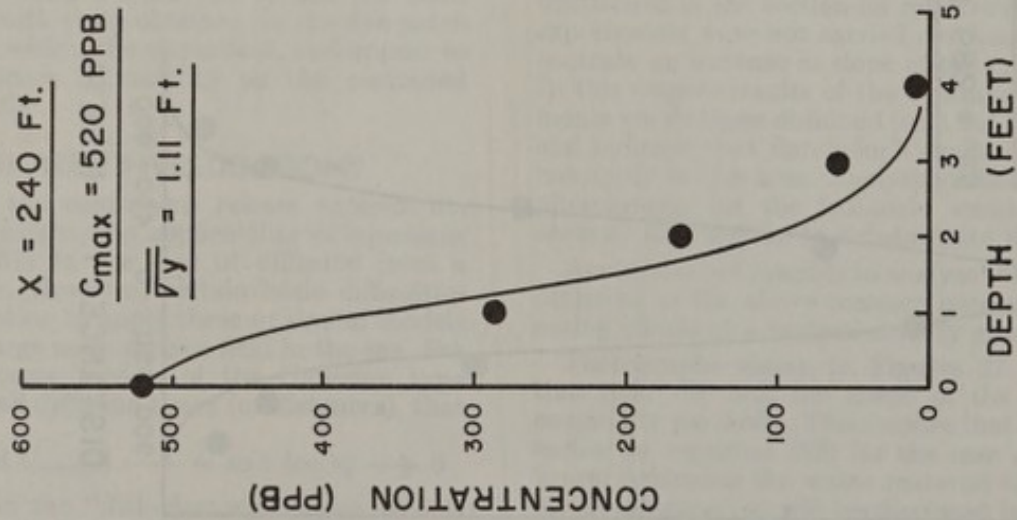ORANGE COUNTY OUTFALL
T = 5 HOURS
10 NOVEMBER 1963

FIGURE 37

VERTICAL DISTRIBUTION
OF DYE CONCENTRATION
ORANGE COUNTY OUTFALL
10 NOVEMBER 1963

LEGEND

● Observed Av. Concentration

— Computed Concentration with
Given $\overline{\sigma_y}$ and C_{max}

$X = 1660$ Ft.

$C_{max} = 70$ PPB

$\overline{\sigma_y} = 1.4$ Ft.

$X = 240$ Ft.

$C_{max} = 520$ PPB

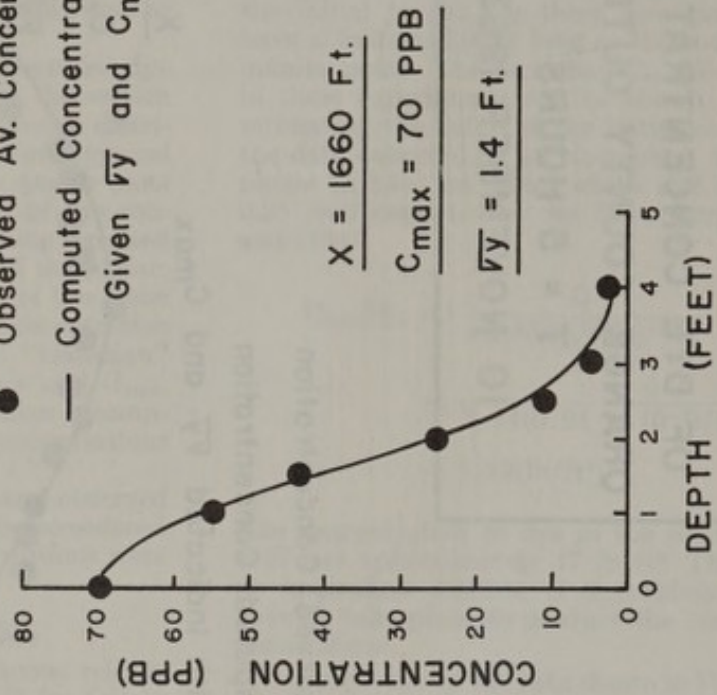$\overline{\sigma_y} = 1.11$ Ft.

FIGURE 38

neither equation (16a) nor (17a) was applicable to the full-scale waste field.

In order to investigate the details of the diffusion phenomenon in the waste field as it actually occurs, an experiment was performed in which the entire waste effluent was tagged with rhodamine B. The dye was injected into the effluent at the Orange County Sanitation District's Treatment Plant No. 2 prior to discharge through the outfall line. Since the flow from the plant is variable with time, it was necessary to proportion the rate of dye injection by use of a variable speed positive displacement pump. A constant dye concentration of 2 ppm was maintained in this manner for approximately 5 hours. During this period the flow rate from the plant varied from approximately 42 to 100 million gallons per day, the greatest increase in flow rate occurring during the last two hours of the experiment.

Figure 39 is a composite photograph (oblique) taken approximately 1.5 hours after the dye appeared at the boil. The wind moved across the dye plume throughout the test and apparently contributed to the "layering effect" shown. A visual estimate of the scale of the figure can be obtained by noting the position of the RV VELERO IV (106 ft. long) in the upper left-hand corner of the photograph.

The complicated nature of the dispersion phenomenon for this particular day can be seen in Figure 40. This figure is a composite of several vertical photographs taken 3.5 hours after the start of the test. The overall complexity of the dispersion pattern for this experiment is further illustrated by comparison of the waste plume for this study with those shown in Figures 27 through 28. The waste field was moving in approximately the same direction in all three experiments (see Figure 31). The reasons for the different flow patterns are difficult to determine. The magnitude and direction of the wind and surface currents were approximately the same (see Table 6). The rates of waste discharge, while variable during each day, were similar, since all three tests were conducted at approximately the same time. It was obvious that any attempt to describe the space-time distribution of dye for this particular experiment would be extremely difficult.

The sampling procedure followed for this study was similar to that employed for the other continuous release experiments. Samples along the longitudinal axis of the plume were made at various average time periods. Figure 41 shows the results obtained when C_{max} was plotted against distance on log-log paper. The results show that the logarithm of the concentration drops gradually with distance from the boil and becomes approximately linear for distances greater than about 1000 feet. The least squares equation for the linear portion of the curve indicates that $C_{max} \propto (x)^{-0.55}$, quite different than might be expected from the results of the previous experiments, as will be discussed later.

The vertical distribution of dye concentration was determined at known distances along the visual center line of the plume, and the results are indicated in Figure 42. Plots of dye concentration with depth indicate the distribution was approximately Gaussian.

One especially interesting aspect of this experiment was the lateral distribution of dye concentration. Previous (visual) observations of the waste plume near the boil indicated that a sharp concentration gradient existed between waste and background water in this area. The effect appeared to extend downstream for several thousand feet. This observation was confirmed by dye concentration measurements as shown in Figure 43. The plot indicates that there was a sharp increase in dye concentration as sampling proceeded across and toward the center of the plume at the boil. The concentration then leveled off and subsequently increased to a peak value at the center of the boil. A similar pattern was manifest on the other side of the plume. Figure 43 shows that a distance of 1350 feet downstream the concentration distribution was quite different from that found at the boil. The fact that lateral dye concentration distribution was non-Gaussian is also evident.

The sharp drop-off in dye concentration at the lateral limits of the plume persisted for several thousand feet downstream and was somewhat more pronounced on the seaward side. The reasons for this effect are not known, but the phenomenon also has been observed by Gunnerson (18) around the old City of Los Angeles outfall in Santa Monica Bay. Gunnerson drew an analogy between this effect and those of "mixing" and "stirring," originally proposed by Eckart (36). Eckart distinguished between "stirring" and "mixing" processes, by considering "stirring" as the distortion of fluid elements by a shearing current. Large concentration gradients are produced by this mechanism, which promote "mixing" in the direction of the gradient. Supposedly these two processes interact to produce the overall observed diffusion effects. Further discussion on this phenomenon will not be given here except to state that the diffuser system at the terminus of the Orange County outfall line is relatively inefficient and probably is responsible for the sharp concentration gradients shown in Figure 43. The diffuser consists of a series of small circular openings on both sides of the effluent line near the outlet. The end of the line is open, and observations by divers indicate that approximately 70% of the waste discharges through the open end. The result is poor initial dilution as the effluent jet rises to the surface. An outfall located in deeper water with a more efficient diffuser would provide better initial dilution, reducing the sharp concentration gradient at the effluent—sea water interface. It is possible that under these conditions the lateral concentration distribution within the waste field would be more nearly Gaussian.

6. DIFFUSION FROM A VOLUME SOURCE

The plot of C_{max} (Figure 41) suggests that equations of the point source type could not accurately describe the process as shown for all distances from the source. Gifford (37) proposed a series of statistical models for the case of atmospheric diffusion from volume sources, which indicate a relationship similar to that shown in Figure 41. His proposed models are for instantaneous volume sources in an isotropic, homogeneous, and stationary atmosphere and thus are not directly applicable to the case at hand. We will present a brief review of his work and try to illustrate how at least one of Gifford's models can be extended to describe the results of the experiment of 17 June.

Gifford assumed a volume source to be the sum of an infinite number of instantaneous point sources each

OBLIQUE – NO SCALE

T = 1.5 HOURS

Ū = 0.32 KNOTS

COAST LINE
APPROX. 1.2 MILE

CONTINUOUS DISCHARGE

ORANGE COUNTY OUTFALL

17 JUNE 1964
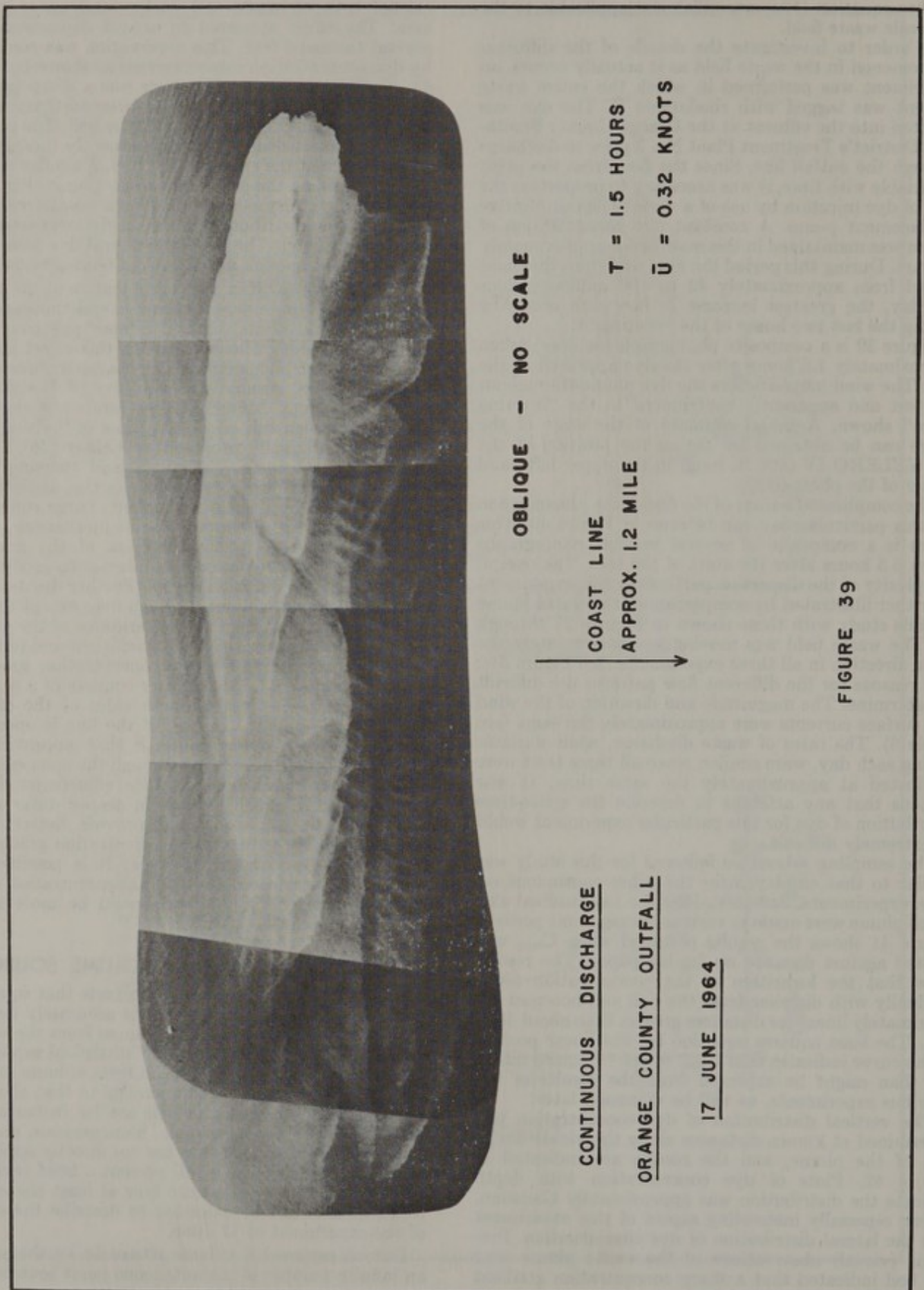
FIGURE 39

CONTINUOUS DISCHARGE

ORANGE COUNTY OUTFALL

17 JUNE 1964

T = 3.5 HOURS

$\bar{U}$ = 0.32 KNOTS

COAST LINE
APPROX. 1.2 MILE

FEET
1000   0   1000

FIGURE 40

MAXIMUM CONCENTRATION
vs.
DISTANCE FROM BOIL
ORANGE COUNTY OUTFALL
17 JUNE 1964

$C_{max} = 34.50 \ (X)^{-0.55}$

(Field Data)
$(X \leq 1000 \ Ft.)$

Eq. 39

LEGEND

● 1.25 Hours
◐ 3 Hours
△ 4.25 Hours

DISTANCE — (FEET)
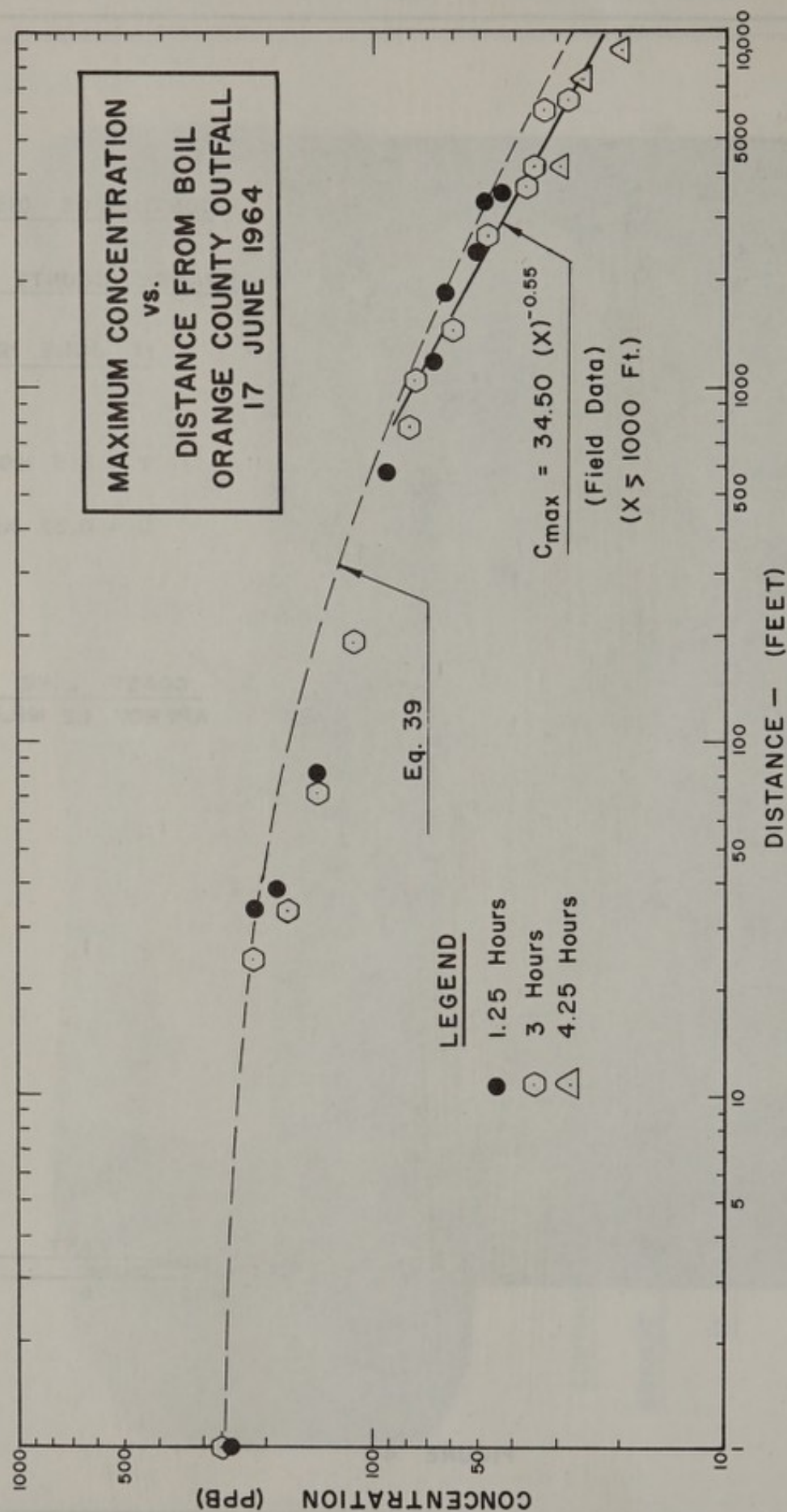
FIGURE 41
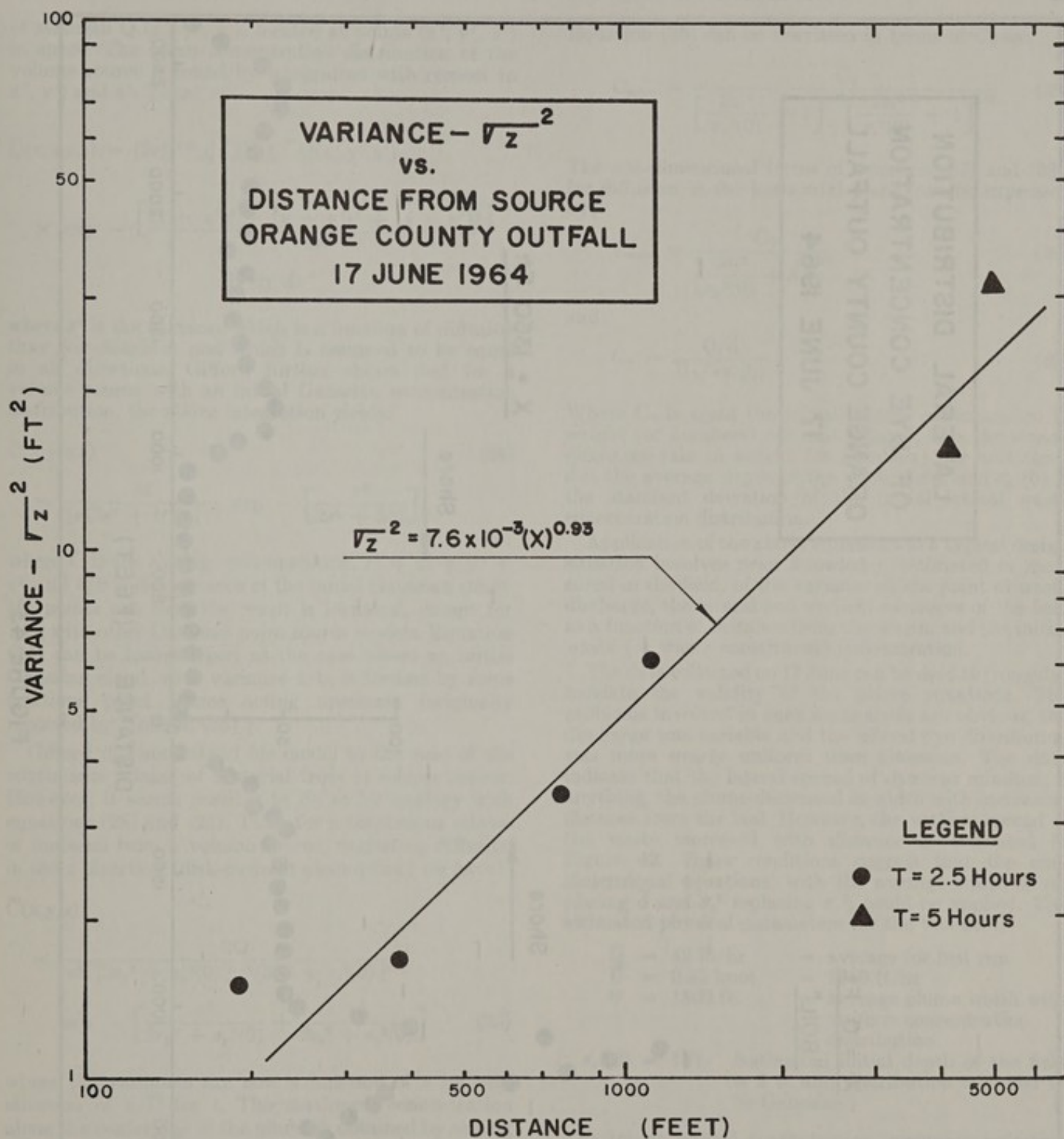
CONCENTRATION (PPB)
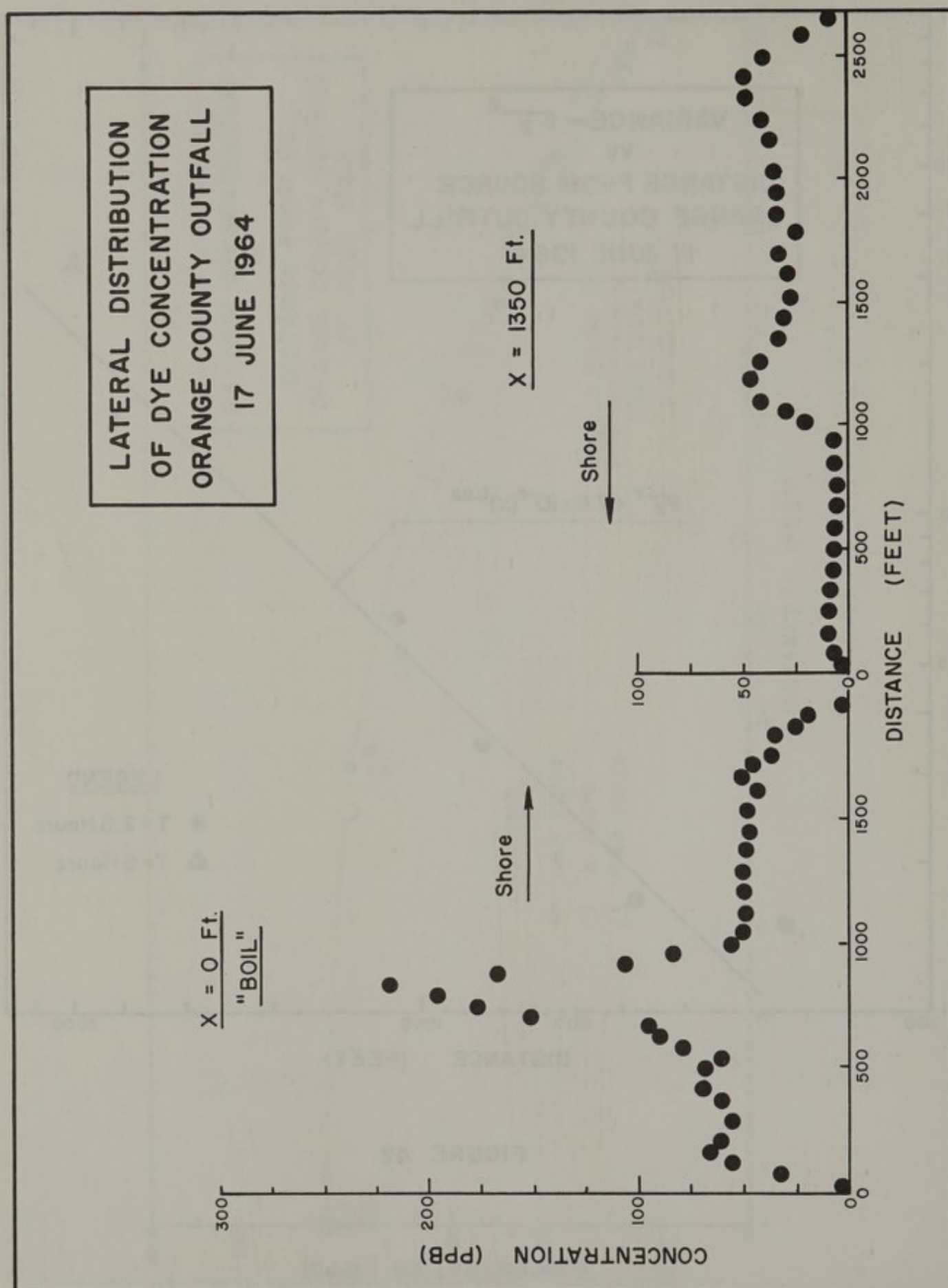
FIGURE 42

FIGURE 43

of strength Q (x', y', z'), located at points (x', y', z') in space. The mean concentration distribution of the volume source is found by integration with respect to x', y', and z'. Thus:

$$\bar{C}(x,y,z,t) = (2\bar{\sigma}^2)^{3/2} \int_0^\infty \int_0^\infty \int_0^\infty Q(x',y',z')$$

$$\times \exp - \left[\frac{(x - x')^2 + (y - y')^2 + (z - z')^2}{2\bar{\sigma}^2}\right]$$

$$dx'dy'dz'$$

where $\bar{\sigma}^2$ is the variance which is a function of diffusion time (or distance) and which is assumed to be equal in all directions. Gifford further shows that for a volume source with an initial Gaussian concentration distribution, the above integration yields:

$$\bar{C}(x,y,z,t) \tag{34}$$

$$= \frac{M}{[\pi(2\bar{\sigma}^2 + b^{-1})]^{3/2}} \exp - \left[\frac{r^2}{2\bar{\sigma}^2 + b^{-1}}\right]$$

where $\bar{C}$ is the average concentration, $r^2 = x^2 + y^2 + z^2$, and $1/b$ is the variance of the initial Gaussian cloud. He points out that the result is identical, except for $1/b$, with other Gaussian point source models. Equation (34) can be looked upon as the case where an initial Gaussian cloud, with variance $1/b$, is formed by some fictitious point source acting upstream (originally reported by Holland (38)).

Gifford did not extend his model to the case of the continuous release of material from a volume source. However, it seems possible to do so by analogy with equations (28) and (29). Thus, for a continuous release of material from a volume source, neglecting diffusion in the x direction (disk-element assumption) we have:

$$\bar{C}(x,y,z)$$

$$= \frac{2Q}{\pi \bar{U} [2\bar{\sigma}_y^2 + \bar{\sigma}_y^2(0)]^{1/2} [2\bar{\sigma}_z^2 + \bar{\sigma}_z^2(0)]^{1/2}}$$

$$\exp - \left[\frac{y^2}{2\bar{\sigma}_y^2 + \bar{\sigma}_y^2(0)} + \frac{z^2}{2\bar{\sigma}_z^2 + \bar{\sigma}_z^2(0)}\right] \tag{35}$$

where the variances are now a function of x by substitution of $x/\bar{U}$ for t. The maximum concentration along the center line of the plume is obtained by setting $y = z = $ zero in (35). Thus:

$$C_{max} = \frac{2Q}{\pi \bar{U} \bar{\sigma}_y(0)\bar{\sigma}_z(0)\left[\frac{2\bar{\sigma}_y^2}{\bar{\sigma}_y^2(0)} + 1\right]^{1/2}\left[\frac{2\bar{\sigma}_z^2}{\bar{\sigma}_z^2(0)} + 1\right]^{1/2}} \tag{36}$$

The initial maximum central concentration where $x = $ zero is:

$$C_{max}(0) = C_0 = \frac{2Q}{\pi \bar{U} \bar{\sigma}_y(0)\bar{\sigma}_z(0)} \tag{37}$$

Equation (36) can be rewritten in terms of C_0 as:

$$C_{max} = \frac{C_0}{\left[\frac{2\bar{\sigma}_y^2}{\bar{\sigma}_y^2(0)} + 1\right]^{1/2}\left[\frac{2\bar{\sigma}_z^2}{\bar{\sigma}_z^2(0)} + 1\right]^{1/2}} \tag{38}$$

The one-dimensional forms of equation (37) and (38), for diffusion in the horizontal plane, can be expressed by:

$$C_{max} = \frac{C_0}{\left[\frac{2\bar{\sigma}_y^2}{\bar{\sigma}_y^2(0)} + 1\right]^{1/2}} \tag{39}$$

and:

$$C_0 = \frac{Q/\bar{d}}{\bar{U}\sqrt{\pi}\bar{\sigma}_y(0)} \tag{40}$$

Where C_0 is again the initial central concentration in weight (or numbers) per unit volume, Q is the steady discharge rate in weight (or numbers) per unit time, $\bar{d}$ is the average depth of the waste field, and $\bar{\sigma}_y$ (0) is the standard deviation of the initial lateral waste concentration distribution.

Application of the above equations to a typical design situation involves prior knowledge, estimated or measured in the field, of the variance at the point of waste discharge, the lateral and vertical variances of the field as a function of distance from the origin, and the initial waste (or waste constituent) concentration.

The data collected on 17 June can be used to (roughly) indicate the validity of the above equations. The problems involved in such an analysis are obvious, the discharge was variable and the lateral dye distribution was more nearly uniform than Gaussian. The data indicate that the lateral spread of dye was minimal; if anything, the plume decreased in width with increasing distance from the boil. However, the vertical spread of the waste increased with distance as indicated in Figure 42. These conditions suggest that the one-dimensional equations, with the average width $\bar{w}$ replacing $\bar{d}$ and $\bar{\sigma}_z^2$ replacing $\bar{\sigma}_y^2$, could be applied. The estimated physical parameters for the test are:

$\bar{Q}$ = 42 lb/hr = average for test run
$\bar{U}$ = 0.32 knot = 1950 ft/hr
$\bar{w}$ = 1500 ft. = average plume width with *uniform* concentration distribution

$\bar{\sigma}_z$ (0) = 1 ft. (estimated initial depth of the field is 2 ft and distribution assumed to be Gaussian.)

The initial central concentration, assuming reflection of the boundary for the vertical case, is:

$$C_0 = \frac{2Q}{\bar{U}\sqrt{\pi}\bar{\sigma}_z(0)\bar{w}}$$

$$= 16.3(10)^6(lb/ft^3)$$

$$= 254(ppb)$$

This value should be compared to a measured value of approximately 265 ppb at the boil. The maximum

concentration along the center line of the waste plume is:

$$C_{max} = \frac{C_0}{\left[\frac{2\bar{\sigma}_z^2}{\bar{\sigma}_z^2(0)} + 1\right]^{1/2}}$$

where σ_z^2 is given empirically in Figure 42. The results of this analysis are shown in Figure 41. The fit of the theoretical curve to the observed concentration distribution is good. However, the results of this analysis obviously can not be taken as confirmation of the proposed equations, and additional data on large scale diffusion of surface waste fields is needed for further analysis.

In most cases the horizontal component of diffusion within the waste plume would be the most significant, if not the controlling, factor in the overall dilution process. Therefore, the volume source equations used to predict C_{max} would be, including vertical diffusion, of the two dimensional type. An example of the method of analysis applicable to this case will aid in the present discussion. Using the data collected for the experiments of 27 June 1963 and 17 June 1964 as a guide, we can solve the following hypothetical problem.

Basic assumptions:
1. Diffusion of the waste plume is two-dimensional, i.e., in the Y and Z directions. Longitudinal diffusion is assumed to be negligible.
2. The diffusing substance (dye) is conservative.
3. Diffusion will be at or near the ocean surface.
4. Steady state conditions exist.
5. The lateral and vertical distribution of diffusing material is Gaussian in form.

Physical Conditions:
$\bar{Q}$ = 42 lb/hr (dye)
$\bar{U}$ = 2200 ft/hr = 0.36 knots
$\sigma_y(0) \cong$ 45 ft $\cong$ width/4
$\sigma_z(0) \cong$ 1 ft $\cong$ depth/2
$\bar{\sigma}_y^2$ = 60(x), ft^2
$\bar{\sigma}_z^2$ = 7.6 $\times$ 10^{-3} (x)$^{0.93}$, ft^2

Applying equations (37) and (38) gives the following results:

C_0 = 2.8(ppm)

$$C_{max} = \frac{2.8}{\left[\frac{2\bar{\sigma}_y^2}{\bar{\sigma}_y^2(0)} + 1\right]^{1/2}\left[\frac{2\bar{\sigma}_z^2}{\bar{\sigma}_z^2(0)} + 1\right]^{1/2}} \quad (ppm)$$

Substitution of the assumed empirical equations for the coordinate variances into the above equations yields the relationship for C_{max}. The results are shown in Figure 44 and are labelled "example A."

The point source equation for C_{max} for the assumed conditions can also be solved for comparison. Thus, substitution of assumed values for the variances into equation (28) gives

$$C_{max}(x) = \frac{42}{(2200)\pi[60 \times 7.6 \times 10^{-3}]^{1/2}(x)^{0.97}}$$

$$= 0.903(10)^{-2}(x)^{-0.97}(lb/ft^3)$$

$$= 141.1(x)^{-0.97}(ppm)$$

The results are also shown in Figure 44 as example B. A comparison of the volume and point source equations indicate that the equations converge, giving essentially the same results, for X > 1000 ft. However, for distances between 0 and 1000 ft. the point source equation gives values of C_{max} that are much too large. These results indicate that for diffusion near the source, the volume source equations give a more accurate and realistic estimate of waste dilution.

The effect of neglecting the vertical component of diffusion in the above example can be seen by solution of equation (39) with Co = 2.8 ppm for purposes of comparison. Thus

$$C_{max} = \frac{2.8}{\left[\frac{2\bar{\sigma}_y^2}{\bar{\sigma}_y^2(0)} + 1\right]^{1/2}}$$

The resulting expression for $C_{max}(x)$ is shown for comparison in Figure 44 as "example B." The effect of neglecting vertical dispersion in this hypothetical example is obvious.

The assumed expression for the lateral variance indicates that in this example the lateral spread of dye (or waste) is parabolic, as indicated in Figures 26, 27 and 28. The spatial distribution of dye concentration can be determined by solving equation (35) for values of y (at given values of x) corresponding to any arbitrary dye concentration. Figure 45 shows a series of iso-concentration contours computed by use of equation (35) and the values of Co and σ_y^2 given in example A above.

Whether σ_y^2 is proportional to x to the first, second or third power will depend on the initial size of the volume source as compared with the range of eddy sizes (eddy spectrum) characteristic of a given oceanic area, as suggested by Orlob (39).

The proposed volume source equations are obviously approximate and need further verification. Additional full-scale data on horizontal and vertical diffusion from existing outfalls is needed.

The proposed equations if valid, give the engineer an additional means of estimating the dilution and physical spread of a surface waste field. It should be pointed out that these equations offer a means of estimating the initial central dilution (1/Co) of the waste at the boil, as well as subsequent minimum dilution (1/C_{max}) due to diffusion of a steady waste plume. The equations can be modified to include the diffusion of microorganisms (coliform bacteria for example) by inclusion of a term for bacterial disappearance (die-off, settling, etc.). Since the equations developed for C_{max} are based on probability density relationships we can assume that for the case of microorganisms

$$C_{max} \hspace{6cm} (41)$$

$$= \frac{C_0}{\left[\frac{2\bar{\sigma}_y^2}{\bar{\sigma}_y^2(0)} + 1\right]^{1/2}\left[\frac{2\bar{\sigma}_z^2}{\bar{\sigma}_z^2(0)} + 1\right]^{1/2}} \exp - \left[\bar{k}\left(\frac{x}{\bar{U}}\right)\right]$$

Where the last term in (41) is the so-called "die-off" factor as a function of diffusion time (t = x/$\bar{U}$), and

MAXIMUM CONCENTRATION
vs.
DISTANCE FROM SOURCE
VOLUME SOURCE ANALYSIS

FIGURE 44

DYE PLUME
CONTINUOUS VOLUME SOURCE
TWO—DIMENSIONAL DIFFUSION

25 PPB

50 PPB

100 PPB

150 PPB

C_o= 2.8 PPM

$\bar{U}$

DISTANCE (FEET x 10^3)

Y — (FEET x 10^2)
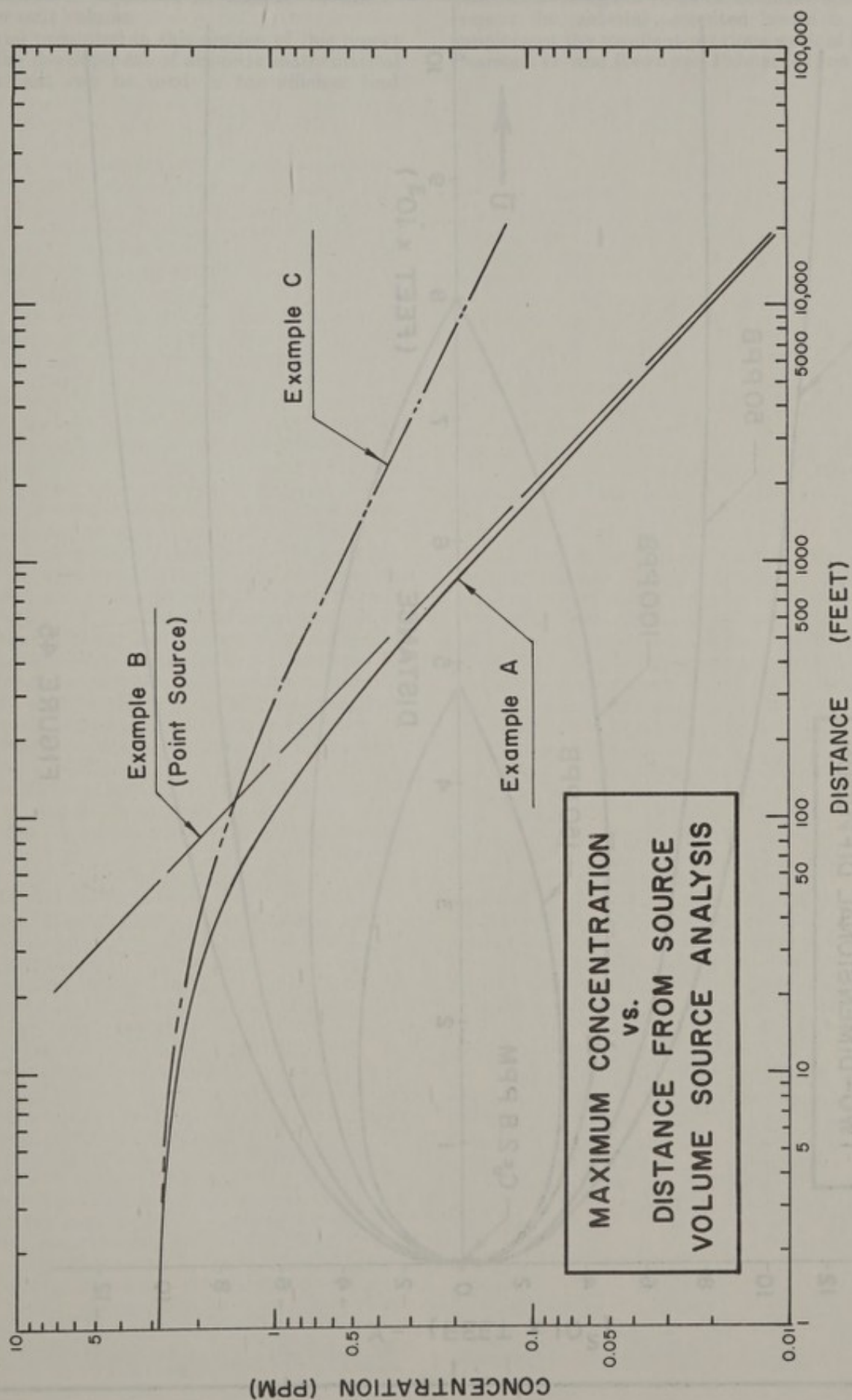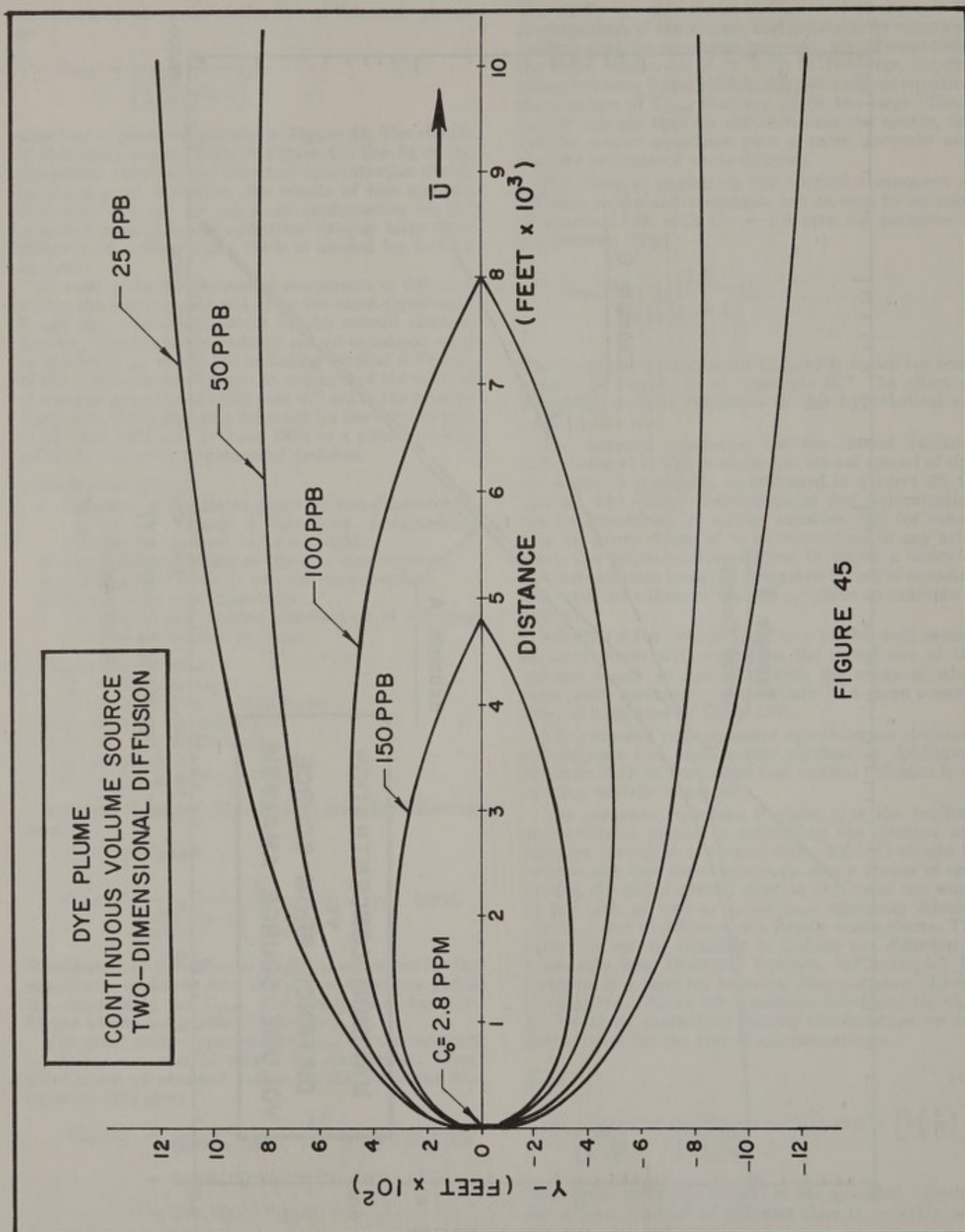
FIGURE 45

the concentration is expressed as number of micro-organisms per unit volume.

The material presented in this section of this report is to aid in the development of accurate mathematical formulations that can be used in the efficient and economical design of future submarine outfalls. In this respect the material presented herein is intended to supplement the excellent previous work of Brooks (40), Pearson (42) and Rawn and Palmer (41) on this subject.

C. PRIMARY PHYTOPLANKTON PRODUCTIVITY AND PRODUCTION IN A MARINE WASTE FIELD

1. INTRODUCTION

The utilization of natural bodies of water as receptacles for unwanted wastes predates the written history of man. With the growth of communities and industries the increase in the quantity of such wastes resulted in drastic changes in the quality of the receiving waters and concurrent inevitable changes in the biota.

The biotic changes, first noted as the alteration, depletion, or disappearance of certain faunal populations, are still most frequently assessed in terms of standing crops, i.e., the presence and quantity of various biotic elements. Examples of such observations include the increase in quantity of tube worms and the decrease of benthic algae as outlined by Bartsch (43), the appearance, subsequent loss, and later recovery of a commercial fishery (Hubbs (45)), and alterations in biological associations (Hartman (44), Tibby and Barnard (46)).

Understandably, a great proportion of such studies have dealt with the effects of sewage disposal in bodies of fresh water such as rivers, lakes and streams. Much of this work has been summarized by Hynes (47). Confining water masses and restricting currents to well-defined channels permits the build-up of concentrations of sewage effluent and its products to a quasi-steady state condition along the water course downstream from the outfall. As a function of distance and hence of dilution and alteration of the sewage, a series of intergraded ecological niches are found in which populations characteristic of the changed conditions will supplant earlier communities. Observations of this nature have led to variously defined systems of biological "indicator species" to evaluate levels of pollution. Those systems are reviewed by Hynes (loc. cit.) and will not be discussed in detail here other than to indicate that any single system may not be universally applicable because each stream, river or lake may have different normal populations and different ecological conditions.

The differences between fresh water and marine environments require some modification of the methods used in their biological study. Some of the methods for marine work are detailed by Jannasch and Jones (48), Lackey (49) and Barnard and Jones (50).

Studies in the southern California marine environment of standing crops of organisms (Clendenning and North (51), Reish (52), Resig (53), Bandy, Ingle and Resig (54, 55), Hartman (44), Tibby and Barnard (46), Allan Hancock Foundation (56)) have described arrangements of biotic communities in relation to outfalls, arrangements which are similar in principle to those in fresh water environments.

Assessment of the influence of sewage in fresh and sea water on biological processes such as photosynthesis and respiration often has been made on the basis of standing crop or BOD. However, direct measurement of the processes involved, and particularly in algal populations, has been utilized only in isolated instances and for specific purposes. Among such studies are those of Goldman (57) who considered the role of sewage in accelerating the natural eutrophication of Lake Tahoe, and Lackey and Sawyer (58) and Lackey (59) who concluded that nutrients added by sewage contribute to the growth and blooms of planktonic algae. Steeman-Nielsen (60) believed that the productivity of a Danish lake fertilized by nutrient salts of sewage origin was limited by damage to the plants caused by a rise of pH engendered by CO_2 depletion. However, Eppley and MaciasR (61, 62) have found that under certain conditions an organic source of carbon may be utilized in photosynthesis by sewage pond algae. Algal blooms in small embayments have been attributed to the nutrients added by polluted water (Ryther (63)) although for open coastal waters there are apparently no factually documented reports.

Standing crop measurements give a summation of the momentary states of balance between the processes that are occuring but do not give an accurate picture of the physiological effects of the sewage on the biota or any indication of the rate of turnover of the biota or of the organic and inorganic nutrients contributed by the sewage. Such information on rates are of first importance in considering the effective capacity of an area to handle sewage without profound alterations in the biota, and in predicting the effect of an outfall on the biological resources of the area. It has been the intent of this project to utilize existing methods and to develop new techniques in an attempt to assess this magnitude of biological and chemical turnover within a marine sewage field.

2. AREAS STUDIED, AND METHODS

The area selected for study lies off Newport Beach, California, where the Orange County Treatment Plant #2 discharges about 75 mgd of mixed domestic and industrial wastes through a pipeline terminating about 1⅛ miles off the mouth of the Santa Ana River in about 60 feet of water (Figure 31). The sewage, most of which has had only primary treatment, is warmer and less saline than sea water and rises to form a visible boil on the surface. At the surface the water contains about 5–10% sewage effluent. Currents in the area consist largely of longshore currents running southward roughly parallel to the coast, although occasionally a northward flowing current is present. Frequently there is an onshore movement of the surface waters in addition to the longshore currents. The general southward transport of surface water along the coast is disrupted about 3 miles south of the outfall line by turbulence associated with the Newport Submarine Canyon.

This area was selected over others on the southern California coast for several reasons. First, the surface boil and the downstream sewage field were nearly always

easily seen, in contrast to the situation in Santa Monica Bay where the Hyperion effluent field is much larger but is extremely difficult to locate. Second, the type of mixed domestic and industrial effluent discharged is fairly representative of the other major outfalls along the coast. Third, the Orange County outfall was within convenient sailing time from the ship's berth in San Pedro.

Except for some special purposes, stations were occupied in relation to the trajectory of the diffusing sewage field. The method of choice in identifying and tracking specific water masses was to use the fluorescent dye, rhodamine-B, supplemented by drogues. Occasionally a dog-leg or grid pattern was established in relation to the boil and to the currents prevailing at the time.

The use of current markers of one sort or another has the great advantage of permitting a study of the time-sequence of events along the trajectory of the diluting sewage field. Stations were occupied at timed intervals near the marker which (supposedly) stayed in the same patch of diluting sewage. The selection of appropriate types of current markers can be quite critical. Drogues, although easy to use and inexpensive, can give an inaccurate picture of the currents being measured since they are subject to wind drift and may be caught in eddies that are not following the main current. Dye patches or dye streams released at the boil are less subject to wind drift and, as they disperse to form a larger sized patch, are less subject to being retained in small eddies or other peculiar, small-scale features of the circulation. However, the patches ultimately diffuse beyond the level of easy detection, and they cannot be readily followed at night. The dye itself (rhodamine-B) has a slight adverse effect on carbon-14 uptake of phytoplankton, and for this reason productivity samples usually were taken just ahead of the dye field. The most effective current marker we have tried is to utilize the entire sewage field by continuous release of dye in the treatment plant prior to pumping it and the sewage effluent through the outfall line. In this case, the entire sewage field was highly visible and the relative concentration of sewage in the field was well defined. Because of the expense of a sufficient quantity of dye to provide a continuous-release tag adequate for extended periods of study, this method does not seem promising as a routine measure.

For comparison with the study area, a control area along a 20 mile stretch of coast was selected off Camp Pendleton equidistant between Oceanside and San Clemente. Oceanside lies some 35 miles south of the study area. Although the submarine topography and general hydrographic conditions are not exactly like those of the study area, there was no other site within easy sailing distance that could be assumed to be free of sewage. Camp Pendleton, the nearest sizeable center of population, reprocesses its sewage and does not discharge any of it into the coastal waters. San Clemente, 9 miles north and upstream is the nearest community utilizing the sea for waste disposal. The average volume flow of this outfall is 0.5 mgd., and its effect is apparently negligible in the control area.

Stations in this control area were occupied either using a predetermined dog-leg pattern or lines of stations at right angles to the shore. Sampling was carried out as time and boat scheduling permitted and yielded data representative of the situation to be expected in uncontaminated water along a stretch of coast roughly similar to the study area in size and hydrographic conditions.

All samples for determining productivity and pigments were collected in non-metallic samplers to avoid the problem of poisoning by metals. For surface samples three gallon plastic buckets were used. Subsurface samples were collected using "snatch" bottles, Van Dorn samplers, and a specially designed and constructed valve sampler. The "snatch" bottle was a weighted 2-liter plastic bottle which was lowered on a hand line to the appropriate depth. A separate line connected to a rubber stopper in the mouth of the bottle was used to "snatch" the stopper from the bottle. The Van Dorn samplers with a capacity of about 6 liters were purchased from Kahl Scientific Instrument Co., San Diego, California. These samplers consisted of a plastic tube closed by rubber force cups held under tension by a piece of rubber tubing. The specially designed samplers were constructed to our specifications by Logan Smith and Associates, Harbor City, California, and were extensively used in the later stages of this study. They are described in the later section on chemistry.

The method of assaying productivity used during this project was slightly modified from the isotopic carbon tracer method first described by Steeman-Nielsen (64). Each sample collected at each station was subdivided and a portion was used to completely fill duplicate series of clear and opaque 125 ml. glass-stoppered Pyrex bottles. These bottles were stored at ambient temperatures in a covered box. Addition of the isotopic tracer in a $34^o/_{oo}$ NaCl solution containing 2 micro-curies of carbon-14 as sodium carbonate, and incubation was begun the following morning. Using a standard time of day for incubation eliminated the correction for diurnal periodicity in the photosynthesis of phytoplankton reported by Doty and Oguri (65). Incubation was carried out for production measurements by suspending the bottles at the depth and location of collection from a buoyed and anchored line, or for productivity measurements by placing the bottles in a box on deck where they were immersed in running sea water and exposed to ambient daylight. Following an incubation period of about 3–4 hours for samples incubated in the deck box, and 5–7 hours for samples incubated *in situ*, samples were filtered through Millipore AA filters and the filters were stored in a desiccator for return to the laboratory where the activity retained on the filtered samples was counted in a low-background flow counter. Counts from the clear bottles minus counts from the opaque bottle were used to compute milligrams of carbon fixed per day per cubic meter.

Pigment analyses were carried out according to the method of Richards and Thompson (66). For this purpose, one-half to one liter of sample water was filtered through a Millipore AA filter. As the last of the water went through the filter, a small quantity of a suspension of $MgCO_3$ was added to retard breakdown of chlorophyll. The filters were then stored in a darkened desiccator held at refrigerator temperatures. In the laboratory, pigments were extracted by placing the dried filters in 90% acetone for 12 to 24 hours in the refrigerator. The optical absorption at the wavelengths

of the peak absorption for the chlorophylls was then measured either in a Beckman model DU or DB spectrophotometer with, respectively, 10 cm. or 4 cm. light paths through the sample. Pigment concentrations were calculated as mg. or MSPU of the different pigments per cubic meter according to the formulae listed by Richards and Thompson (loc. cit.).

3. CHANGES IN PRODUCTIVITY ASSOCIATED WITH WASTE

In the Annual Report for 1962–63 (1) the reasons for considering the productivity as a function of standing crop were discussed. Briefly, due to a persistent and patchy red tide in the study area the pattern of productivity found both in the background and the sewage field was variable and inconsistent. It was believed that a clearer and more readily interpreted pattern might be obtained if productivity were considered as a function of the biological standing crop rather than as a function of volume or surface area of water. The inherent tedium of cell counts and species lists precluded their use in this survey. Photosynthetic pigments, the chlorophylls, were selected as a measure of the standing crop because of the ease and rapidity of their determination and their more direct relationship to the productivity of the organisms. Although correlations between productivity and changes in chlorophyll content in marine phytoplankton are not expected to be high, our work was confined to a relatively small area containing a population that can be assumed to be relatively uniform in make-up and in photosynthetic efficiency during any one cruise.

Table 8 presents data from one cruise during which samples were collected both in the control area south of San Clemente, and in the study area off the Orange County Treatment Plant. Both areas are about the same relative size, extending 6–7 miles along the coast and 2–3 miles offshore. The data for all stations show correlation between productivity and total chlorophyll

TABLE 8

The correlation and regression of productivity per unit of chlorophyll of surface and sub-surface samples at a series of stations in the control area south of San Clemente, and in the study area at the Orange County outfall, 31 October–2 November 1962. Stations in the study area are numbered consecutively in order of time occupied during drift from the boil with Station 1 located at the boil and Station 8 farthest from it. The time between stations was approximately two hours.

Station number	Control area all stations	Study area					
		All stations	Pairs of stations				
			1 & 2 (0–2 hr)	3 & 4 (4–6 hr)	5 & 6 (8–10 hr)	7 & 8 (12–14 hr)	
	1–8	1–8					
No. of samples	24	23	6	5	6	6	
Correlation	0.925†	0.581†	−0.625	0.089	0.890*	0.918†	
Regression	25.80	45.73	−8.27	3.03	49.91	91.22	

* Significant
† Highly significant

of 0.925, n = 24, at the control site and 0.581, n = 23, in the diluting sewage field at the Orange County area. The data for the Orange County area are further broken down to cover pairs of consecutive stations starting at the boil and ending 14 hours after discharge. The correlations then run from negative nearest the boil to high and positive away from the boil. The correlation at the pair of stations 7 and 8 farthest from the boil is similar to that in the San Clemente area. The lack of good correlation close to the boil reflects the confused picture and rapid change of the relationship in the first few hours following discharge of the sewage.

The regressions of productivity per unit of chlorophyll indicate that even at the last pair of stations in the field there was an enhancement of productivity compared to the control area while the correlations suggest that the sewage remaining no longer exerted the inhibiting effect that was prominent during the first six hours (Stations 1 & 2, 3 & 4).

Figure 46, reproduced from the Annual Report for 1962–63 (1), shows the production and productivity per unit of chlorophyll found in the surface sewage field during eleven cruises in the study area at a time of intense red tide. In this and subsequent Figures, and in the discussion, one may read "production" for "productivity", where "production" is measured by carbon-14 uptake in seeded bottles suspended at the depths from which the samples were originally taken, and "productivity" is the potential production determined from samples incubated in the box on deck at ambient conditions of light and temperature. During the time-interval covered by each of the field studies, the sewage field remained at the surface and productivity therefore closely approximated production in situ at the sea surface. A number of early experiments confirmed the fact that productivity of surface samples and production in situ at the surface yielded almost identical results. This was a fortunate circumstance because time-consuming in situ measurements then became unnecessary for purposes of this study.

Figure 46 shows a fairly clear pattern of low productivity near the boil, an increase to a high some distance away from the boil, and then a dropoff towards background values. The situation near Newport Canyon is somewhat confused because of interruption of the normal longshore currents toward the southeast. Although the intensity of the red tide in the area during this period varied, as long as it did persist the phytoplankton of the area were essentially a unialgal population. The overall photosynthetic efficiency of the phytoplankton, therefore, did not appear to vary in time as it might under more normal conditions when populations of different relative composition would succeed one another. Consequently, subsequent cruise data showed a smaller and more variable rate of carbon fixation per unit of chlorophyll, although the same general sequence of low-high-background productivity occurred with remarkable regularity.

The data for the later cruises (after May, 1963) when there was little or no red tide were grouped according to season and the resulting patterns showed some consistency. These seasonal patterns are presented in Figures 47, 48, 49 and 50.

Neither the seasonal coverage nor the station patterns were as extensive in the control area as those in the

FIGURE 46

PRODUCTION AND PRODUCTIVITY
AS mgC/day/mg
OF TOTAL CHLOROPHYLL
ORANGE COUNTY OUTFALL
AUGUST 1962 – MAY 1963

FIGURE 47

SPRING PRODUCTIVITY

AS mgC/day/mg

OF TOTAL CHLOROPHYLL

FIGURE 48

SUMMER PRODUCTIVITY
AS mgC/day/mg
OF TOTAL CHLOROPHYLL

FIGURE 49

FALL PRODUCTIVITY

AS mgC/day/mg

OF TOTAL CHLOROPHYLL

FIGURE 50

WINTER PRODUCTIVITY
AS mgC/day/mg
OF TOTAL CHLOROPHYLL

1 Nautical Mile

study area, but the data for the control area can be extrapolated to cover the same size and shape of area for purposes of comparison. The data on surface productivity (production) shown in Figures 47 through 50 are tabulated by seasons in Table 9 together with similar data from the control area. In the study area it is evident that there was a seasonal pattern showing high production in the spring and summer and low production in fall and winter. It is of interest to note that a red tide in the study area added a second and greater maximum of productivity in the fall with production about 5 times higher than in non-red tide periods. In the winter and spring the effect of the red tide on total production was considerably smaller. Red tide productivity in the winter months was 65% higher than in the absence of red tide and in spring it was 23% higher. With or without red tide, winter production was relatively low. No red tide was evident during the summer cruises.

The control area was investigated only in the spring and fall. For these two seasons the results were similar to those from the study area in that spring production was about double that in the fall. Red tide in the control area was evident in only a few isolated samples during the few cruises to that area and these samples were omitted from the calculated data in Table 9.

A comparison of the non-red tide data in the study area to those in the control area indicates that total production in the area of the sewage field was approximately double that in the control area. Although enrichment by the sewage undoubtedly contributed to this increase, it may be speculative to assign all of it to that cause. The submarine canyon off Newport, with its upwelling of nutrients from aphotic depths, may well have contributed to the difference.

The relationship of red tide to waste discharge is still doubtful. Its presence in the study area and its general absence in the control area may reflect chance conditions encountered in the relatively few cruises to the control area. Alternatively, the net water movement through the study area requires less than 24 hours and the previous history of the water is of some importance in determining its phytoplankton population. In addition, red tide was commonly heavy upstream and offshore from the sewage field. This, together with the fact that heavy red tide occurs in coastal areas quite remote from any outfall, makes it doubtful that sewage

TABLE 9

The mean daily production at the surface for the four seasons in the study area off Orange County, and the control area off Camp Pendleton. The data are expressed as metric tons of carbon fixed per day over a total area of 60.2 square kilometers or 17.6 square miles. Figures in parentheses are from samples collected in the study area during periods of red tide.

Season	Study area	Control area
Winter	4.8 (7.9)	No observations
Spring	9.7 (11.9)	4.2
Summer	10.0 (no red tide)	No observations
Fall	4.4 (23.6)	2.4

is related to the periodic development of heavy red tide along this coast.

4. FACTORS POSSIBLY RELATED TO OBSERVED CHANGES

From the work in fresh water, Hynes (47) made certain assumptions regarding the sequence of changes that may be of biological significance in receiving waters; a) dissolved oxygen content will be sharply reduced at the point of sewage discharge and will rise gradually downstream as the BOD is satisfied; b) the addition of suspended and dissolved matter in the effluent will sharply decrease water transparency near the outfall and return to normal downstream; c) the suspended material will settle out forming a graded bed of sediment along the course of the current; d) toxic and inhibitory substances normally absent, or present in low concentrations, together with e) nutrient substances normally present in small quantity, will be in high concentration in the vicinity of the outfall and will gradually decrease downstream as both chemical and biological processes remove, dilute, or alter them. Each of these factors as they affect productivity in open coastal waters are discussed as follows:

a. Dissolved oxygen—

The oxygen content of the sewage field rapidly approaches that of the background waters, with the most rapid increase occurring during initial mixing when the plume rises to the sea surface. At the surface, oxygen is present at about 75% of saturation. Subsequent eddy diffusion brings about a further increase. This rapid mixing rate with receiving water which contains oxygen at 90–140% saturation more than satisfies BOD requirements and the oxygen pattern within the spreading field is entirely different than that described by Hynes (loc. cit.). It is unlikely that levels of oxygen are sufficiently low to interfere with the respiration of pelagic organisms within the surface field.

b. Transparency—

Low transparency of the water near the boil obviously limits the euphotic layer to an extremely shallow depth. Over the area as a whole, turbidity is of great significance to the benthic biota but is of less significance to the pelagic life of the area. Due to the variability in direction and magnitude of the currents, unlike the confined flow in streams and rivers, steady state conditions do not exist at any point in space except in the immediate vicinity of the boil. Consequently the portion of the total area that is continuously affected is relatively small. Dilution at a relatively high rate also restricts the magnitude of the effect.

In considering pelagic populations, the situation is comparable to that in streams and rivers if one deals with events along the trajectories of the sewage field, except for the important difference that the availability of the diluting water and its contained population is very large and the rate of dilution is high and continuous.

Direct measurements of water transparency indicate that at and near the boil the transparency of the surface water was reduced to 10% or less of the transparency in air (Kahl transparency meter, path length = ½

meter). At a depth of about 5 to 10 meters transparency was very variable depending on whether or not the meter was in the rising sewage plume. At about 2 hours downstream, transparency at the surface was about 70–75%, and at 5 meters or more it was about 80–85%, a value which was approximately that of background. Further downstream the surface transparency increased slightly but somewhat lower transparency was encountered beneath the surface. The averaged data are presented in Table 10. Inspection of these data indicates that alteration of natural conditions is relatively short-lived. The sinking of the band of lowered transparency to at least 10 meters after 6 hours, and its increasing vertical dimension, seem to reflect vertical diffusion combined with settling of particulate material.

The effect of this reduction in water transparency on photosynthesis of phytoplankton may be estimated by the ratio of production to productivity of subsurface samples. Such a comparison is made in Figure 51. No red tide was present during these cruises. Samples were collected at 2-hour intervals in the path of a dye marker or drogue released in the boil. Obviously a blanket of red tide would produce the same effect as a loss of water transparency due to sewage but the data would not be directly attributable to the discharge of wastes into the waters. Inspection of this Figure shows that at 8–12 meters the effect of light reduction is apparently negligible after 12 hours. There is no significant effect on productivity apparent at this depth that could be attributed to the presence of sewage. At 1–3 meters the production and productivity relationship is disturbed by the presence of sewage during the first 10 hours. Beyond that time the level is similar to that from the deeper samples. Thus, the effect of reduced light transparency on phytoplankton production is relatively short lived. This agrees with Hynes' conclusion, although the time and distance scale will vary depending on the particular environmental situation.

c. Sedimentation—

The formation of graded beds of debris deposited by sedimentation of particulate matter from the sewage is of minor importance to the pelagic organisms with which this project is concerned. Therefore no studies were made of rates of settling or deposition. It is worth noting, however, that although the bottom may be greatly altered ecologically (Hartman (44)) there is no observational evidence that static beds of material continuously accumulate despite many years of operation of various marine outfalls along this coast.

d. Toxic and inhibitory substances, and

e. Nutrients—

These two headings are dealt with jointly since the methods employed do not determine the specific physiological role of the various substances for which analyses were made. For example, many nutrients can inhibit photosynthesis if they are present in too high a concentration. Our data show that after an initial depression, productivity starts to rise in the sewage field. Continued dilution results in a return to background levels of all nutrients and other parameters which were measured. Other processes which occur at the same time as physical dilution can result not only in a further

TABLE 10

Average transparency of water at stations occupied at timed intervals along the course of a diluting sewage field. The data are in percent transmittance along a light path of one-half meter compared to the transparency in air.

Depth	Hours			
	0 (Boil)	2	4	6
Surface.............	9%	75%	79%	81%
5–10 Meters.........	66%	84%	70%	70%
10+ Meters.........	62%	82%	75%	61%

alteration of absolute concentrations of substances but also in a change in their relative composition. These changes may be biological (uptake and release of substances by living organisms such as bacteria and phytoplankton), physical (adsorption on particles), and chemical (breakdown and synthesis of compounds). Thus, the pattern of productivity found in a diluting sewage field can be hypothetically attributed to the change in concentration, or to the alteration in composition of the effluent, or to a combination of the two. The analytical methods in use during the course of this study have been aimed at determining the concentration of selected compounds generally considered to be of biological significance.

The hypothesis that the sequence of events described above for productivity can be related to changing concentration of sewage was tested by the experimental exposure of a natural population to various concentrations of filtered effluent. The results of this experiment are listed in Table 8 of the Annual Report for 1962–63 (1) and indicate that high concentrations of effluent as found in the boil were indeed inhibitory. More dilute effluent stimulated productivity. It is worth noting that these effects were still evident after 14 hours storage of the mixture of phytoplankton and effluent.

Attempts to relate biological uptake of nutrient salts to reduction in concentration of the same nutrients in the medium have not been conclusive. In one field experiment, changes in the concentration of nitrate, phosphate and silicate were measured in both the light and dark bottles used for productivity determinations. The changes which occurred between the beginning and the end of the incubation period were less than the limits of error of the analytical procedures.

The three major nutrient substances for which extensive analyses have been made are nitrate, phosphate and silicate. These three, because of their biological importance, have been among the most widely measured and considered. The first two, nitrate and phosphate, are universal requirements for algal growth, and the last, silicate, is essential to the diatoms. The correlation between productivity and these nutrient salts in the field was poor whether the data were considered as a whole or for each individual cruise. Figures 52 through 60 illustrate the problem and show both the productivity and chemical data for different cruises plotted as a function of time of drift from the boil. The
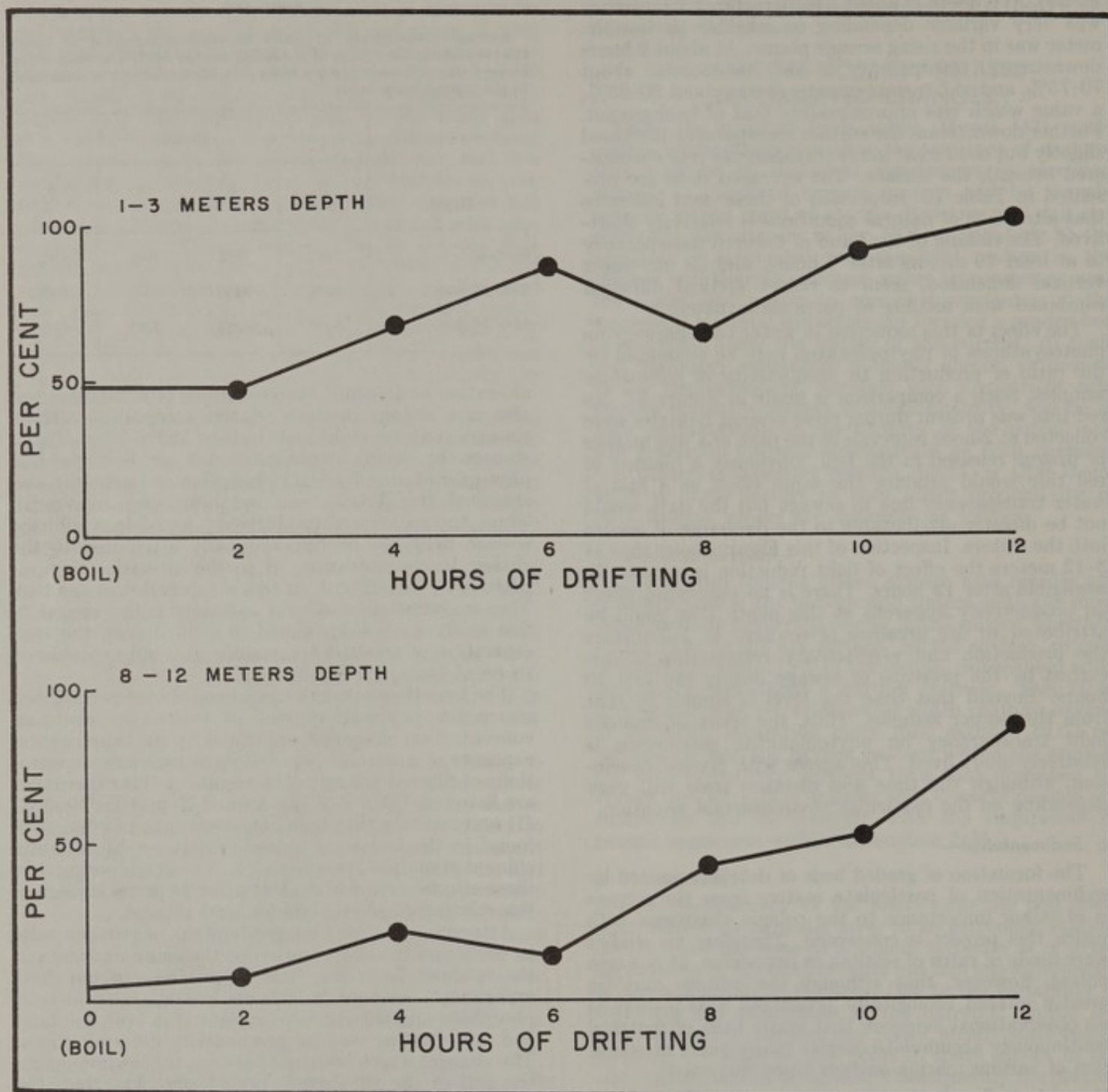
FIGURE 51

AVERAGE PERCENTAGE RATIO OF PRODUCTION TO PRODUCTIVITY

OF SUBSURFACE SAMPLES

FIGURE 52

31 OCTOBER 1962

LEGEND

● Productivity
▲ Productivity / T. Chl.
■ SiO$_2$
◆ PO$_4$

FIGURE 53
18 DECEMBER 1962

LEGEND
● Productivity
▲ Productivity / T. Chl.
■ SiO$_2$
◆ PO$_4$
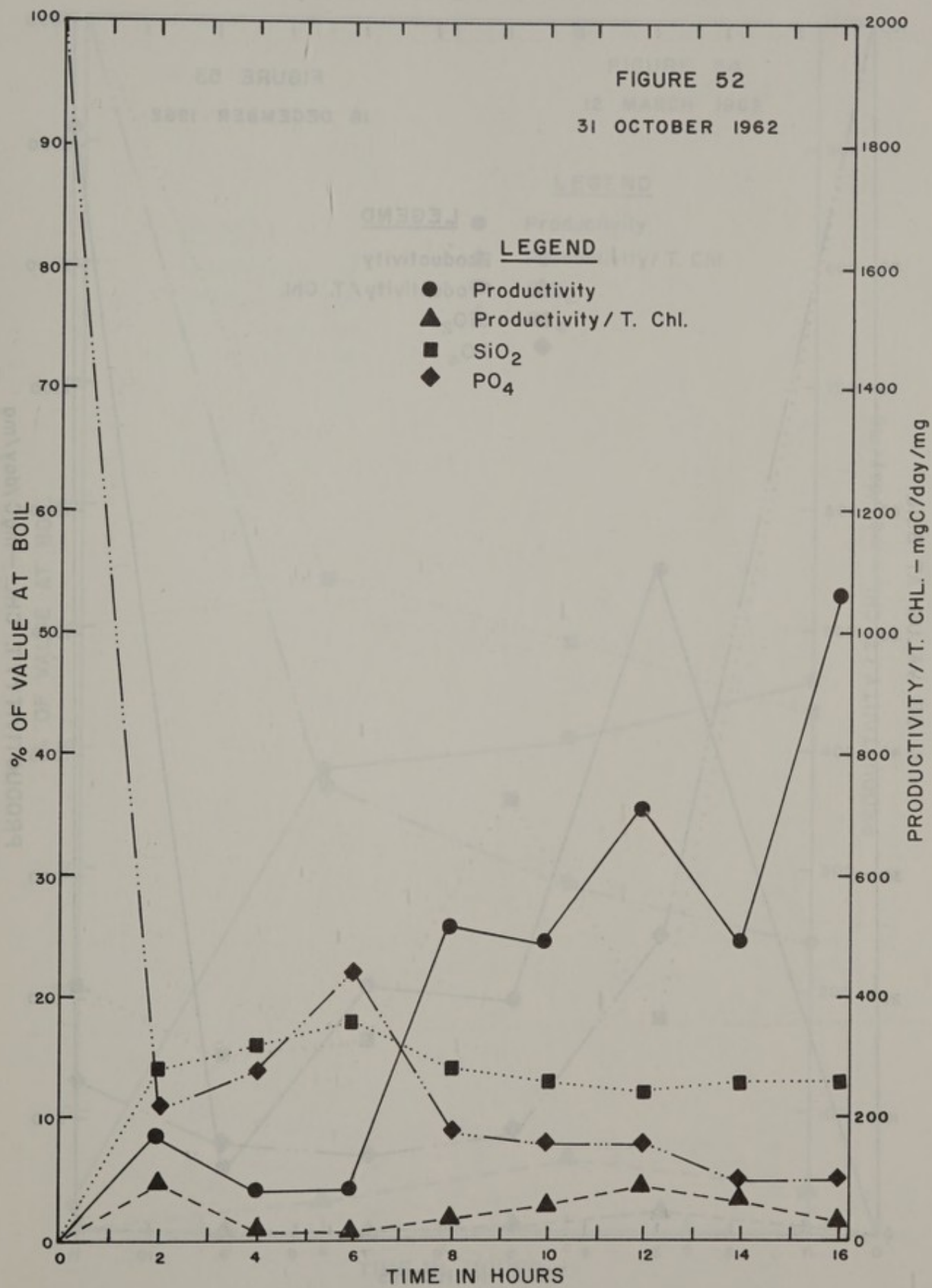
FIGURE 54
12 MARCH 1963

LEGEND
● Productivity
▲ Productivity/T. Chl.
■ SiO$_2$
◆ PO$_4$

FIGURE 55

13 MARCH 1963

LEGEND

● Productivity
▲ Productivity / T. Chl.
■ SiO₂
◆ PO₄

FIGURE 56
II APRIL 1963

LEGEND

● Productivity
▲ Productivity/T. Chl.
■ SiO$_2$
◆ PO$_4$

FIGURE 57
II SEPTEMBER 1963

LEGEND
- ● Productivity
- ▲ Productivity/T. Chl.
- ■ SiO$_2$
- ◆ PO$_4$
- ▼ NO$_3$
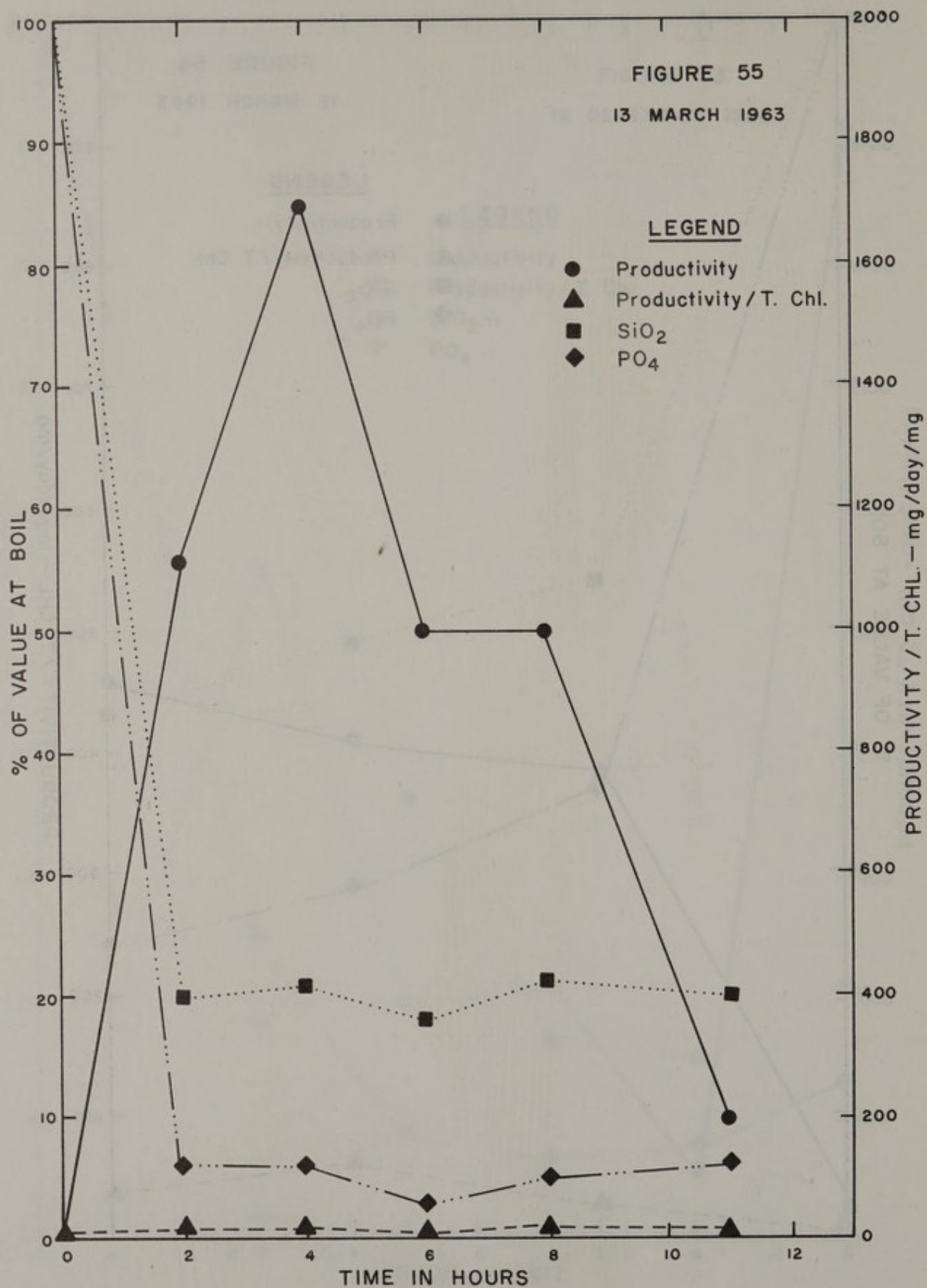
FIGURE 58
9 NOVEMBER 1963

LEGEND

● Productivity
▲ Productivity / T. Chl.
■ SiO₂
◆ PO₄

FIGURE 59
10 NOVEMBER 1963

LEGEND

●   Productivity
▲   Productivity / T. Chl.
■ SiO_2
◆ PO_4
▼ NO_3

FIGURE 60
17 JUNE 1964

LEGEND

- ● Productivity
- ▲ Productivity/T. Chl.
- ■ SiO$_2$
- ◆ PO$_4$
- ▼ NO$_3$
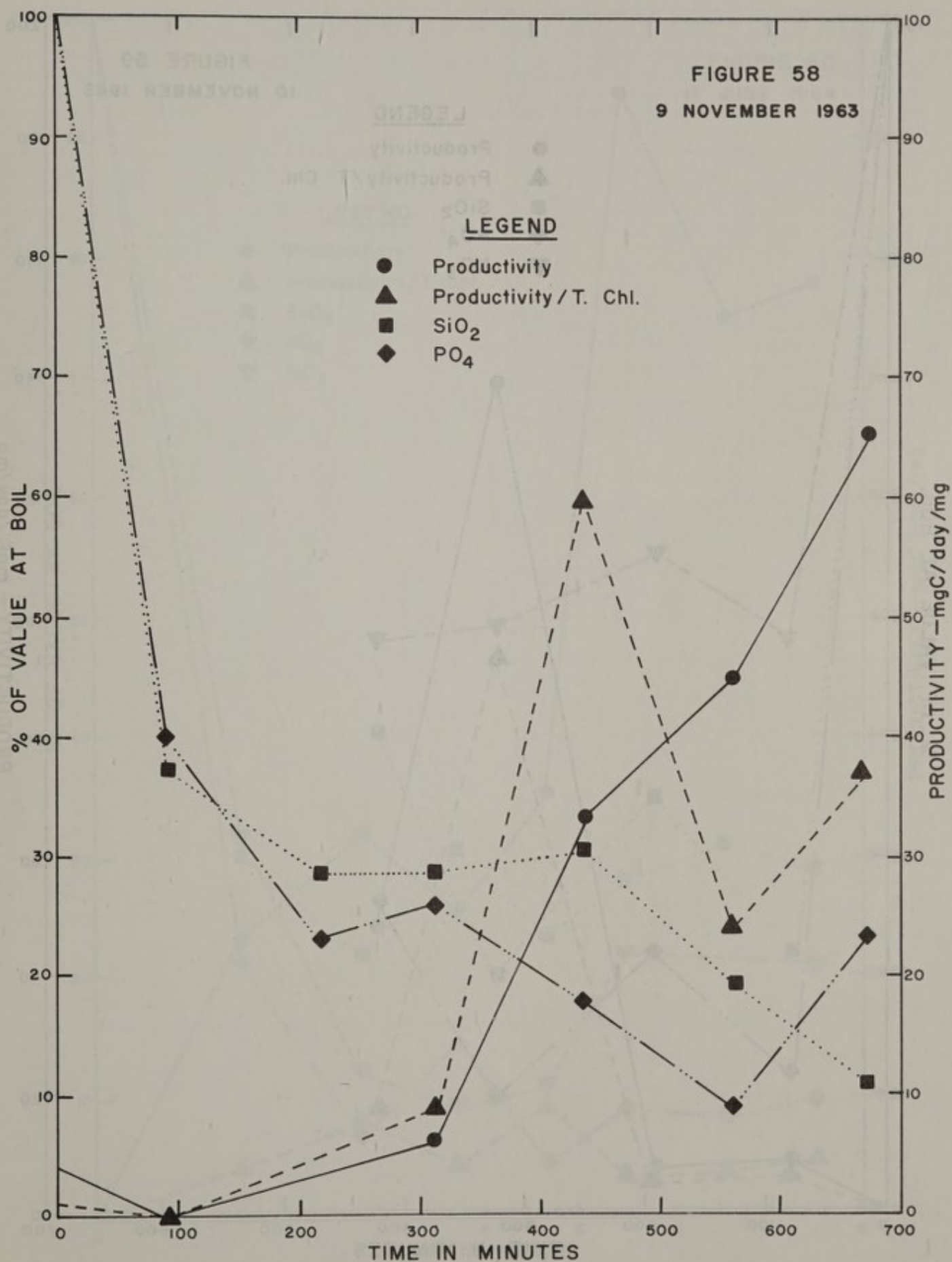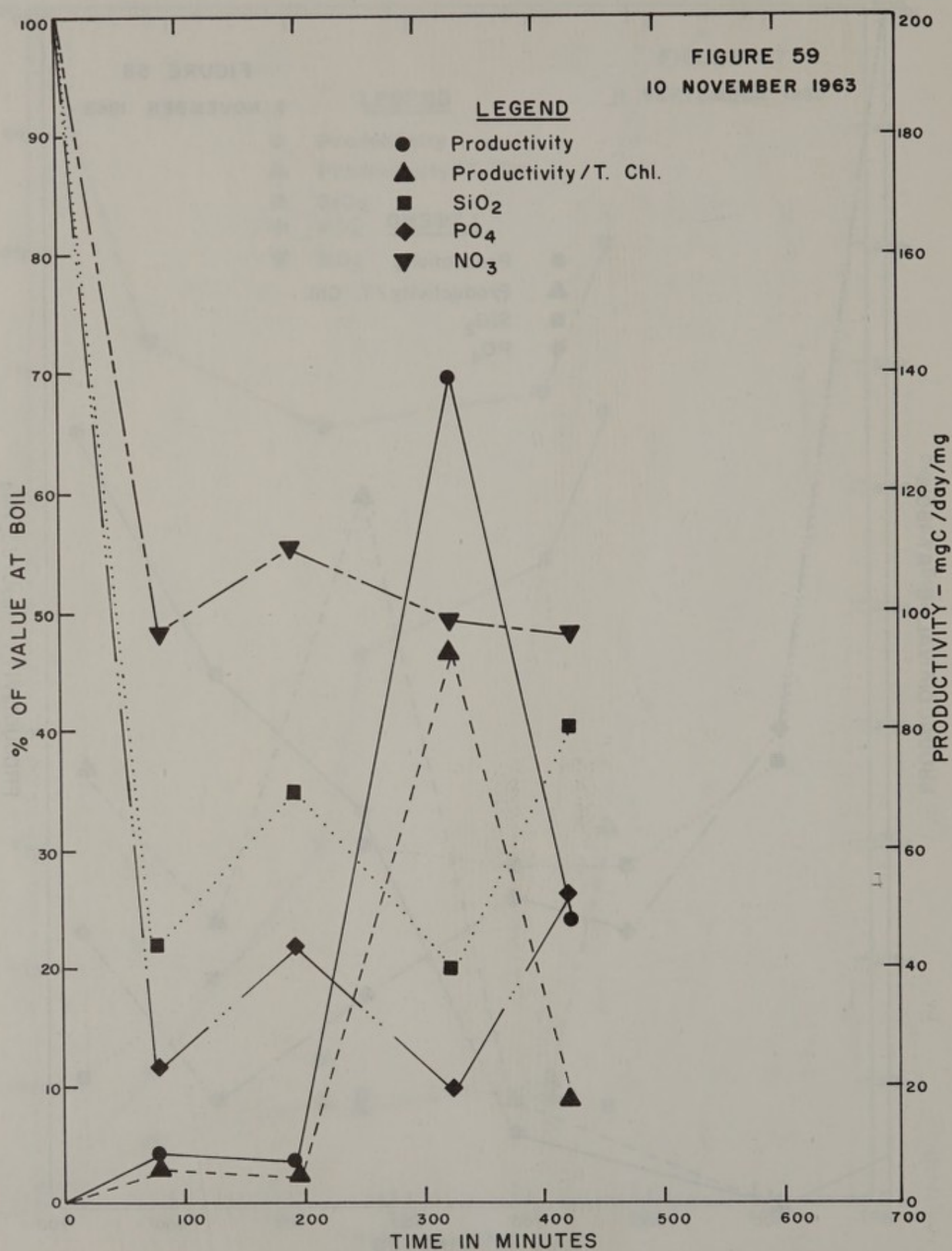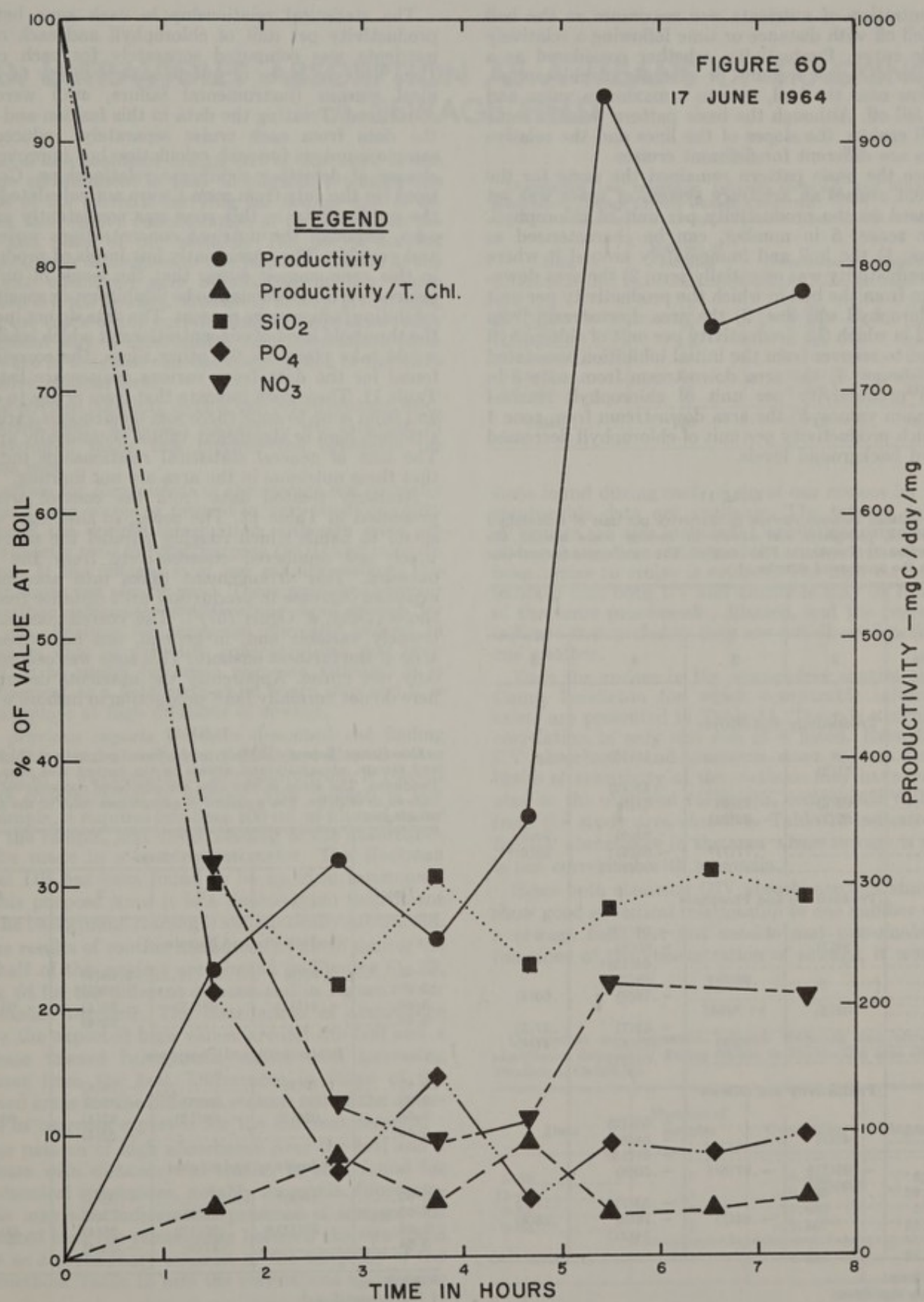
concentration of nutrients was maximum at the boil and fell off with distance or time following a relatively simple curve. Productivity, whether considered as a function of water volume or of units of chlorophyll, was low near the boil, rose to a maximum value and then fell off. Although the basic pattern was the same for all cruises, the slopes of the lines and the relative values are different for different cruises.

Since the basic pattern remained the same for the different cruises an arbitrary system of zones was set up based on the productivity per unit of chlorophyll. These zones, 5 in number, can be characterized as follows: 1) the boil and immediately around it where the productivity was essentially zero; 2) the area downstream from the boil in which the productivity per unit of chlorophyll was low; 3) the area downstream from zone 2 in which the productivity per unit of chlorophyll started to recover from the initial inhibition associated with sewage; 4) the area downstream from zone 3 in which productivity per unit of chlorophyll reached maximum values; 5) the area downstream from zone 4 in which productivity per unit of chlorophyll decreased toward background levels.

TABLE 11

Correlations between surface productivity per unit of chlorophyll and nitrate, phosphate and silicate in various zones around the Orange County Treatment Plant outfall. The numbers in parentheses refer to the number of samples.

Date	Zone 2	Zone 3	Zone 4	Zone 5
Productivity and Nitrate				
10-62			.16(12)	
11-62	.71(3)			
12-62			.43(12)	
9-63	−.09(5)	.12(5)	.61(8)	
11-63	−.52(3)	−.52(31)		
12-63			.32(6)	.90(5)
3-64		.77(7)*	−.98(5)†	.85(6)*
6-64			−.60(19)†	
Productivity and Phosphate				
10-62			−.02(12)	
11-62	.94(3)		−.00(6)	
12-62			.65(12)*	
3-63		.98(5)†	.59(3)	
4-63			−.16(9)	.00(4)
11-63	.02(3)			
12-63			−.32(7)	.37(5)
3-64		.15(7)	.75(5)	.41(6)
6-64			.01(21)	
Productivity and Silicate				
10-62			−.05(12)	
11-62	.48(3)		−.64(6)	
12-62			−.51(12)	
9-63	−.98(5)†	−.97(6)†	−.50(8)	
11-63	0.00(3)			
12-63			−.53(7)	.11(5)
3-64		−.44(7)	−.76(5)	.25(6)
6-64			.14(21)	

* Significant
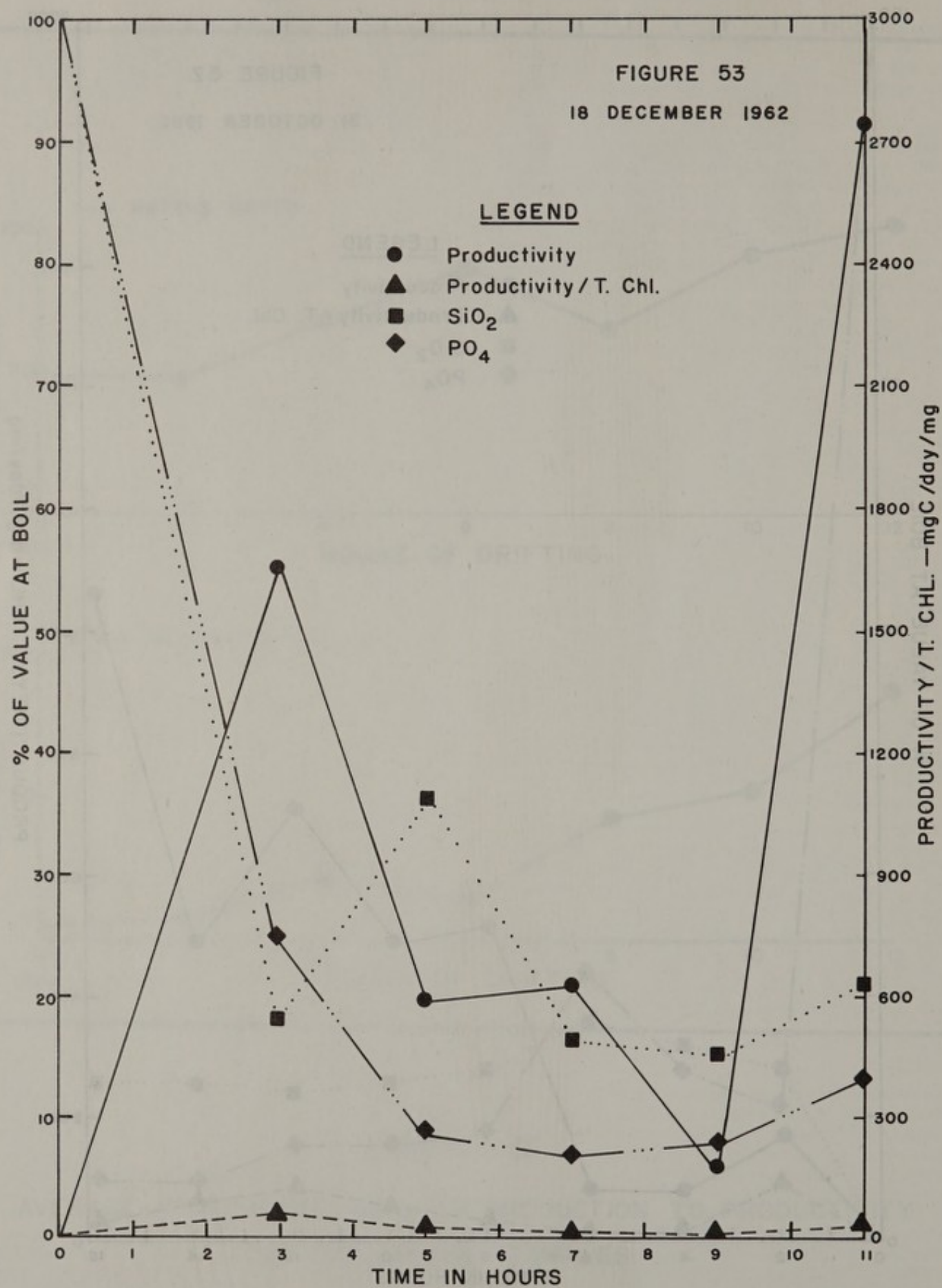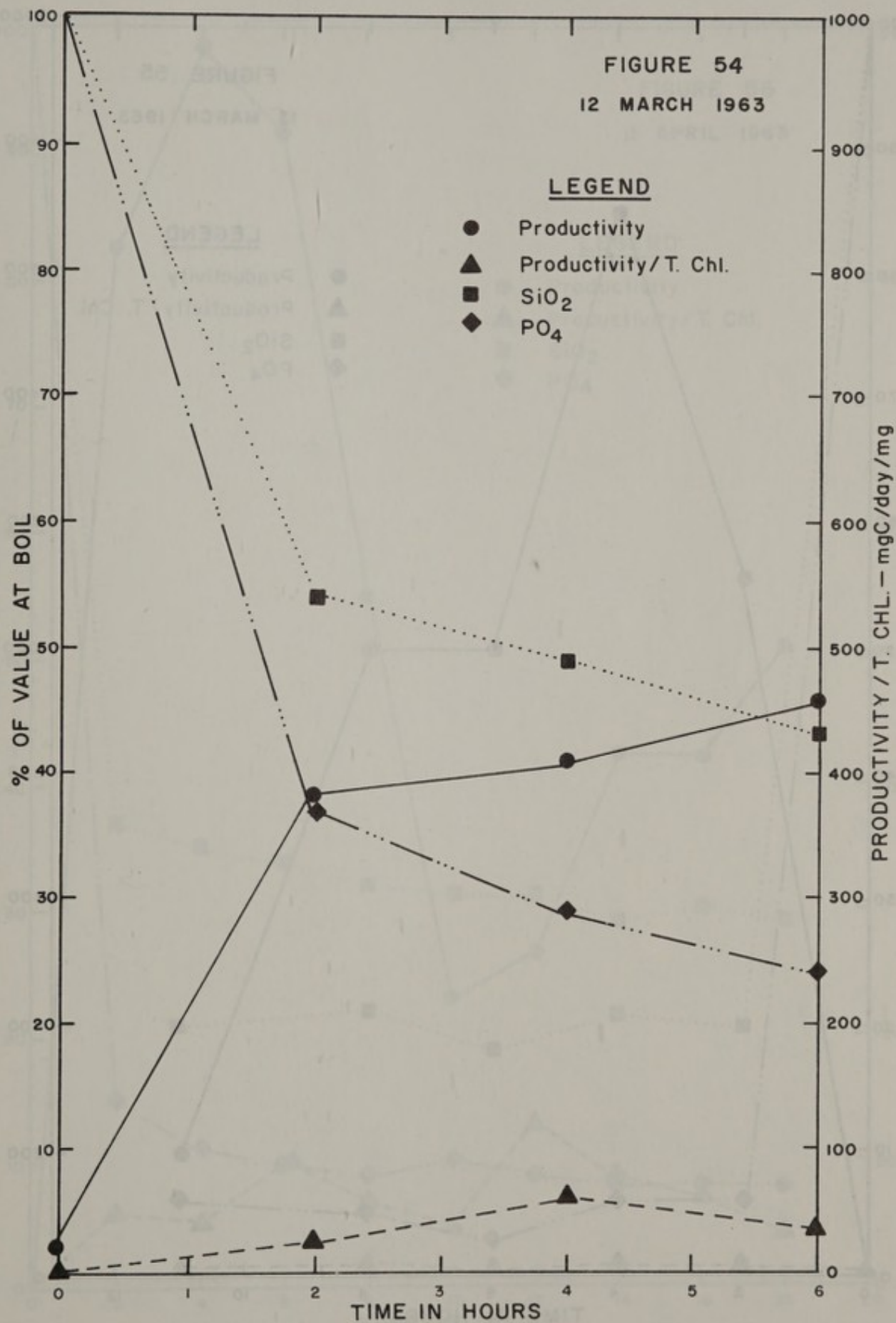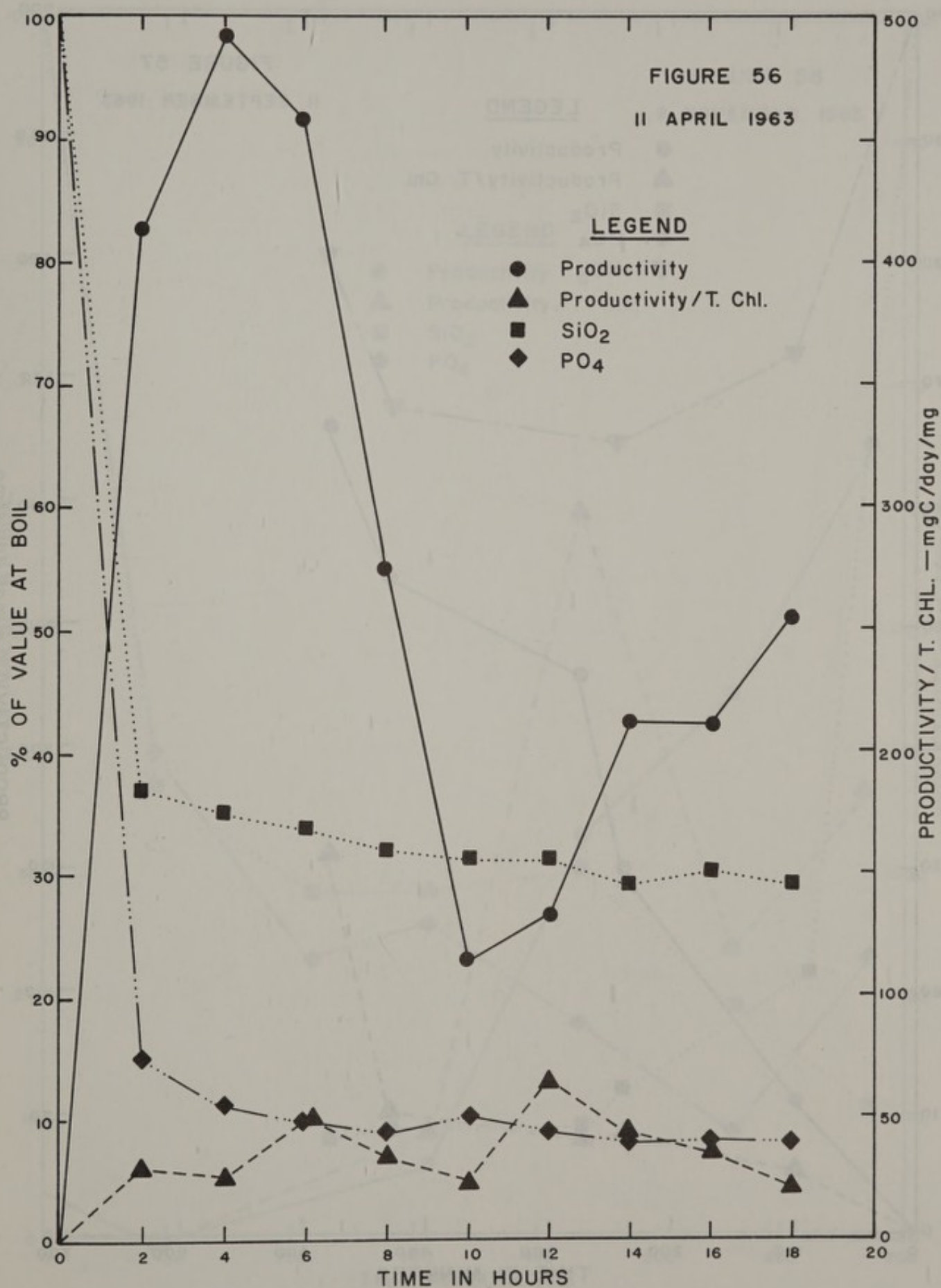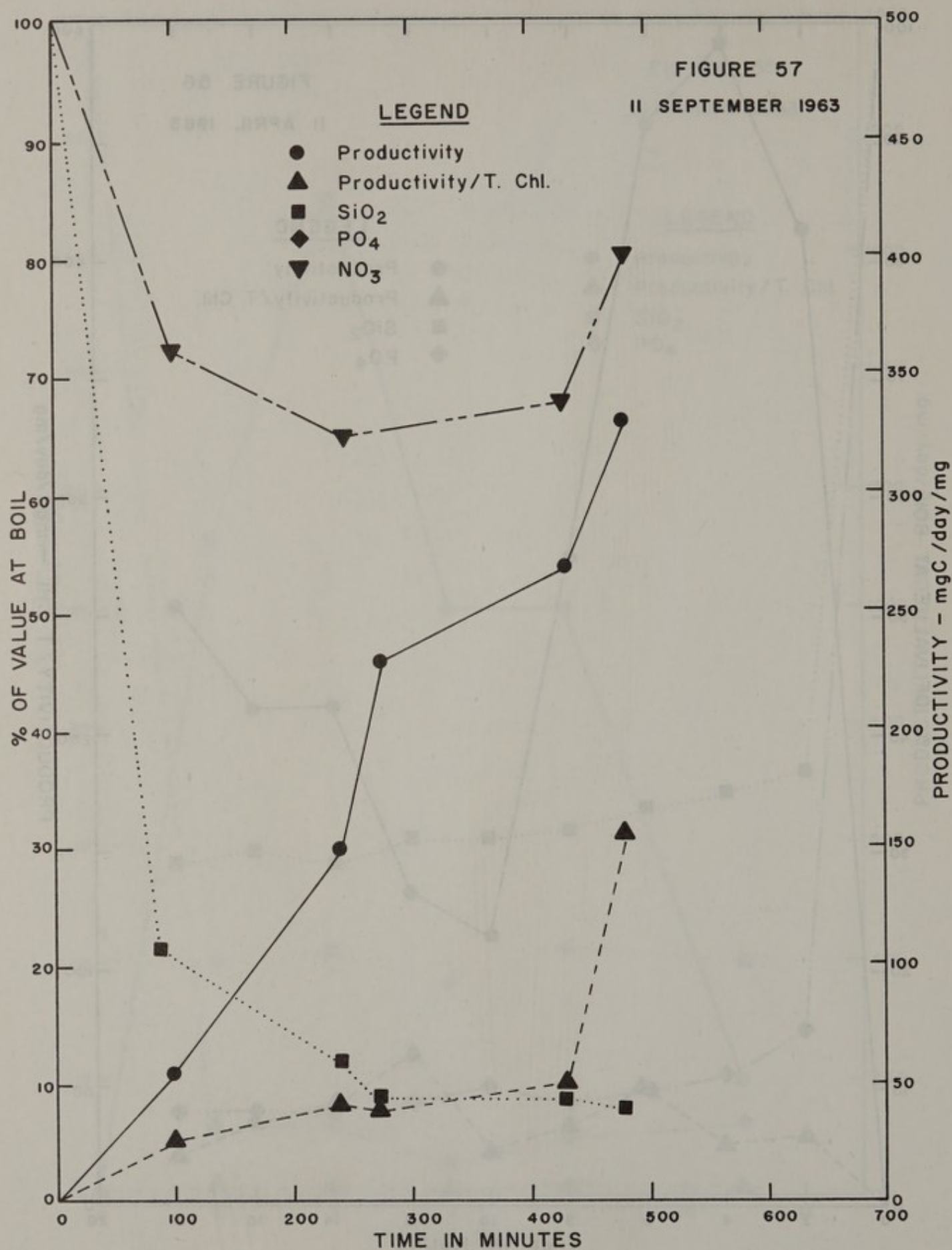† Highly significant

The statistical relationship in each zone between productivity per unit of chlorophyll and each of the nutrients was computed separately for each cruise. Data believed to be of questionable validity for technical reasons (instrumental failure, etc.) were not considered. Treating the data in this fashion and using the data from each cruise separately, reduced the sample numbers for each calculation but improved the chance of detecting significant relationships. Correlations for the data from zone 1 were not calculated since the productivity in this zone was consistently around zero, although the nutrient concentrations were high and variable. The consistently low levels of production in this zone suggest either that the levels of nutrient present were high enough to be inhibitory, or specifically inhibiting factors were present. The data do not indicate the threshold level of concentrations at which inhibition would take place. In the other zones, the correlations found for the data from various cruises are listed in Table 11. These data indicate that from cruise to cruise and from zone to zone there was tremendous variation, although high or significant values occasionally appear. The lack of general statistical relationships indicates that these nutrients in the area are not limiting.

Similarly treated data from the control area are presented in Table 12. The zones, in this case, correspond to bands which roughly parallel the shore and which are numbered consecutively from the shore outward. This arrangement takes into account the expected decrease in production with distance from the shore (Doty & Oguri (67)). The correlations are extremely variable and, in general, not high except in zone 4, the furthest offshore. This zone was occupied on only one cruise. Apparently the nutrients determined here do not normally limit production in inshore waters.

TABLE 12

Correlation between surface productivity per unit of chlorophyll and nitrate, phosphate and silicate in the control area near Camp Pendleton. The zones in this case are numbered consecutively from inshore to offshore. The numbers in parentheses refer to the number of samples.

Date	Zone 1	Zone 2	Zone 3	Zone 4
Productivity and Nitrate				
10-62	0.95(3)		0.68(4)	
12-63			.33(3)	
3-64	−.44(11)	.08(13)	−.36(4)	−.95(3)
6-64			.52(4)	
Productivity and Phosphate				
10-62	.72(3)		−.78(4)	
12-63		.94(3)	−.35(6)	
3-64	.02(11)	−.06(13)	.42(4)	−.86(3)
6-64			−.22(4)	
Productivity and Silicate				
10-62	.99(3)*		−.08(4)	
12-63		.70(3)	.72(6)	
3-64	.90(11)†	.35(13)	.25(4)	−.90(3)
6-64		.87(3)	−.02(4)	

* Significant
† Highly significant

D. ULTRAVIOLET ABSORPTION AS A MEANS OF TRACKING A SEWAGE FIELD

One of the problems arising out of our work in the marine environment is that of physically tracing the course of the currents carrying the sewage and of assessing the relative concentration of the sewage at the time and place of our stations. The use of current markers, such as drogues or dye patches released at the boil, can effectively give information on the course followed by the sewage. However, at any given point along the track of the current marker there is no really convenient way of ascertaining that the stations occupied were in the most concentrated portion of the more extensive effluent field.

The obvious solution, dyeing the entire effluent field, was tried once. Although successful, the quantity of dye required made this method too expensive for routine use.

Analyses for components of the sewage not normally present in sea water or present in very small quantity can yield the desired information, although some are not primarily used for that purpose (BOD and coliform counts). If the effluent is of low salinity, salinity determinations can also be used. These analyses, however are neither sufficiently sensitive nor rapid enough for field use. Analysis for ammonia, normally present in sea water only in very low concentrations, has been found to be useful for some purposes although it is inconvenient as a field method on board ship and it is not adequate at high dilutions of sewage.

In previous reports we have described the finding that high optical absorbance of Millipore-filtered water to light at a wavelength of 230 millimicrons is related to the concentration of sewage. This method is fast and simple, it requires less than 100 ml. of filtered water from the sample, and direct reading of the absorbance can be made in a spectrophotometer. The Beckman Model DB has been found to be an ideal instrument for this purpose since it is a double-beam instrument and the background reading is automatically subtracted.

The results of routine measurement made during the last half of this project are plotted in Figures 61, 62, 63, & 64 for the different seasons and in Figure 65 for all seasons together. The distribution of absorbance shows the expected high values around the boil and a decrease toward background values with increasing distance from the boil. Differences in shape of the affected areas for the different seasons reflect the differences in currents expected for the different seasons.

The pattern of high absorbance near the boil and a decrease with distance was similar to that found for the chemical substances, notably ammonia. Since ammonia may also indicate the presence of sewage, this suggested that the relationship between the two could serve as a preliminary measure of the adequacy of the UV method. Table 13 lists the correlations and regres-

sions found during each of six of our cruises for which comparable data are available. The totaled data for all cruises are also included. Correlations were high in all but the earliest cruise, and the variation in regression from cruise to cruise is evident. The high correlations indicate that both UV and ammonia may be functions of the same process, i.e., dilution, and the regressions indicate that probably they are not direct functions of one another.

Data for cruises in the sewage-free control area off Camp Pendleton for which comparable information exists are presented in Table 14. There is a significant correlation in only one run of 4 listed. Even though UV absorbance and ammonia were so low that the limits of sensitivity of the methods may have contributed to the observed variations, comparison with data from the study area shown in Table 13 indicates that the UV absorbance in the area where sewage is absent is not correlated with ammonia.

Since both elements (UV absorbance and ammonia) show good statistical relationship to one another within a sewage field but not outside and presumably are functions of the concentration of sewage, it would be

TABLE 13

Correlation and regression between ammonia and ultra violet absorbance, Orange County outfall, California.

Date	Number of samples	Correlation	Regression
9–11–63	12	0.524	114.8
11– 9–63	26	0.475	106.7
11–10–63	18	0.924	394.2
12–14–63	25	0.760	187.5
2– 8–64	34	0.853	170.0
6–17–64	28	0.974	231.1
Total	143	0.732	263.4

TABLE 14

Correlation and regression between ammonia and ultra violet absorbance data found during cruises to the control area off Camp Pendleton, California.

Date	Number of samples	Correlation	Regression
5–63	7	0.090	8.4
12–63	15	0.700	29.3
3–64	5	0.662	2.3
6–64	5	−0.357	23.6
Total	32	0.286	34.1

reasonable to expect similarly good correlation between them and the degree of dilution of the sewage field. The correlations in Table 15 show that the expected good relationship was not found. The diffusion data for these correlations were obtained from the overall diffusion equations for each particular run and the maximum dye concentration (C_{max}) was computed for the time or distance at which the stations for UV and ammonia were occupied. This was necessary since the field observations for diffusion data are collected independently and by a different method from the other information. The diffusion data represent the overall behavior of a relatively large dye patch in a larger sewage field. The chemical and biological data represent the findings at a series of discrete locations just ahead of the dye patch. Other differences in methods of treating the data also may be among the reasons for the apparent lack of good correlation. One limitation may be associated with the attempt to use dilution equations for computing the instantaneous concentration at specific points of field observation. It is also possible that UV absorbance and ammonia are not conservative properties. Testing on these points will continue.

TABLE 15

Correlations of ammonia and ultra violet absorbance with calculated maximum concentration of rhodamine-B dye (C_{max}) at the time or distance from the boil corresponding to sampling stations for the chemical samples. The field observations were all made in the study area off Orange County, California.

Date	C_{max}–distance		C_{max}–time	
	UV	NH$_2$	UV	NH$_2$
9–63	0.333 n = 5	0.958 n = 3	0.725 n = 4	—
11–63	0.968 n = 3	0.697 n = 3	−0.968 n = 3	−0.858 n = 3
6–64	0.554 n = 4	−0.228 n = 4	0.449 n = 4	0.261 n = 4
6–64	0.408 n = 6	0.801 n = 6	0.019 n = 6	0.804 n = 6
Total	0.634 n = 18	0.390 n = 16	−0.028 n = 17	−0.193 n = 13

FIGURE 61

SPRING DISTRIBUTION

OF

UV ABSORBANCE

(230 millimicrons)

FIGURE 62

SUMMER DISTRIBUTION
OF
UV ABSORBANCE
(230 millimicrons)

FIGURE 63

FALL DISTRIBUTION

OF

UV ABSORBANCE
(230 millimicrons)

FIGURE 64

WINTER DISTRIBUTION
OF
UV ABSORBANCE
(230 millimicrons)

FIGURE 65

YEARLY DISTRIBUTION
OF
UV ABSORBANCE
(230 millimicrons)
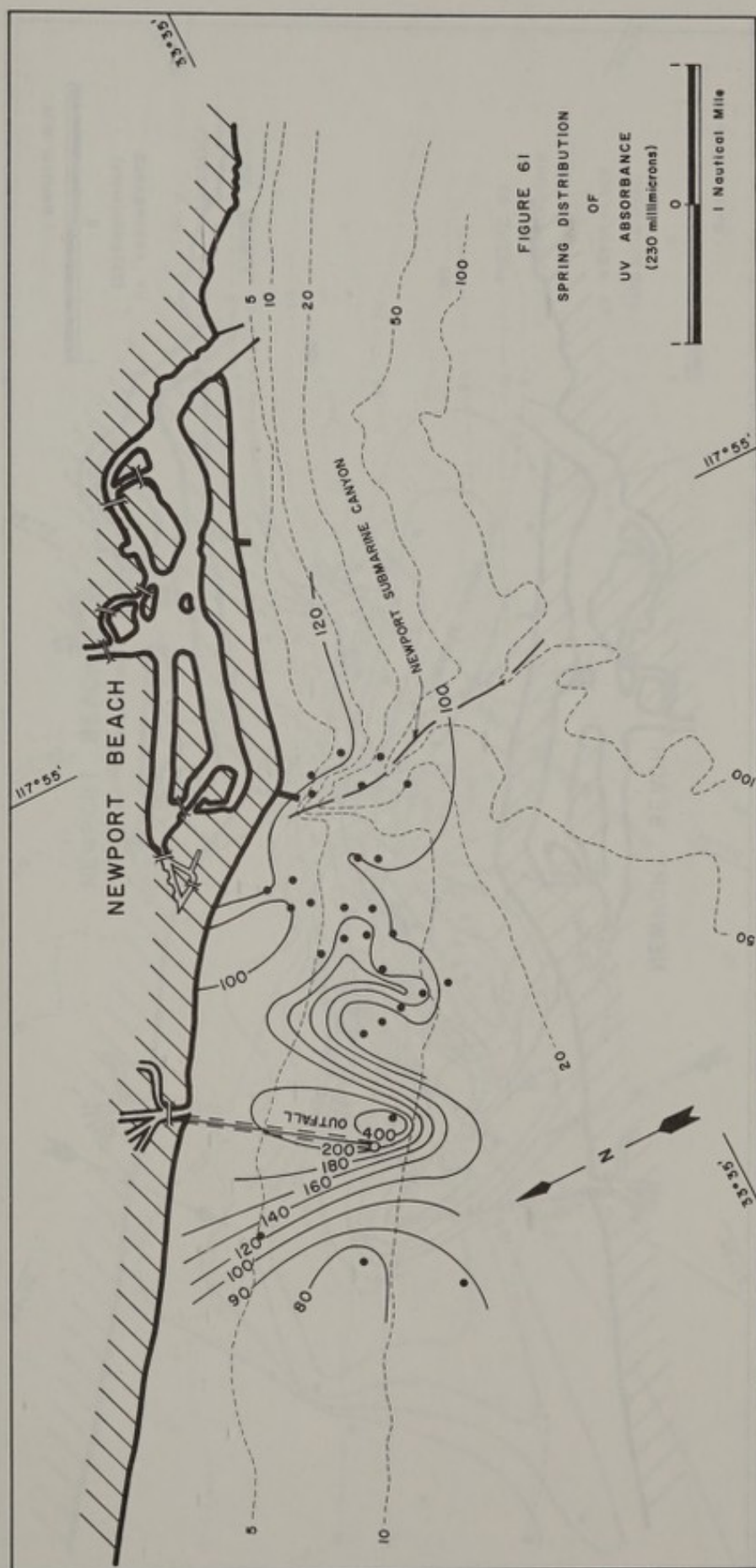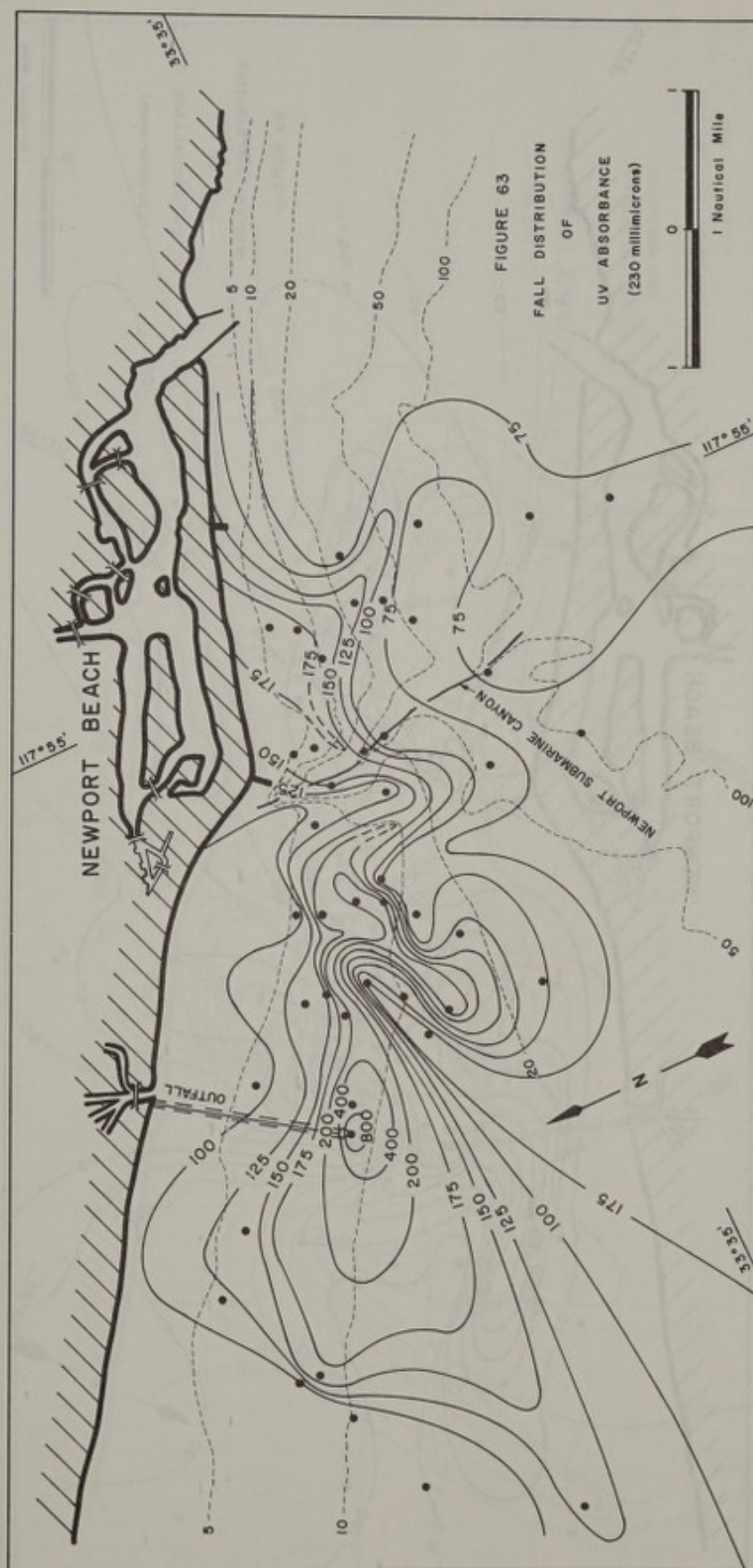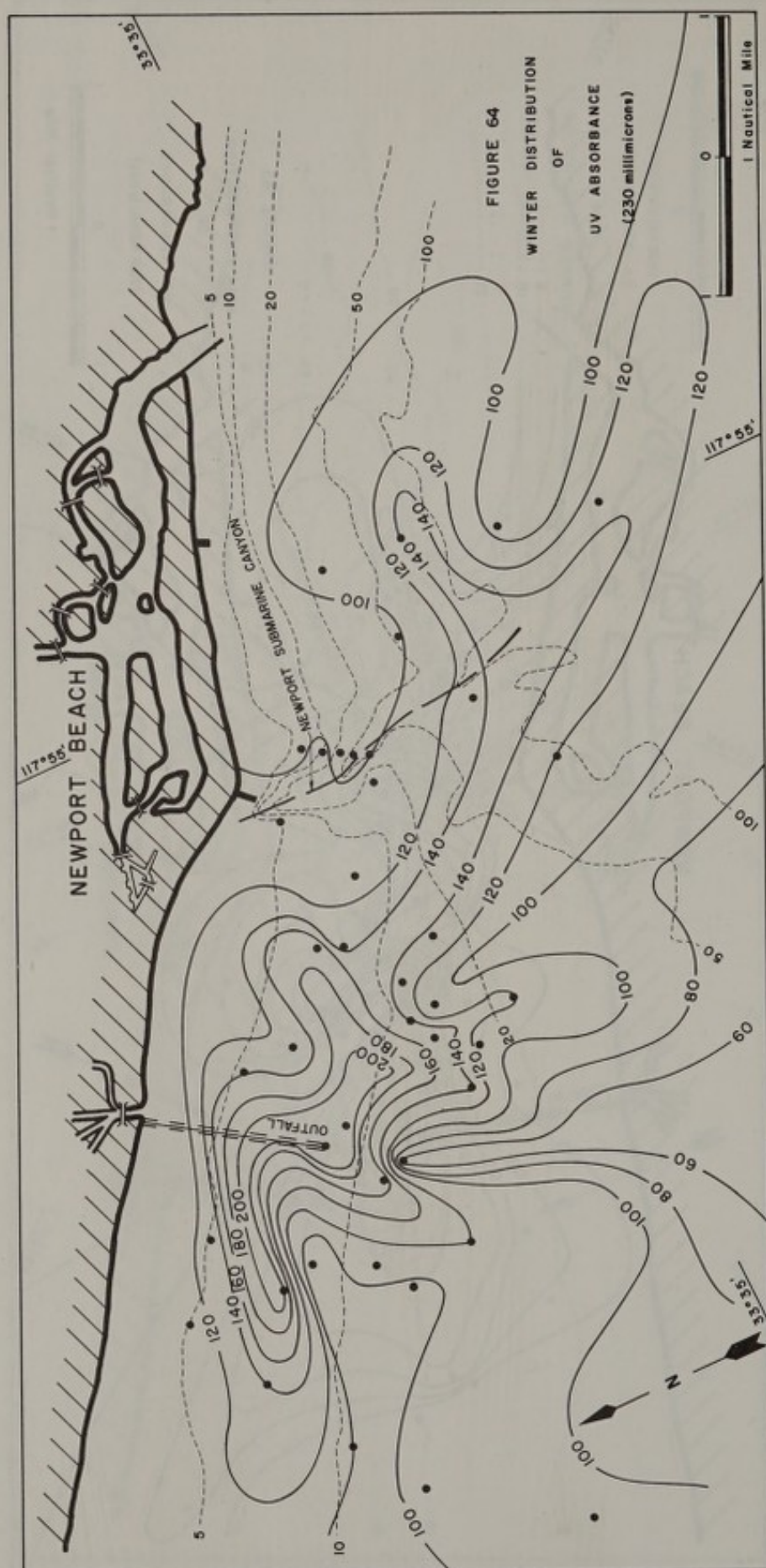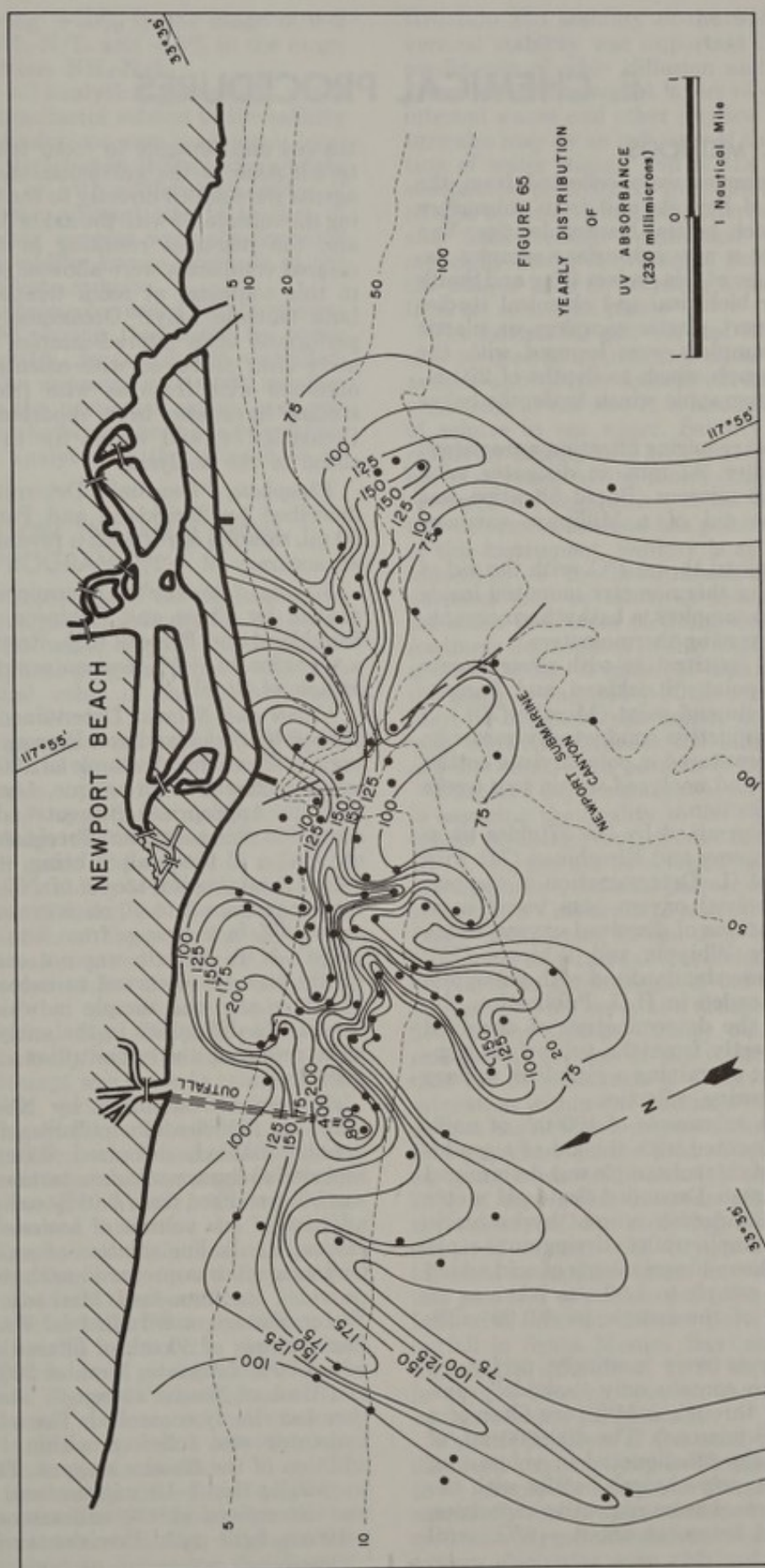
E. CHEMICAL PROCEDURES

1. METHODS

Sampling: Water samples were collected from the surface with the aid of buckets and from subsurface with the aid of a snatch bottle, Nansen bottles, Van Dorn type sampler, or a new subsurface sampler developed during the course of this project (Fay and Smith (68)). All samples for biological and chemical studies were collected with inert plastic samplers or plastic buckets. Subsurface samplers were lowered with the aid of a bethythermograph winch to depths of 200 m. or less and with a hydrographic winch to depths below 200 m.

Filtration: Subsamples requiring filtration were passed through a Millipore filter, 47 mm. in diameter, of a nominal porosity of 0.8 microns. Rapid filtration was accomplished with the aid of a Millipore vacuum-pressure pump.

Temperature: Determined to $\pm 0.1°C$. with the aid of a bucket thermometer, a thermometer mounted inside of the plastic subsurface samplers, a bathythermograph, or to $\pm 0.02°C$. with reversing thermometers.

Salinity: Determined by titration with silver nitrate to the chromate end point (Strickland and Parsons (69)) or to the fluorescein end point (Miyake (70)) to $\pm 0.02°/_{00}$ or with an inductive conductivity meter to $\pm 0.003°/_{00}$. Samples were stored in polyethylene bottles in a dark, cool location and analyzed within two weeks to one month after collection.

Dissolved Oxygen: Determined by the Winkler titration as modified by Pomeroy and Kirschman (71) with a precision of ± 0.05 ml./L. Determination of the percent saturation of dissolved oxygen was based upon the predicted concentrations of dissolved oxygen in sea water as computed by Whipple and Whipple (72). Thiosulfate solutions were standardized with potassium dichromate as recommended in H.O. Publication No. 607 (73). Samples for the determination of dissolved oxygen were taken directly from the subsurface samplers or from the bucket containing a sample of surface water immediately following collection.

pH and Alkalinity: A subsample of 100 ml. of unfiltered sea water was aliquoted with the aid of a graduated cylinder. The pH of this subsample was determined with the aid of a Beckman Expanded Scale pH meter to $+0.01$ pH units. Hundredth normal hydrochloric acid was added to the sample whilst stirring until a pH of 4.00 was obtained. The milliequivalents of acid added to bring the pH of the sample to 4.00 was taken as an index of the alkalinity of the sample to $+0.02$ milliequivalents/L.

The following analyses were routinely performed assuming the sample to contain only "soluble" components (those passing through a Millipore filter of a nominal porosity of 0.8 microns). The 400–600 ml. of filtrate thus obtained was subaliquoted in volumes of 50 or 100 ml. into 4 oz. polyethylene bottles with the aid of graduated cylinders of these respective capacities, frozen, and maintained frozen at about $-8°C$. until

thawed and brought to room temperature for the determination of the particular analyte of interest. Reagents were added directly to the plastic bottle containing the subsample with the aid of Miscomatic Dispensers and the reactions resulting in the formation of the colored complexes were allowed to come to completion in this container at room temperature or in a water bath (nitrate only). Occasionally the analyses were performed upon filtered samples aboard ship immediately after collection with essentially the same results obtained with fresh as with frozen samples (similar studies have also been reported by Stefansson and Richards (74) and within the expected limits of precision of the analysis.

Phosphate, "Reactive": Determined by the methods described by Strickland and Parsons (69). Replicate 50 ml. samples agree with a precision of $+2\%$ and with an accuracy of $+2\%$.

Silicate, "Reactive": Determined by the method described by Chow and Robinson (75) and defined by Strickland and Parsons (69). Results are reported with a precision of $+5\%$ and an accuracy of $+10\%$, for a sample of 50 ml.

Nitrite and Nitrate: Determined by the methods described by Strickland and Parsons (69) with the following modifications. A sample of 100 ml. of filtered water was transferred to an opaque, 4 oz. polyethylene bottle and the appropriate reagents added directly to the sample in this container. Precision varies with the concentration of the analyte being $+10\%$ in the range of 0.2 to 2 microgram-atoms of NO_3-N/L. and $+5\%$ in the range from 2 to 40 microgram-atoms of NO_3-N/L. and $+5\%$ in the range from 2 to 40 microgram-atoms of NO_3-N/L. Nitrate was not corrected for nitrite as nitrite was not observed to exceed 5% of the nitrate found in any one sample in which both were determined. No difficulties in the analysis were experienced as a result of the substitution of plastic bottles for glass flasks.

Ammonia: Determined by Nesslerization with the following modifications. All reagents were made up in double distilled, deionized water. Sodium tartarate replaced sodium, potassium tartarate. Sodium tartarate was recrystalized from 0.05% sodium hydroxide by the addition of one volume of acetone to five volumes of a saturated, alkaline solution of sodium tartarate. Nessler's reagent was prepared according to the directions provided in "Standard Methods for the Analysis of Water, Sewage, and Industrial Wastes", 10th Ed. (75). Each sample of 50 ml. of filtered sea water received 2 ml. of 30% tartarate, 3 ml. of 20% sodium hydroxide, and 1 ml. of Nessler's reagent. The timing of the addition was closely controlled. The addition of the sodium hydroxide was followed within 1–5 minutes by the addition of the Nessler reagent. The color was allowed to develop for 7–10 minutes and the optical density was determined at 420 millimicrons in a cuvette with a 10 cm. light path. Precision varies with the concen-

tration of ammonia being +20% in the range of 0–2 microgram-atoms of NH_3-N/L. and +5% in the range of 2–100 microgram-atoms NH_3-N/L.

General Remarks: In all analytical procedures which are subject to a correction factor related to the salinity of the sample, standard solutions were made up in local sea water deficient or depleted in the specific analyte (e.g. ammonia, nitrate) or with artificial sea water of a composition (phosphate, silicate) similar to that of local sea water. Recovery samples were also included with the standards by adding known amounts of the specific analyte to duplicate samples.

Polyethylene bottles were color coded for the various components determined during this study by spray painting the sample bottles. As each bottle was filled, it was labelled with the appropriate station number, the depth from which the particular sample was collected, then frozen immediately in the ship's deep freeze and kept frozen until analyzed in the shore base laboratory.

2. COMMENTS ON THE ANALYTICAL PROGRAM

In keeping with the objectives of the demonstration grant to develop and evaluate techniques for the study of the biological effects of waste disposal in the marine environment, the analytical program is reviewed with respect to the potential value of the methods and techniques used.

First, the analytical program was primarily designed to support the dilution and productivity studies, but some information was also obtained on the variation in chemical composition of an effluent field. Diffusion studies required knowledge of the vertical stability of the water column both inside and outside of a field of effluent waste as vertical stability is related to both the vertical and horizontal diffusion of the waste field. Independent determination of the patterns and rates of waste dilution also was required to verify the conclusions obtained from the studies of the dye diffusion. This was accomplished by quantitative analyses of potentially useful chemical tags. Primary planktonic productivity varied markedly with the composition of the medium, and an attempt was made to relate planktonic productivity with variations in the chemical composition of both the diluting effluent field and the receiving waters. Also, differences in composition were established in order to distinguish the sewage field from background receiving waters. Finally, the receiving waters themselves deserved attention in order to establish normal background conditions as compared to the sewage field resulting from essentially steady-state discharge of effluent into these waters.

The significance of each of the determinations performed on a routine basis to each of the portions of this study shall now be reviewed as a guide to future work of a related nature. Figure 66 is a diagram of the sampling scheme. At some stations, not all of these determinations were carried out, but a selection was made according to specific requirements.
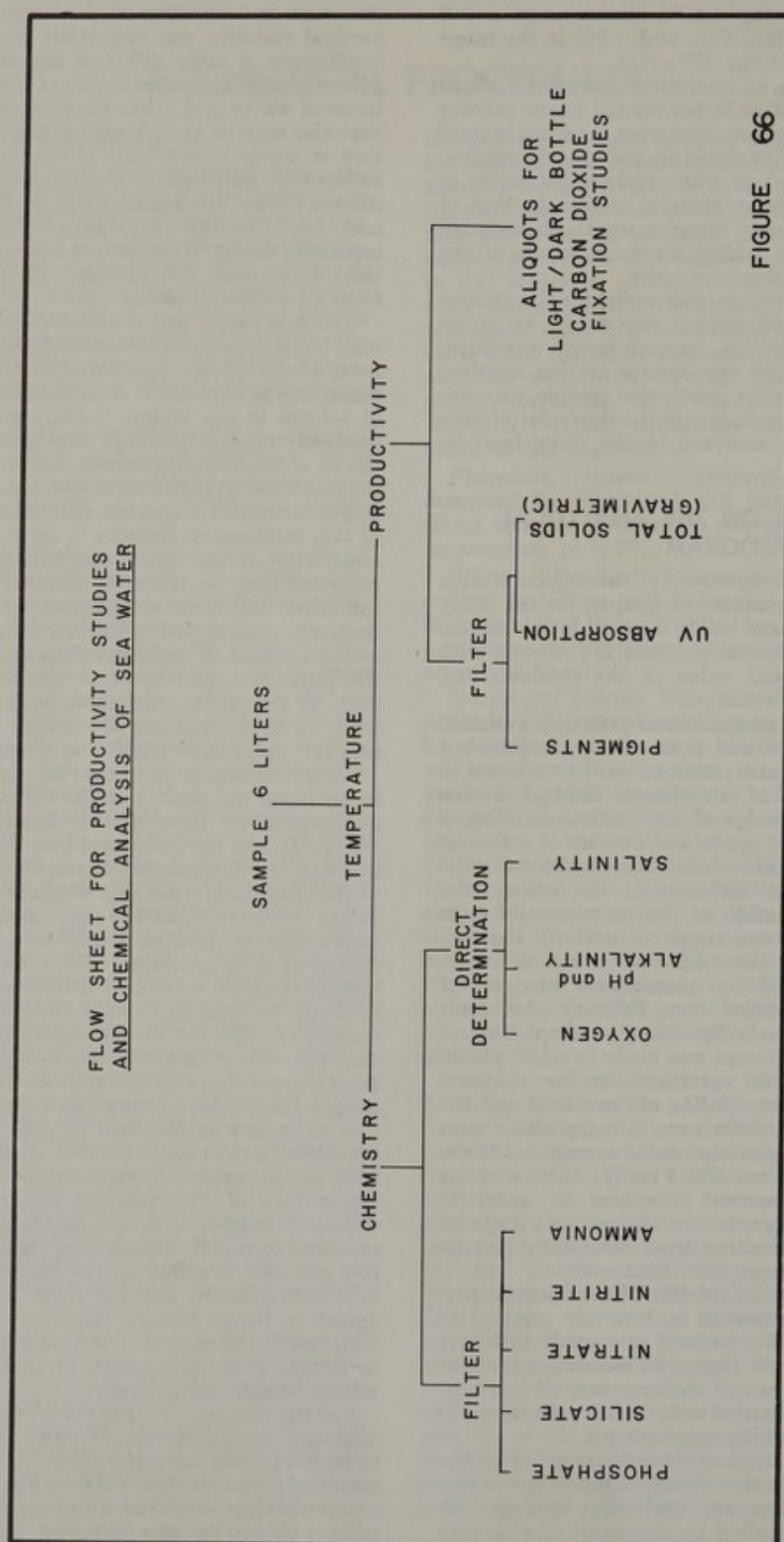
Temperature is the most easily determined of all the variables measured in this study. Knowledge of the distribution of temperature vertically through the water column was required to determine the density structure and stability of the water column. Data on vertical stability was important in studies of vertical coefficients of eddy diffusion and of the vertical displacement of horizontal layers of the water column by internal waves and other physical processes. Temperature also may be an indicator of the horizontal distribution of water masses and of the solubility of various substances, particularly gases, in sea water. It is often related to the distribution patterns of plankton, nekton, and fixed benthic organisms. Temperature is not especially useful in defining a field of waste other than the unique case of following a discharge of hot water from an industrial plant.

The horizontal and vertical distribution of salinity may be used as an indicator of the distribution of water masses and of the associated distribution of various organisms in the sea. It is also related to the activities of solutes in sea water. Salinity may be determined relatively rapidly to a high degree of precision with the aid of a conductivity meter. Caritt (76) has recently reviewed the application of the conductivity meter to this determination and has pointed out the advantages of this instrument. Salinity is as useful at the level of sensitivity of the determination, which for practical purposes may be taken as ±0.005⁰/₀₀, as are any of the other indicators of the presence of effluent wastes routinely determined in this study (phosphate, silicate, and ammonia). If sufficient data are taken to establish the limits of variability of the receiving waters, salinity may be the most convenient determination available with which to estimate the initial dilution of sewage and the short-term pattern of subsequent diffusion.

Dissolved oxygen content is an important constituent in assessing the quality of the receiving water and the effects resulting from effluent discharge (see Reference (75)). Oxygen has been found to vary in concentration in a significant, seasonal pattern in the nearshore waters of southern California to a depth of about 200 meters. Below 200 meters, in the deep basins of the southern California continental borderland, dissolved oxygen decreases to a minimum of 0.2 ml/L (Emery, (77)). Oxygen does not serve as a distinctive tag of the effluent field at the Orange County outfall for the following reasons: 1) dilution of the wastes proceeds so rapidly that the concentration of dissolved oxygen approaches saturation within one-half mile of the boil, 2) dissolved oxygen has not been present at less than 75% of saturation anywhere in the field of effluent waste with the exception of the boil where it is equal to or greater than 70% of saturation, 3) in an effluent field floating on the surface of the receiving waters, equilibration of dissolved oxygen with oxygen from the air may be expected to rapidly restore any localized deficiencies of this gas, and 4) submerged fields established over outfalls with efficient diffuser ports (as at the Hyperion outfall in Santa Monica Bay) are characterized by a high initial dilution of 1:100 or more, and differences in oxygen content between the field and background waters become insignificant.

For the purposes of this study, the determination of dissolved oxygen by the Winkler method has proved to be completely adequate. Titration is simple, reliable, essentially fool-proof, and free of the problems encountered with oxygen electrodes now available. Two different oxygen electrodes were obtained during the course of

FLOW SHEET FOR PRODUCTIVITY STUDIES
AND CHEMICAL ANALYSIS OF SEA WATER

SAMPLE 6 LITERS

TEMPERATURE

PRODUCTIVITY

ALIQUOTS FOR
LIGHT/DARK BOTTLE
CARBON DIOXIDE
FIXATION STUDIES

FILTER

TOTAL SOLIDS (GRAVIMETRIC)

UV ABSORPTION

PIGMENTS

CHEMISTRY

DIRECT DETERMINATION

SALINITY

ALKALINITY pH and

OXYGEN

FILTER

AMMONIA

NITRITE

NITRATE

SILICATE

PHOSPHATE

FIGURE 66

this program from commercial sources. Neither functioned adequately for the purposes of this study. Until a reliable, stable, *in situ* oxygen electrode capable of submersion to 200 m. is developed, the Winkler titration will continue to be the more dependable and useful technique for determination of dissolved oxygen in sea water. Winkler reagents, together with appropriate titration apparatus, should be available in reserve for any electronic equipment when field surveys are conducted.

Use of the Beckman Expanded Scale pH meter aboard ship permitted rapid and reliable determination of the pH of unfiltered samples of sea water. The pH decreased with depth and varied seasonally. Titration with 0.100 N.HCl to determine the alkalinity of the sample of sea water is accomplished with about the same precision as the technique employed to obtain the sample aliquot from which this variable is determined ($\pm 1\%$). The alkalinity of surface samples increased about 20% above background in the immediate vicinity of the boil. Alkalinity decreased slightly with depth, and varied with season and with water mass. Determination of alkalinity was not useful in following a diluting field of effluent waste because the precision of the determination was less than the differences observed between background and the sewage field at radii greater than (about 1 mile) from the boil at the Orange County outfall. Alkalinity data can be useful in following water masses and in determining the productivity of surface waters on the basis of changes in pH, carbonate content, and dissolved oxygen (Sargent and Hindman, 1943).

"Reactive" phosphate is one of the most interesting components quantitatively determined in this study. It is reliably determined although the ease and precision of the analysis could be improved by using reducing agents and molybdate which are specifically purified to remove phosphate, and by developing reducing agents which are stable for at least 30 minutes. Phosphate serves as a reliable tag for the presence of effluent wastes provided a sufficient number of background samples are collected at the same time to provide a clear distinction between the effluent field of waste and the receiving waters. Phosphate also serves as a tag for the study of the dynamics of inshore waters and the identification of different water masses. Phosphate is traditionally determined as an indicator of the fertility of the waters in the euphotic zone.

"Reactive" silicate likewise serves to identify the extent and dilution of an effluent field if sufficient synoptic determinations are made to establish the immediate composition of the receiving waters. Silicate can be determined with sufficient ease and precision to be a useful indicator of the initial effluent field and of the distribution of the water masses found in the inshore area. Silicate appears to be unsatisfactory as an index of the fertility of the receiving waters of Southern California.

At this time, ammonia is the most useful chemical tag of those with which to describe the extent and dilution of an effluent field. As useful as ammonia has proved to be, this substance is also the most elusive analyte with respect to the ease, accuracy, and dependability of the procedure. A rapid, reliable colorimetric method for the determination of ammonia in sea water is still to be developed. Nesslerization offers the promise of such a method but, for as yet unknown reasons, it is not always dependable when applied to samples of sea water. Since a very large number of samples are necessary adequately to describe the dilution and distribution of a field of effluent waste, either colorimetric or potentiometric techniques will be required to expedite this analysis.

Nitrite is determined with comparative ease and accuracy; however, with the possible exception of a detailed study into the rate of oxidation of ammonia through the intermediate stage of nitrite to nitrate, nitrite offers little advantage as a tag for the presence of the field of effluent wastes or as an indicator of the dynamic processes of the inshore water masses.

The nitrate analysis is an inconvenient one; when nitrate is determined by the method described by Stickland and Parsons (69), a reduction time of about 20 hours must be sustained before color development is completed and the method therefore is ill suited to routine use in the field. Other methods, such as the polarographic reduction described by Chow and Robinson (75) or the procedure for the determination of total dissolved inorganic nitrogen described by Riley and Sinhaseni (79), while not satisfactory for use aboard ship, may provide useful cross checks upon the accuracy of the other individual determinations by colorimetric techniques for nitrate, nitrite and ammonia.

For accurate determination of dissolved substances, filtration is indispensable when processing samples from turbid inshore waters. A filter with a nominal porosity of 0.8 microns was used in this study because the amount of suspended material found in the inshore waters was sufficiently great to rapidly plug filters of a finer porosity when filtering volumes of 0.5 to 1.0 liters.

Rapid sampling through the water column is essential to the study of natural waters. An improved sampler was developed which has increased the rate of sampling about 50% over that formerly obtained with the Van Dorn type of sampler, and is a more rugged, seaworthy device.

More reliable and rapid analytical procedures are needed for ammonia, nitrate, total fixed inorganic nitrogen, phosphate, and various dissolved organic compounds found in sea water and sewage. The Beckman DU spectrophotometer should be replaced with a more seaworthy instrument of comparable or increased sensitivity and stability. A simple split beam filter photometer of appropriate sensitivity could well solve the operational shortcomings of the DU spectrophotometer (sensitivity to humidity, clumsy cell compartments, restricted sample cells, bulk, etc.) at a considerably lower cost in instrumentation. Standardization of analytical procedures is also needed. Precedent has been established in this direction by the formulation of "Recommended Interim Procedures for Measurements in Biological Oceanography" (80).

The most useful properties or components for describing background processes and defining the sewage field have included temperature, salinity, dissolved oxygen, pH, phosphate, silicate, ammonia and nitrate. Quantitative determinations of alkalinity and nitrite were of less value although they may be of specific

interest for considerations not included in this study. The principal contribution of the chemical program lay in describing the distribution of a relatively large number of variables on a routine basis throughout a two-year period, which were related to studies of primary planktonic productivity, to the dilution of a field of effluent wastes, and to the physical and biological properties of the receiving waters.

3. SOME ASPECTS OF THE CHEMICAL COMPOSITION OF BACKGROUND WATERS

In order to support the productivity and dye diffusion studies, a flexible pattern of chemical sampling was established within a two mile radius of the Orange County outfall to permit an examination of the composition of the receiving waters as well as that of the diluting sewage field. Since the direction of flow of the sewage field varied, the location of the stations describing background composition also changed. Primary indicators useful in detecting pollution were found to be silicate, phosphate, ammonia, and salinity. Ancillary information was also obtained using pH, dissolved oxygen, and nitrate data. Generally, the studies of the effect of sewage wastes upon planktonic productivity concentrated attention in the sewage field; thus there were 289 stations in the sewage field and 141 which were taken to describe the background concentration of the receiving waters. In addition, a control station was routinely occupied in about 100 fathoms of water (98 hydrocasts during two years) over the axis of the Newport Submarine Canyon about 2 miles southeast of the boil. Other control areas at various locations along the southern California coast and near Catalina Island some 20 miles offshore were examined occasionally for productivity, dye diffusion, and chemistry.

Background samples were collected through the water column generally at the standard depths of 0, 5, 10, and 25 meters or in conjunction with the studies of planktonic productivity, at 0, 3, 6, and 12 meters. This pattern of sampling provided adequate data with which to outline the instantaneous status of the vertical composition of the receiving waters; repetitive sampling through the year revealed successive changes in composition at selected depths through the water column.

Background composition of the receiving waters near the Orange County outfall from mid-1962 to mid-1964 is depicted in Figures 67 and 68. Seasonal trends are evident in spite of certain irregularities in the curves. Temperature showed the expected minima in the late winter and spring and maxima in the summer months. The salinities were also high in the summer but were generally lower in the early fall (September, October, November). Silicate was relatively high toward the end of the spring season of upwelling, but decreased as the summer of 1963 approached and reached a minimum of about 3 microgram-atoms per liter in late July, 1963. Phosphate remained relatively stable with only minor increases in the spring. There was a consistent relationship between changes in the percentage saturation of oxygen, and pH. Nitrate showed an inverse relationship to both oxygen and pH, suggesting that changes in nitrate might be more closely related to biological processes than phosphate or silicate. In January, 1964,
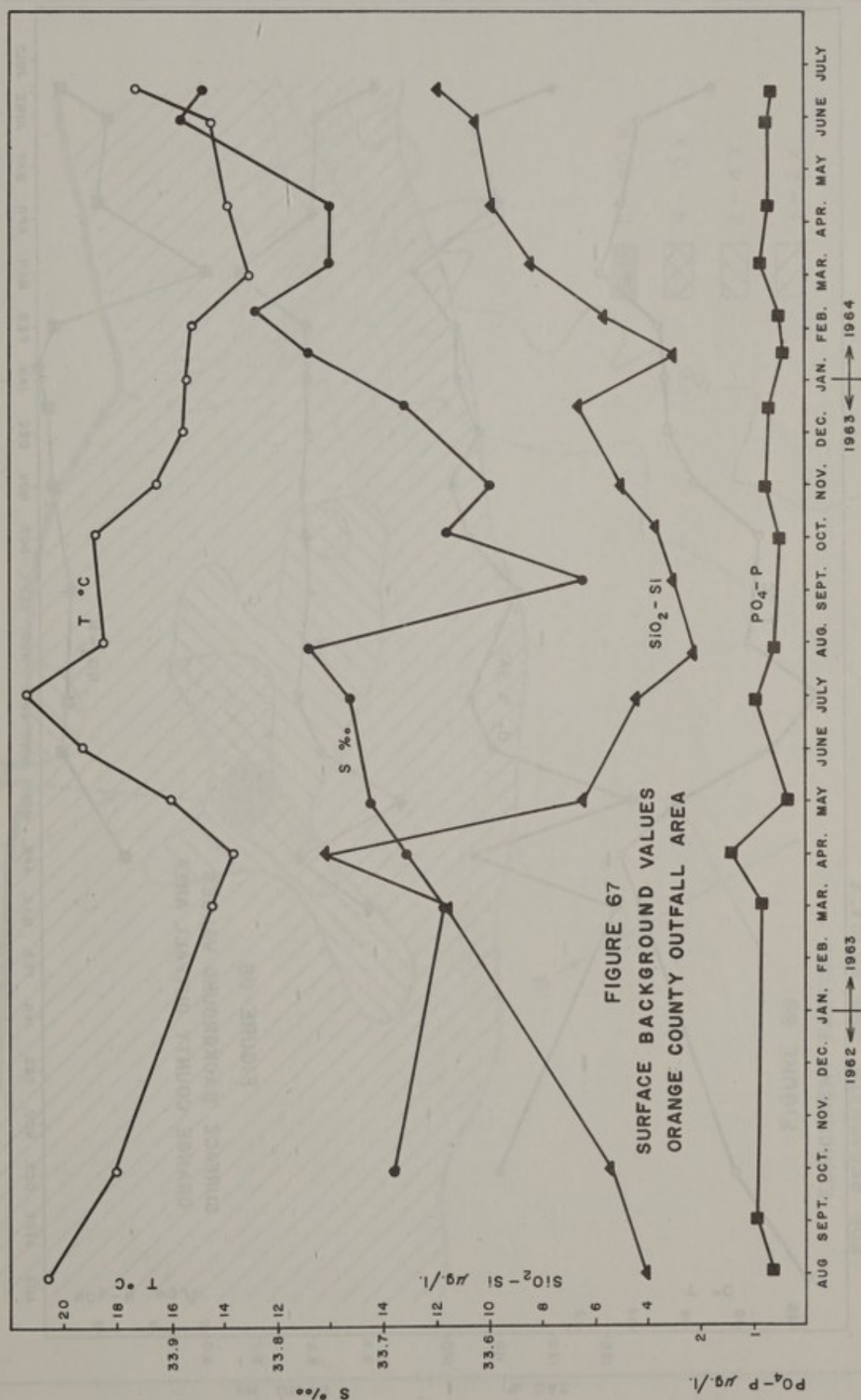
nitrate was minimal and was undetectable at the level of sensitivity of the analysis.

In the waters along the shoreline of Southern California, light and carbon dioxide do not appear to limit the rate of reproduction of phytoplankton. Indeed, small intense local patches of phytoplankton have been observed during every month in which observations were made including the winter months of December and January when daylight is at a seasonal minimum. The pH range of 8.0–8.6, and the CO_2 range of 40–46 ml/L recorded by Moberg, et. al. (81), indicate that carbon dioxide is always present in non-limiting quantities in the inshore waters. Temperature is not a critical factor in the growth of phytoplankton between 5° and 25° C. as carbon fixation is principally a light-dependent reaction. Neither silicate-silicon or phosphate-phosphorous have been determined to be present in any sample at less than 2 and 0.2 microgram-atoms per liter, respectively. Only nitrate has been found at essentially zero concentration. Data on absolute quantities of nutrients present in the water are perhaps suggestive, but the question of what constitutes a limiting quantity in the sea of any substance, either alone or in a synergistic system, is still an open question.

The distribution of the surface sewage field is depicted in Figures 69 through 73 which show typical patterns of enrichment by phosphate and silicate of the area around the Orange County outfall. For this purpose phosphate and silicate were combined because their histories within the field during any one cruise were much the same. The effluent field generally flowed parallel to shore in an easterly direction but there was a seasonal variation. Flow to the northwest was observed more commonly in the winter, and flow to the east predominated in the summer. A similar directional pattern of inshore currents has been observed off Whites Point, Palos Verdes, some 30 miles northwest of the Orange County outfall (Malcolm Whitt, personal communication).

The substances for which analyses were made and which were also contained within the sewage, may be divided into two general groups: 1) substances found in appreciable quantities in both the effluent wastes and in the receiving waters, e.g., silicate, phosphate and carbonate and 2) substances unique to the effluent waste discharge and found in negligible quantities in the receiving waters, e.g., ammonia and, experimentally, rhodamine-B. The difference between these two classes of substances is illustrated in Figure 74 where the relatively higher levels of SiO_2 and PO_4-P are due to mixing with background waters which contain appreciable quantities of those substances. However, Figure 75 shows that the area receives a greater relative enrichment in ammonia than in either phosphorous or silicon. In this area, ammonia may offer a potentially useful enrichment to the receiving waters which are already sufficiently supplied with silicate and phosphate. As for the unknown and variable components of the effluent waste field, their possible role has yet to be investigated with respect to their biochemical effects.

At this time, it appears that little nutritional benefit is gained from the addition of silicate and phosphate to waters where those nutrients may not limit the productivity of phytoplankton. Ammonia may provide

FIGURE 67

SURFACE BACKGROUND VALUES
ORANGE COUNTY OUTFALL AREA
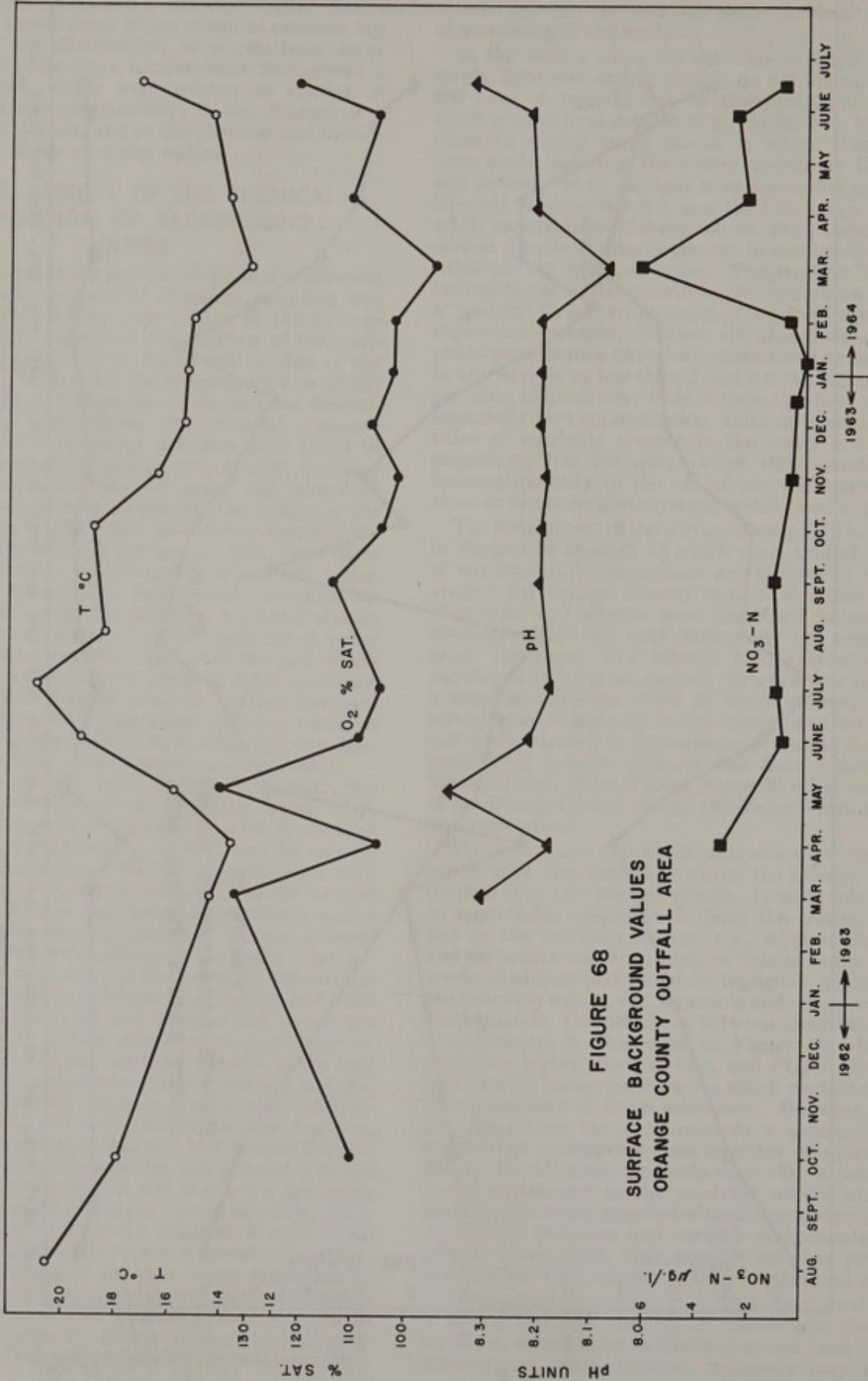
FIGURE 68

SURFACE BACKGROUND VALUES
ORANGE COUNTY OUTFALL AREA

OUTFALL

OCT. 2-4, 1962

10-40 X
4-10 X
2-4 X
1-2 X

FIGURE 69

ENRICHMENT FACTORS

FOR PHOSPHATE AND SILICATE
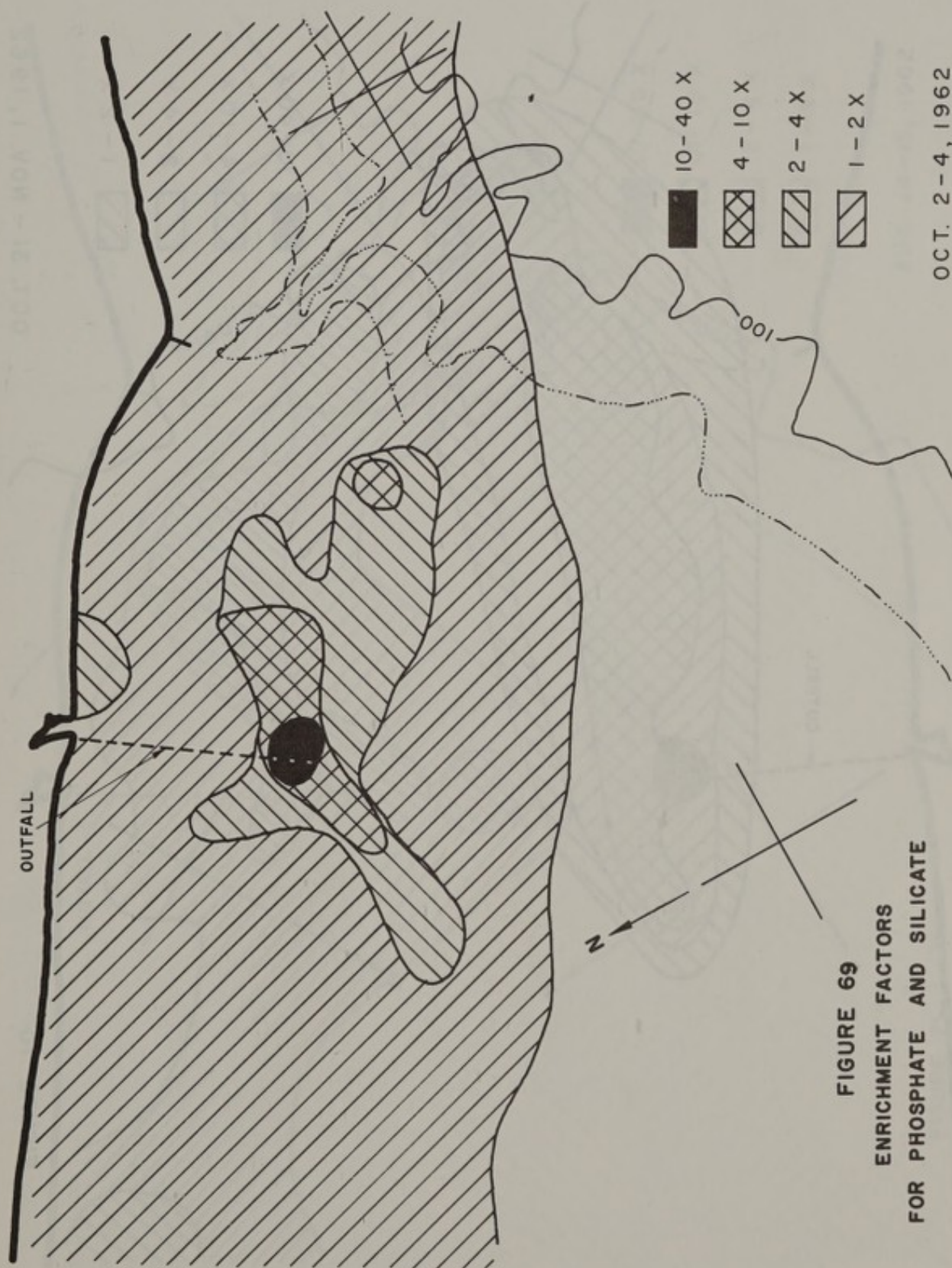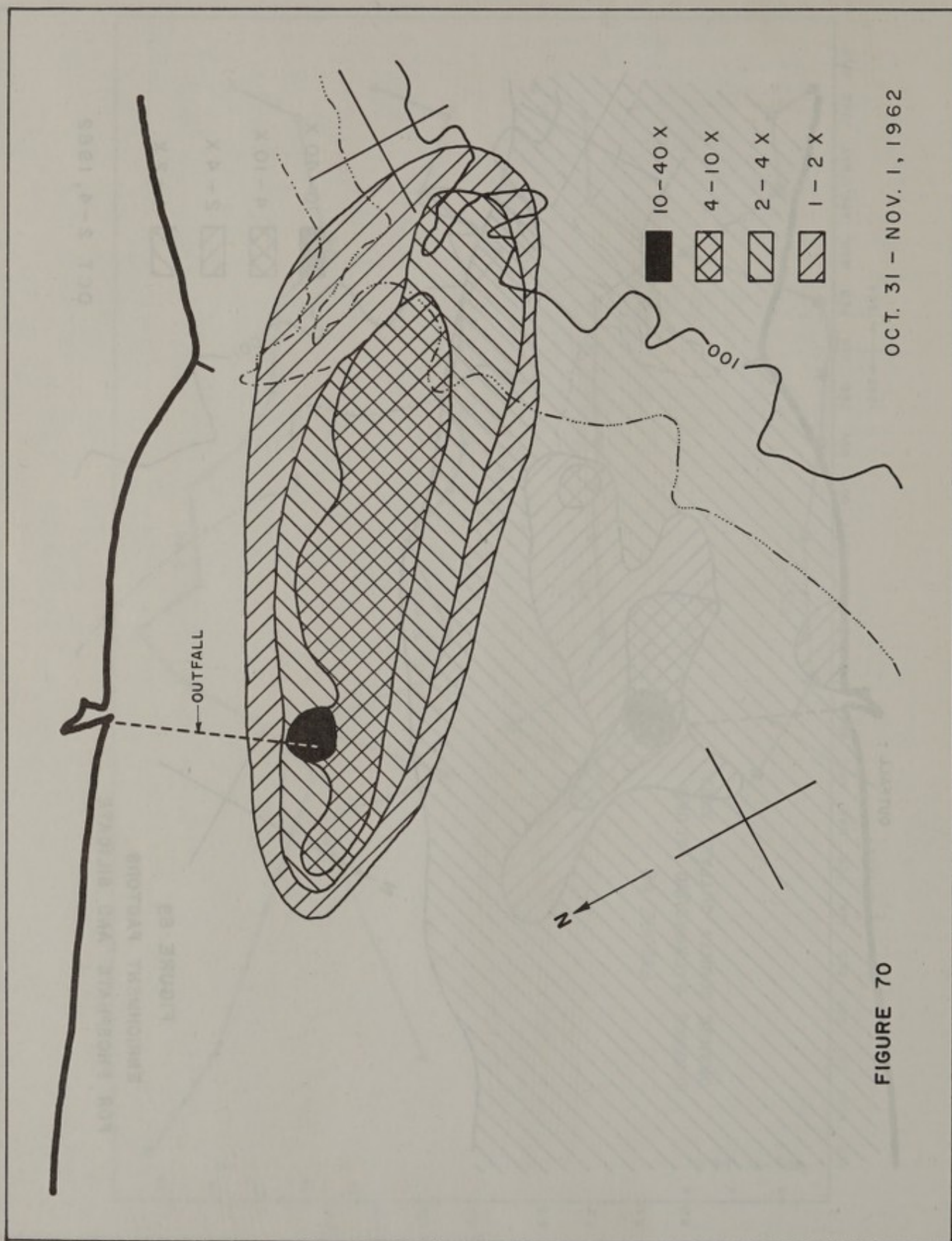
FIGURE 70

OCT. 31 – NOV. 1, 1962

	10 – 40 X
	4 – 10 X
	2 – 4 X
	1 – 2 X

FIGURE 71

AUG. 14–15, 1962

10–40 X
4–10 X
2–4 X
1–2 X

DEC. 18–20, 1962

FIGURE 72

FIGURE 73

APRIL 9-10, 1963

FIGURE 74

PERCENT CONCENTRATION
(INITIAL CONCENTRATION IS TAKEN AS
100% AT THE SURFACE BOIL)
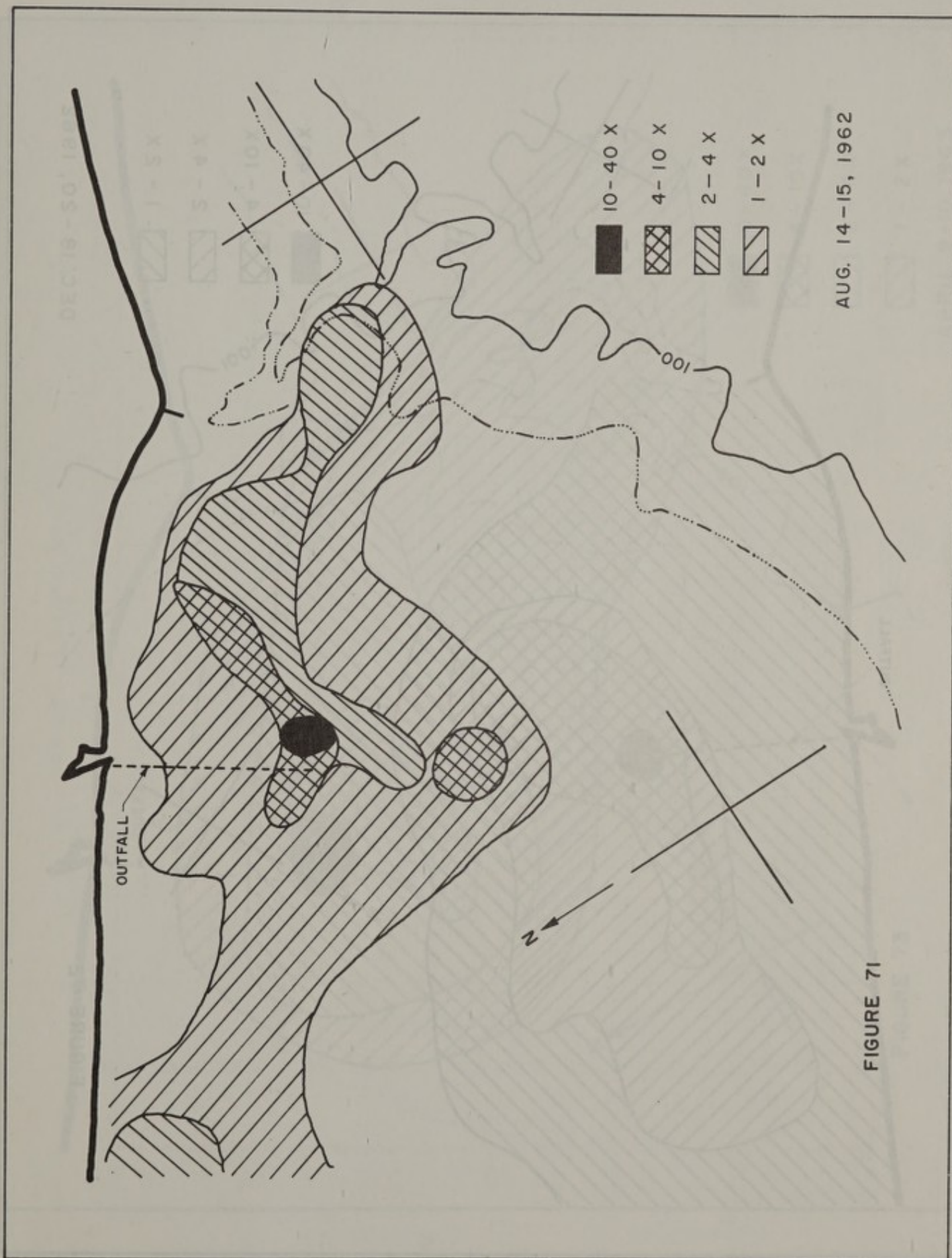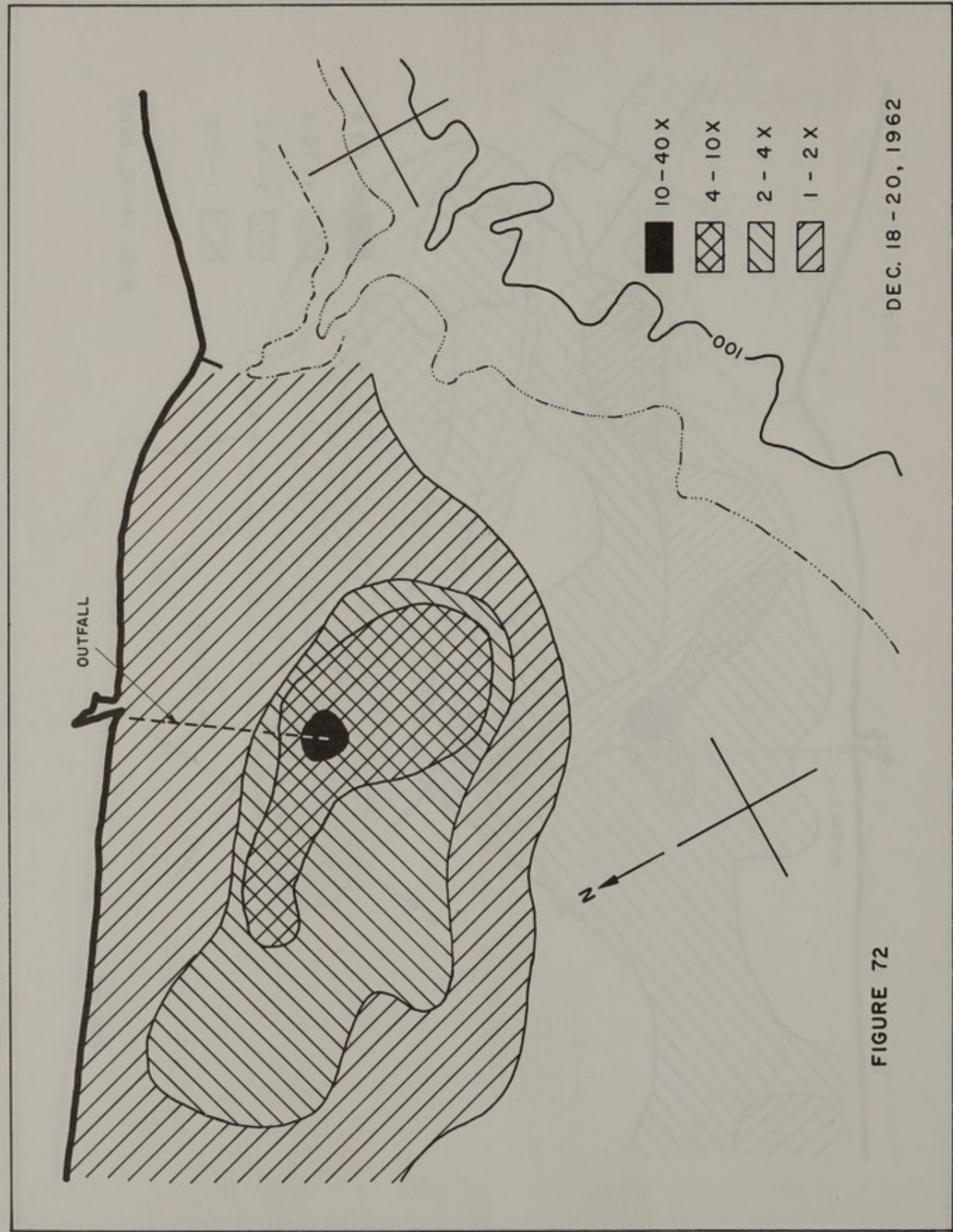
FEBRUARY 8, 1964

FIGURE 75

ENRICHMENT RATIOS
FIELD / BACKGROUND
FEBRUARY 8, 1964

some useful nutriment as a supplement to the available fixed nitrogen normally found in the local receiving waters; however, the total contribution here is slight with respect to the total volume of inshore water along the coast as a whole.

If effluent outfalls should contribute nutrients in sufficient quantity to influence the standing crops of phytoplankton, such an influence may be observed in several ways (Davis (82)). The annual crop of phytoplankton should steadily and significantly increase each year, or in the winter minima in phytoplankton should increase each year, or both may occur. Continuous records of the volumes of phytoplankton have been maintained for the last eight years by the Los Angeles City Bureau of Sanitation in connection with the routine monitoring of the Hyperion submarine outfall in Santa Monica Bay. These records were kindly made available for inspection by Mr. Norman Hume, Director

of the Bureau of Sanitation. There has been no indication of significant change; there has not been a significant increase in the standing crop of phytoplankton during the spring blooms, and the minima in succeeding winters fell to about the same values. This may be expected along an open coastline where 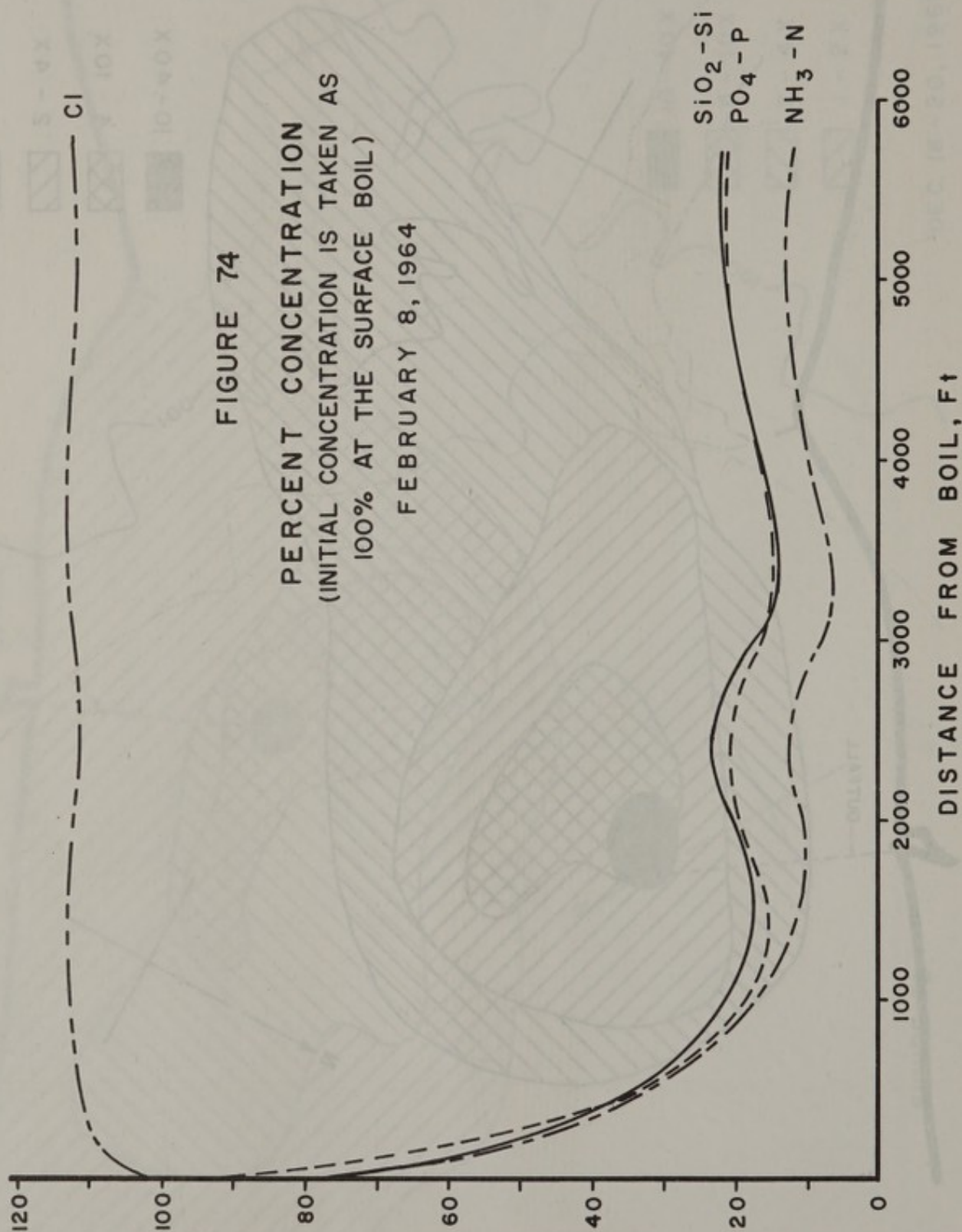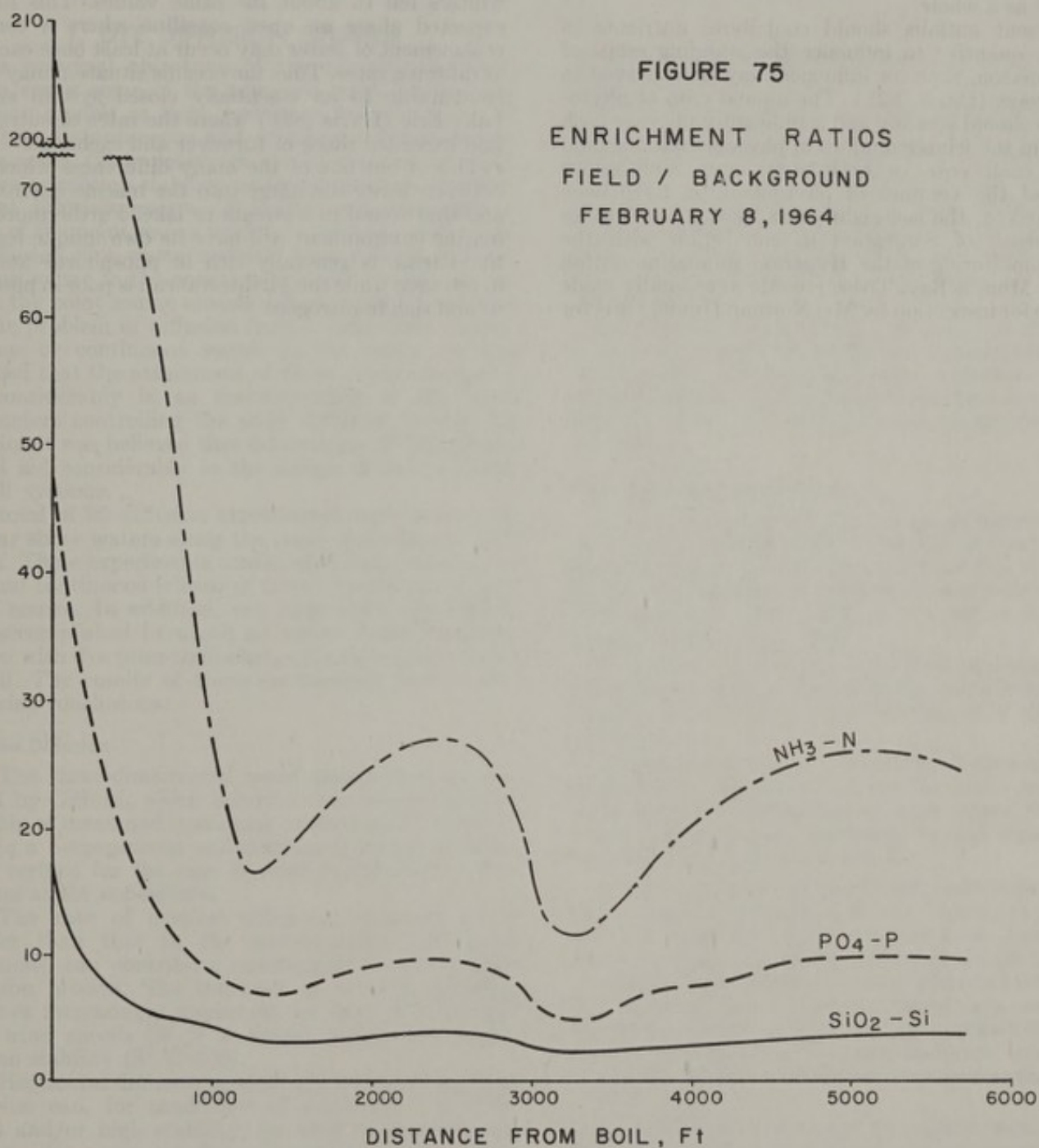a complete replacement of water may occur at least once each year at differing rates. Thus the oceanic situation may not be comparable to an essentially closed system such as Lake Erie (Davis (82)) where the rates of eutrophication exceeded those of turnover and exchange.

This is but one of the many differences which exist between waste discharge into the marine environment and that found in a stream or lake. Furthermore, each marine environment will have its own unique features; the Pacific is generally rich in phosphorus and poor in nitrogen while the Mediterranean is poor in phosphorus and rich in nitrogen.

F. SUMMARY AND CONCLUSIONS

1. DYE DIFFUSION STUDIES

The principal objectives of the experiments were: (1) to verify some of the proposed multi-dimensional diffusion models as they pertain to the dispersion of dye from instantaneous and continuous point sources in the ocean, (2) to determine the effects of wind speed and water column stability on the parameters controlling the diffusion process, (3) to determine the applicability of the point source models in item (1) to the case of diffusion of a waste material from a large scale or volume source in the ocean, and (4) to propose, in the event the point source models did not apply, a solution for the problem of diffusion from a large scale instantaneous or continuous source in the ocean. It was believed that the attainment of these objectives would aid considerably in an understanding of the basic parameters controlling the eddy diffusion process. In addition it was believed that information of this nature would aid considerably in the design of future waste outfall systems.

A total of 32 diffusion experiments were conducted in near shore waters along the coast of Southern California. These experiments consisted of both instantaneous and continuous release of tracer dye from a quasi-point source. In addition, one large scale experiment was accomplished in which an entire waste field was tagged with dye prior to discharge through a submarine outfall. The results of these experiments lead to the following conclusions:

Relative Diffusion

1. The three-dimensional point source models proposed by Gifford, which describe the space-time relationship of mean and maximum concentration distribution in a homogeneous and stationary turbulent field, were verified for the case of relative diffusion of dye patches at the sea surface.

2. The rate of vertical diffusion, although much smaller than that in the corresponding horizontal directions, can contribute significantly to the overall diffusion process. The influence of vertical diffusion becomes increasingly important on days of relatively high wind speeds ($\bar{w} \gtrsim 8$ knots) and/or low water column stability ($S' \lesssim 400$).

3. Horizontal diffusion models which neglect vertical diffusion can, for conditions of relatively low wind speed and/or high stability, be used to describe the decrease in maximum dye concentration with time. However, these models cannot be used to accurately predict the spatial distribution of dye concentration where the apparent rates of longitudinal and lateral diffusion differ considerably, as in the case of these experiments.

4. The rate of vertical diffusion determined in these studies was demonstrated to be a function of average wind speed and average stability. At the same stability, the rate of vertical diffusion increased with increasing wind speeds. Conversely, at essentially the same wind speed, vertical diffusion proceeded at lower rates for high values of stability.

5. The rate of longitudinal and lateral diffusion appeared to be influenced by wind speed but not by stability of the water column. The experiments conducted in the waste field indicated that the rate of longitudinal diffusion increased and lateral diffusion possibly decreased with increasing wind speeds. The latter trend was not well defined and additional data is required before a definite conclusion can be drawn in this respect.

6. Although not specifically discussed in this report, it was not possible to establish a correlation between wind speed or individual diffusion parameters and mean current velocity. There was also no apparent correlation between the individual diffusion parameters, $\bar{\sigma}_{x,y,z}^2$ themselves.

Continuous Release Experiments

1. The two-dimensional point source model proposed by Gifford which describes the maximum concentration-distance relationship along the center line of a steady plume in a homogeneous and stationary turbulent field, was found to be applicable to the results of the continuous release experiments.

2. Vertical diffusion, for conditions of relatively high wind speeds and/or low stability, contributed significantly to the diffusion and dilution of a steady dye plume.

3. The one-dimensional (horizontal) diffusion models proposed by Batchelor and by Schönfeld were found to be applicable to the experiments where the rate of vertical diffusion was suppressed by high water column stability and/or low wind speed.

4. The results of the single full scale experiment in which the entire waste field was tagged, showed that diffusion models of a point source type, based on an assumed Gaussian concentration distribution, cannot accurately describe the observed diffusion phenomenon. The principal reasons for the discrepancy are: (a) the lateral dye concentration distribution within the surface field at Orange County is non-Gaussian, and (b) the initial size of the waste field in no way resembles a true point source.

5. Equations for one- and two-dimensional diffusion from instantaneous and continuous volume sources are presented as a realistic model of the observed large scale diffusion phenomenon. These equations are based on the assumptions of an initial Gaussian distribution of material in a homogeneous and stationary turbulent field, as originally proposed by Gifford. The proposed equation for diffusion from a continuous source was derived from Gifford's instantaneous model by analogy with similar diffusion models. The assumption of a Gaussian material distribution appears to be reasonable for outfalls incorporating a more efficient diffuser sys-

tem than that presently found at the Orange County site.

General

1. The data from both instantaneous and continuous release experiments conducted within a waste field indicate that the spatial distribution of dye concentration at any time (or distance) is approximately Gaussian. This is especially true at small values of dispersion time ($\lessdot$ 30 minutes). In some experiments the observed dye distributions were skewed to the right or left of the maximum concentration; however, it appears the Gaussian distribution can be used in most cases as a good working rule.

2. The data from these experiments indicates that Batchelor's dimensional predictions regarding the relationship between lateral variance and diffusion time (or distance) could not be verified. This implies that, providing the rate of energy dissipation was approximately constant, the "4/3 law" relating the lateral coefficient of eddy diffusion as a function of average eddy scale, does not hold in the particular oceanic areas studied in these experiments.

2. PRIMARY PHYTOPLANKTON PRODUCTION AND PRODUCTIVITY

During this project the production and productivity of the phytoplankton has been used to measure the biological effect of sewage disposal in the open coastal marine environment. Surveys of an area affected by sewage showed a pattern of low surface productivity near the point of discharge. An increase in productivity to values well above background was found downstream after a time of about 6 hours. Maximum values occurred at about 10 hours. This was followed by a decrease towards background levels. The spatial location of these features depended on the direction and magnitude of the current and the rates of dilution.

A seasonal pattern of high productivity in spring and summer (9.9 metric tons of C fixed per day in an affected area of 60.2 Km^2) and low productivity in fall and winter (4.6 metric tons) was found. Red tide conditions resulted in increased productivity to as much as five times the normal seasonal values.

Surveys along a roughly similar coastal area that was presumed to be free of sewage showed only the expected pattern of higher production inshore. There was evidence of a seasonal pattern similar to that in the area affected by waste. Surface productivity in the unaffected area was roughly half of that in the area containing waste.

The same sequence in the pattern of productivity found in the affected area was produced by experimental exposure of subsamples of a uniform phytoplankton population to serially diluted effluent. After fourteen hours of storage no material changes were observed in the rates of photosynthetic uptake in individual samples. The effect of the sewage therefore appears to be closely related to dilution.

The relationship of productivity to specific features of the environment in the sewage field was explored. Although the sewage itself varies in content and quantity, the general pattern of productivity in relationship to the outfall has been consistent. Therefore, the attempt to relate the pattern to specific limiting or inhibiting factors was directed towards those components of the sewage that appeared to be always present and for which convenient analytical techniques were available. Among the conditions imposed on the receiving waters are the reduction of water transparency which limited subsurface production near the boil, and the added load of nutrients which apparently are neither limiting nor stimulating since they showed no consistent statistical relationship to productivity. There was no evidence that the nutrients were limiting in the waters free of sewage except in the areas greater than 3 miles from shore.

3. ULTRAVIOLET LIGHT AS A MEANS OF TRACKING A SEWAGE FIELD

It has been shown that the ultraviolet absorption of effluent at 230 millimicrons from the Orange County outfall was considerably higher than that of background waters. The distribution over the waste field was similar to that of ammonia, although this does not imply any direct relationship between the two except that they are both measures of physical dilution.

Measurement of UV absorption is simple and rapid with the Beckman Model DB spectrophotometer.

4. CHEMICAL PROCEDURES

For use in conjunction with both dilution and productivity studies, analyses were made for salinity, dissolved oxygen, pH and alkalinity, phosphate, silicate, nitrate, nitrite and ammonia. Of these, ammonia proved to be the most useful of the chemical tags with which to describe the extent and dilution of the effluent field although the analytical procedure leaves much to be desired for routine or field use. Much remains to be done in the development of suitable techniques for most of the substances listed.

LIST OF SYMBOLS

Symbol	Definition
a,b,c	Major and minor semi-axes of a semi-ellipsoid.
1/b	Variance of tracer concentration at the point of origin.
$\overline{C}$	Mean tracer concentration as a function of time (or distance) and location within a waste field.
C_0	Initial maximum tracer concentration at the point of origin.
C_{max}	Maximum tracer concentration as a function of time or distance.
$\overline{d}$	Average depth of tracer or waste field.
D_{min}	Minimum dilution of tracer as a function of time or distance.
$\overline{D}^2_{x,y,z}$	Variance of the center of mass of tracer substance.
E	Water column stability.
E'	Approximate water column stability.
ϵ	Rate of energy dissipation per unit mass.
ξ^2	Variance of diffusing particles in given co-ordinate direction.
g	Gravitational acceleration.
k	Constant.
$K_{x,y,z}$	Apparent coefficient of eddy diffusion in co-ordinate directions.
$\overline{K}$	Rate constant.
$L_t{}^{x,y,z}$	Lagrangian time scale of turbulence in coordinate directions.
l	Average eddy scale.
M	Total amount of tracer substance released from an instantaneous source.
M'	Total amount of tracer as computed from mass balance analysis.

Symbol	Definition
m'	Total amount of tracer per foot of depth discharged from an instantaneous source.
n	An exponent.
θ	*In situ* water temperature.
P	Most probable diffusion velocity.
Q	Rate of tracer discharged from a continuous source.
$\overline{Q}$	Average rate of tracer discharged from a continuous source.
r	Average displacement of tracer particles with respect to center of tracer mass.
r_0	Initial particle separation.
ρ	Density.
S'	$E' \times 10^7$.
σ	Standard deviation of particle or tracer concentration distribution as a function of time or distance.
$\overline{\sigma}^2$	Average variance of particle or tracer concentration distribution as a function of time or distance.
σ_t	Density factor.
t	Diffusion time.
T	Observed diffusion time.
$\overline{U}$	Average speed of surface current.
W	Average wind speed.
w	Weighted mean diffusion velocity.
x,y,z	Coordinate axes with x in the direction of the mean current, y perpendicular to x in the lateral direction, and z in the vertical direction.

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STATE OF CALIFORNIA

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As defined by Section 13040 of the
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△ 41572—956 3-65 2M
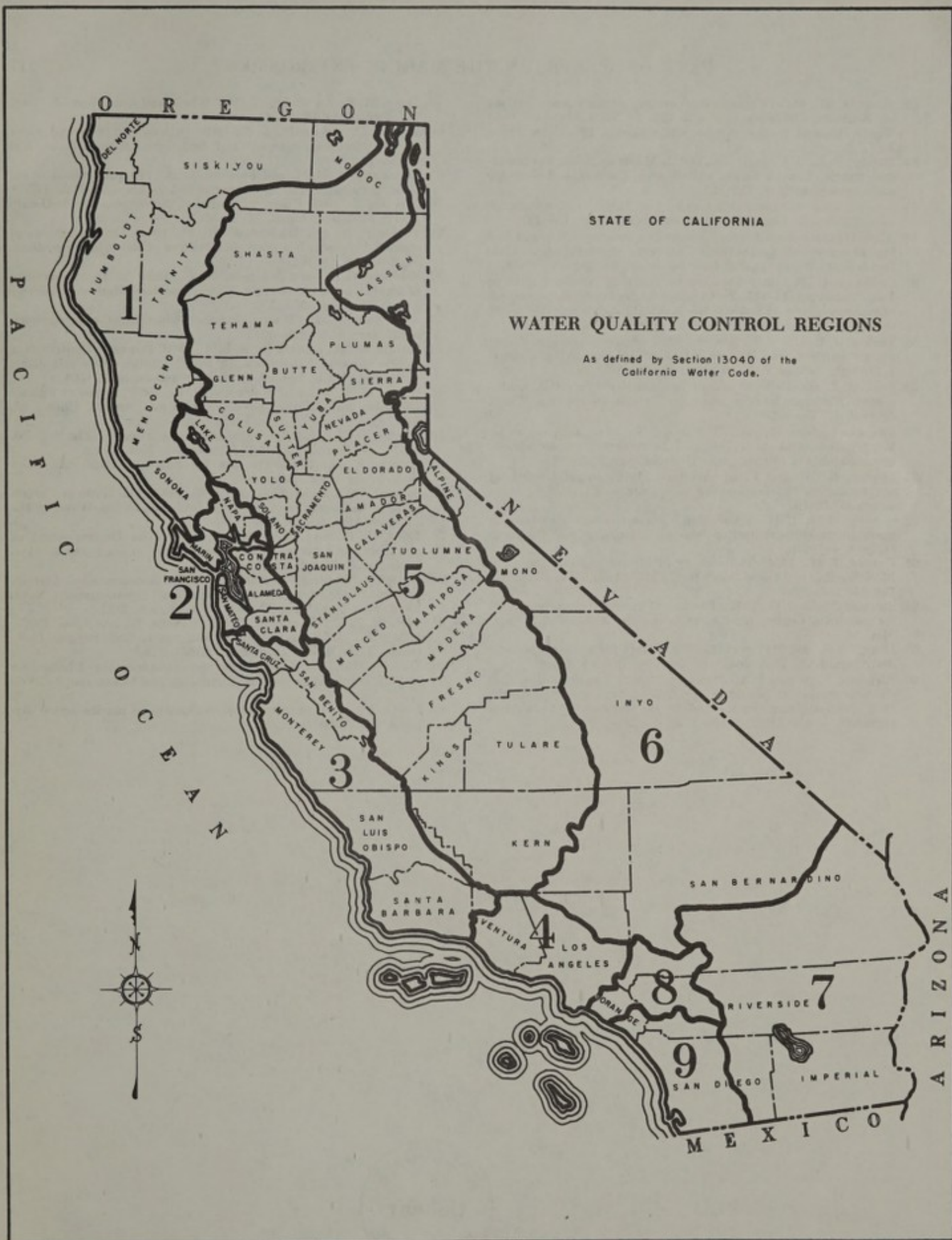
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