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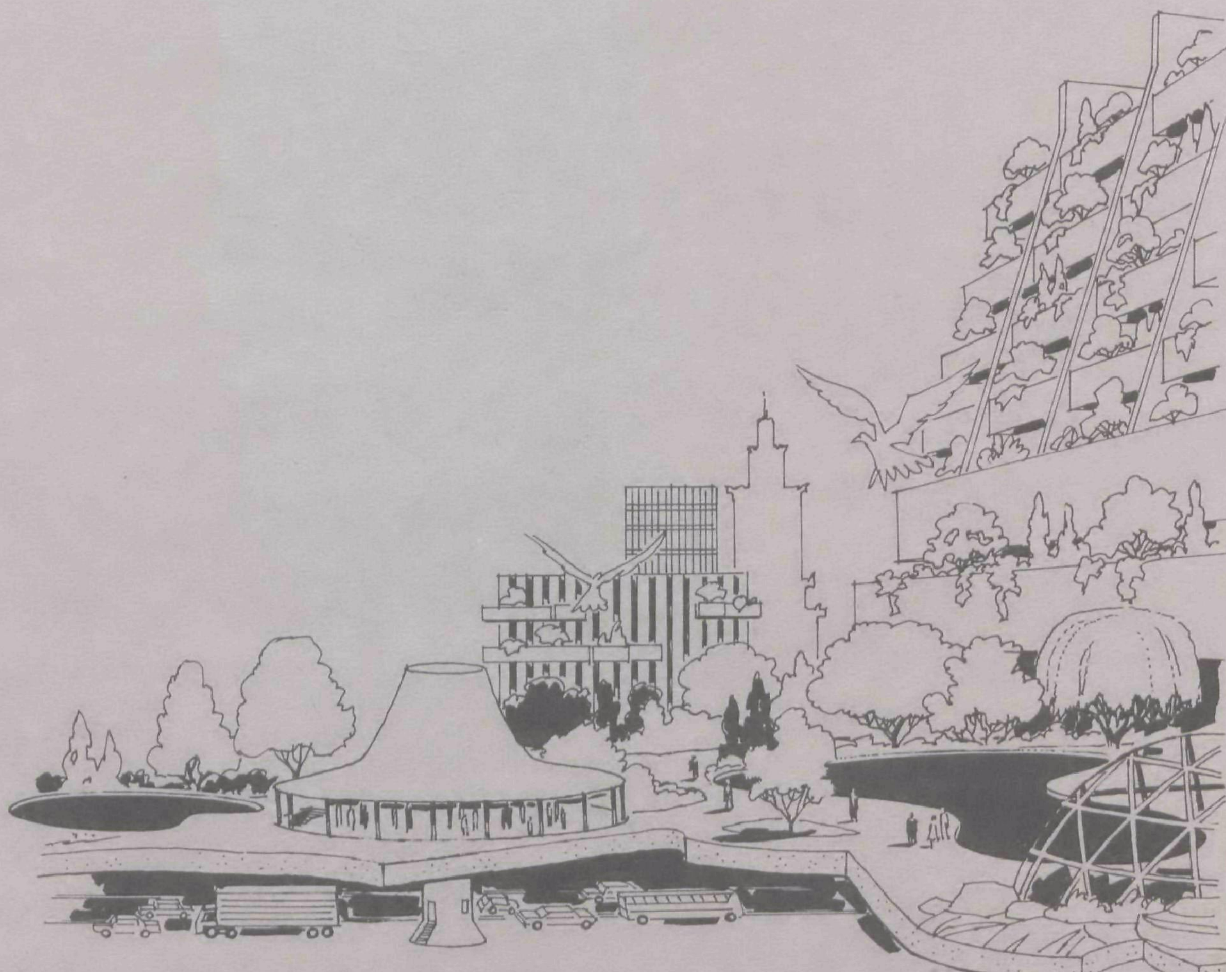
OXYGEN REGENERATION OF POLLUTED RIVERS: THE DELAWARE RIVER



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OXYGEN REGENERATION OF POLLUTED RIVERS: THE DELAWARE RIVER

by

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Water Quality Office

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ABSTRACT

Tests of surface instream aerators and of bottom diffuser aerators were conducted on the Delaware River near Philadelphia in order to determine the practicability of induced oxygenation of deep navigable rivers. Techniques used were based mainly upon those developed previously by Rutgers University upon a smaller river, with special adaptations required to determine oxygen transfer rates, since the equipment affected only a small part of the channel. The diffuser was tested at various depths up to 38 feet, but its performance in pounds of oxygen per horsepower hour decreased markedly in the deeper water. Performance of the surface aerator appeared to be somewhat improved over results previously found in a shallower river. Cost estimates and systems analysis led to the following conclusions:

(a) That induced oxygenation by aerators appears to constitute an economical alternative to advanced waste treatment on the Delaware River.

(b) That surface aerators can readily be reinforced to operate economically on large rivers, but can only be used in areas where they will not interfere with navigation.

(c) That diffuser aerators of the type tested are closely comparable in economy to surface aerators, and can be used in port areas without interference with navigation.

(d) That oxygen diffusers developed by others may provide an even more economical means of induced oxygenation in waters subject to navigation, provided certain problems can be solved.

This report was submitted in fulfillment of Grant No. 16080 DUP under the partial sponsorship of the Environmental Protection Agency.

Key Words: Dissolved oxygen,* water quality control,* oxygen sag,* aeration,* stream improvement,* stream pollution, biochemical oxygen demand, dispersion, pollution abatement, surface aerators,* air diffusers,* induced oxygenation,* instream aeration.*

CONTENTS

FIGURES

FIGURES (Cont'd)

TABLES

CONCLUSIONS

1. Induced oxygenation of deep navigable rivers by river aeration appears to be an entirely feasible and economical alternative to advanced waste treatment under appropriate conditions, costing approximately half as much to achieve a given dissolved oxygen level on the Delaware River.

2. Mechanical surface aerators provide an economical means of adding oxygen to deep rivers; but they may need to be reinforced structurally, and can only be used for areas where they will not interfere with navigation.

3. The submerged diffuser aerators, with coarse holes, have about the same costs as surface aerators for oxygenation of deep rivers. They are relatively most efficient in waters 15 - 20 feet in depth. They should not adversely affect navigation, except perhaps for small, rapidly-moving craft, such as outboards. Their relative economy declines rapidly where long underwater pipelines are required.

4. Based upon experiments of others, it appears that diffuser aerators would have a much higher transfer rate if built with smaller apertures. Diffusers with small apertures have been found to plug up when not in use, due to both physical and biological causes. However, means may be found to avoid the plugging.

5. On the basis of available estimates, oxygen diffusers developed by others appear to be less costly than aeration, especially in deep water. However, the problem of dispersion would have to be solved before they could be used in a large navigable river.

RECOMMENDATIONS

1. That in planning increased consideration should be given to the possibilities of induced oxygenation of rivers, either by aeration or oxygenation, or a combination of both, as appropriate to the circumstances.

2. That research and development should be continued upon oxygen diffusers and fine bubble air diffusers, including means of minimizing plugging of apertures, and of obtaining dispersion throughout the river cross section.

SECTION I

INTRODUCTION

In 1967 and 1968, the Water Resources Research Institute of New Jersey conducted tests of instream aeration on the Passaic River, supported by EPA grants (Phase I, 16080 DUP) and accompanying OWRR research projects (B-010-N.J., B-011-N.J., A-017-N.J., and B-002-N.J.). Financial support also was provided by the Department of Conservation and Economic Development, State of New Jersey. The results, which have been reported previously (1, 2, 3, 4, 5) indicate that the artificial or induced aeration of rivers may provide a more economical method of improving oxygen levels than advanced waste treatment of effluents and that for small rivers, surface aerators are more economical than diffusers. The present study constitutes Phase II of the original program. It is based upon field tests conducted upon the Delaware River in the summers of 1969 and 1970. The purposes of the study were to test both surface and diffuser aerators on a wide, deep, navigable stream; to determine efficiency, economy, and operating characteristics of these aerators; and to prepare prototype designs and cost estimates of aerator installations appropriate to such rivers.

The lower Delaware River, below Trenton, N.J., is designated as the Delaware Estuary; and it is the sections between Philadelphia and Chester, Pa., inclusive, which constitute the main problem area from the viewpoint of water pollution (see map, Figure 1). The situation on the Delaware Estuary is recognized nationally as a major water quality problem. It was analyzed in a 1966 report (6) and has been the subject of much action by the Delaware River Basin Commission. The situation is well summarized in a recent paper (7) and a report (8). About 40 miles of the river suffer from insufficient dissolved oxygen at times, as shown in Figure 2. The oxygen deficiency interferes with important runs of anadromous fish, besides impairing the quality of the river for recreational and living purposes. Adopted dissolved oxygen standards will require bringing minimum daily average dissolved oxygen (DO) levels up to about 3.5 mg/l. The cost of implementing this program is very great, of the order of $40 million annually;[1] and it will require a high degree of treatment. In view of the economic importance of the situation, and the definitive evaluation of the optimum program obtainable by means of treatment alone, the Delaware Estuary provides an ideal situation to study the feasibility of a program of instream aeration, to be used as a supplement to a (somewhat reduced) program of effluent treatment.

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1 Reference 7 indicates annual cost estimates of $46 million and $34.4 million, respectively, for two given objectives, the adopted plan lying somewhere between them. Comparison of these figures, taking into account differences in dissolved oxygen objectives for various reaches of the river, indicates that the annual cost of adding the last 1.0 mg/l of dissolved oxygen to the critical section of the river would be over $9 million annually.

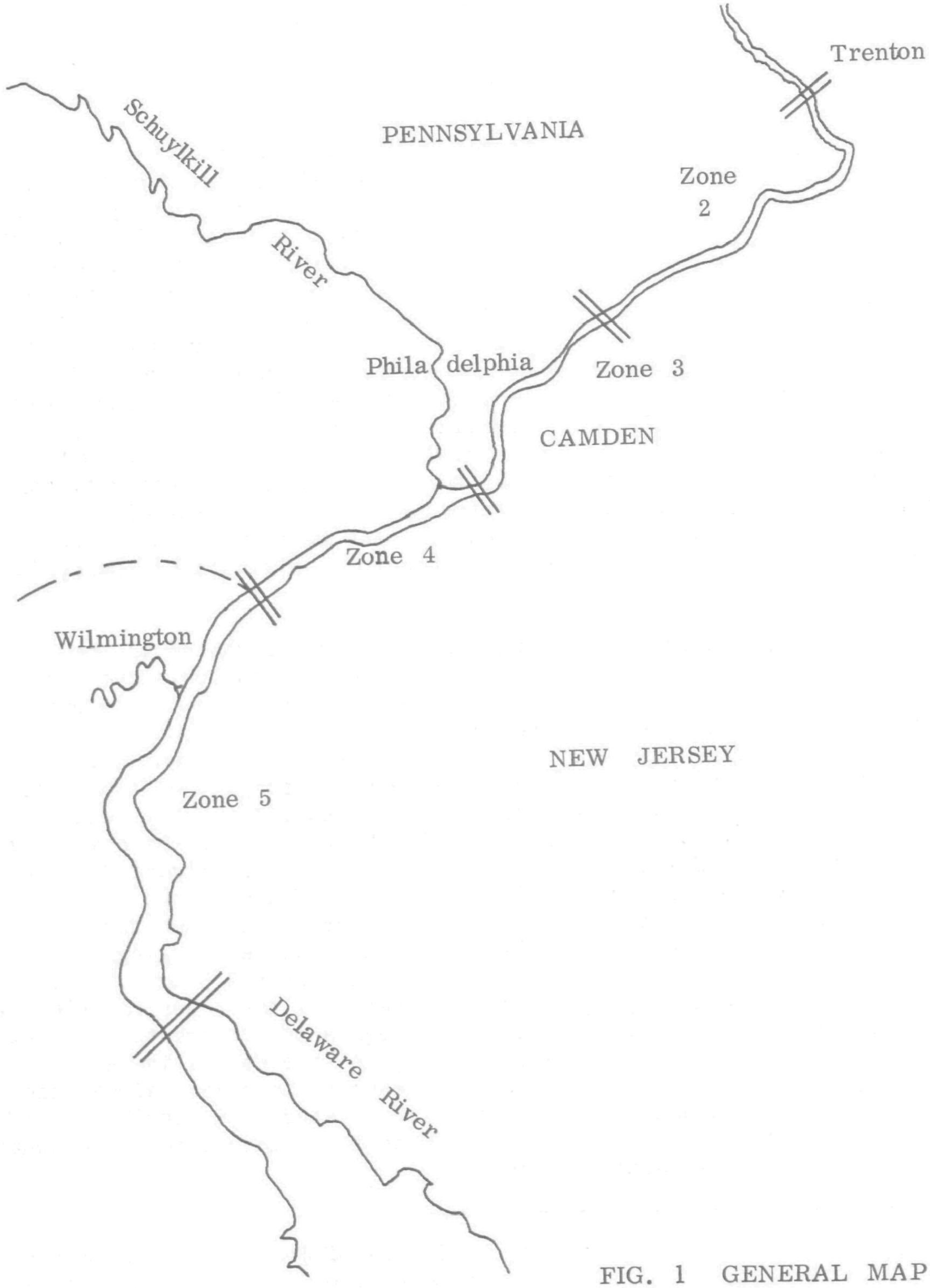

FIG. 1 GENERAL MAP

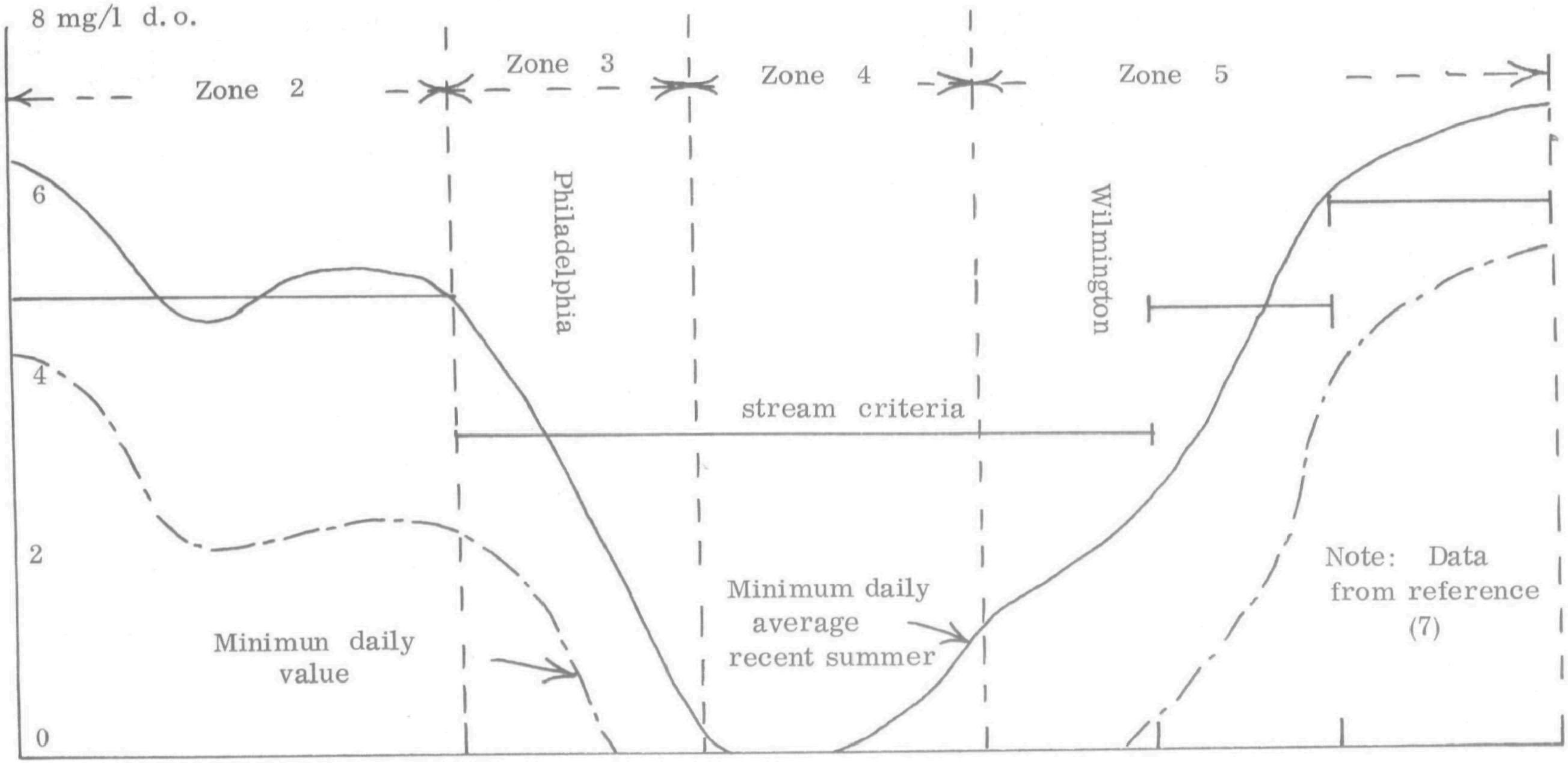

FIG. 2 DISSOLVED OXYGEN CRITERIA AND RECENT CONDITIONS

The Delaware River at the test site is about a half-mile wide. The normal tide range is about 6 feet. Just after high or low tide, the river flows relatively quickly for a short time; then velocity decreases slowly, usually ranging between 1 and 1½ ft/sec, in water depths of 20 to 30 feet. The main navigation channel is maintained at 40 feet of depth, or over.

The demonstration project (Phase II) approved was for a year only, ending 30 November 1969, but notification of the grant was only given in May 1969, leaving little time for preparations. The tests of surface aerator and diffusers were carried out during the summer of 1969 substantially as planned, at a site near Camden, N.J. However, upon later analysis of results and discussions with the Corps of Engineers and Delaware River Basin Commission, it was found that, as regards diffuser aerators, the conditions tested did not include water of sufficient depth. The requirements of navigation entirely preclude the use of surface aerators in port areas and limit diffusers to areas outside the channels and anchorages. In view of channel configuration and river dispersion characteristics, diffusers must be utilized in water of 30 or even 40 feet in depth along considerable reaches. Since performance at such depths had not been tested, it was decided to postpone submission of the report and to arrange for additional diffuser tests in deeper water in June 1970. The Federal funds had by that time administratively terminated; but tests were conducted with remaining state funds.

During the final period of analysis, information was received indicating that under some conditions use of pure oxygen may be more economical than air diffusers. Also certain other types of air diffusers may be preferable to those tested. These possibilities, although beyond the project scope, are mentioned as a matter of perspective.

The first phase of the project was the field operations of the aerators in Camden, N.J., described in Section II. As previously indicated, part of the field operations took place during the second summer. The second phase was the calculation of oxygen transfer of the aerators. (See Section III.) In principle, this analysis resembles similar calculations for the Passaic River aerators (1); except that subsequent laboratory work has indicated a change in one of the constants. In practice, however, much more elaborate methods were necessary to obtain oxygen uptakes on the Delaware River, since, in the larger river, it is much more difficult to determine which portions of the flow are affected by the aerator. Also, entirely different methods involving a gas chromatograph were required to obtain oxygen uptake of the deeper diffusers. Section IV describes the dispersion field tests, using fluorescent dyes, and the analysis required to determine dispersion characteristics of the river.

Once the transfer rates, navigation requirements, and dispersion characteristics had been determined, it was possible to develop a series of prototype aeration sites which would be practicable on such a river. Different sizes are required, in order to apply to reaches needing more or less supplementary oxygen. Cost estimates were prepared for these systems by design consultants, Hazen and Sawyer. These considerations are covered in

Section VI. Section V is a discussion of a systems analysis of oxygen characteristics of the Delaware Estuary, which derives an estimate of the amount of supplemental oxygen required to raise the dissolved oxygen level by a given amount, and draws inferences as to approximate costs of river oxygenation by means of mechanical facilities.

This report incorporates mainly the work of the following:

William Whipple, project director, general planning and coordination, basis for design.

Joseph V. Hunter, Department of Environmental Science, water chemistry and biochemistry.

Frank W. Dittman, Department of Chemical Engineering, field operations, power estimates and gas chromatography.

Shaw L. Yu, Department of Civil and Environmental Engineering, oxygen uptake and systems analysis.

George E. Mattingly, Department of Civil and Geological Engineering, Princeton University, dispersion analysis.

Francis P. Coughlan, Jr., and Melvin Stein, Hazen and Sawyer, design consultation and cost estimates.

Personnel of U.S. Geological Survey, Trenton, N.J. and Washington, D.C., whose contributions are acknowledged elsewhere in this report.

Dr. Dittman was primarily responsible for Section II, Dr. Yu for Section III and V, Dr. Mattingly for Section IV, and General Whipple for Sections I and VI. Various students also assisted in field work or office operations.

SECTION II

FIELD OPERATIONS

Operating headquarters for the 1969 Delaware River tests was located in Camden, New Jersey, at a pier projecting into the river from the east bank. The pier is part of the Camden Sewage Treatment Plant, located about midway between the Ben Franklin and Walt Whitman bridges. It was generously made available by the city, free of charge, on recommendation of the plant manager, Mr. John Frazee.

The mechanical and diffuser aerators were located on a common north-south centerline about 75 feet west of the end of the pier, and about 150 feet downstream (see Figures 3 and 4). About 12 pile clusters or individual pilings had to be driven into the bottom for several purposes--to anchor the aerators, to support the necessary services extending outward from the end of the pier, and to provide reference points for locating the boats while instream measurements and samples were being taken. The Corps of Engineers granted an official permit for the work, being in navigable waters.

The services extending out from the pier included: (a) one 12-inch steel pipe carrying compressed air for the diffuser aerator; (b) one 440-volt, 3-phase, 200 KVA electrical supply cable for the mechanical aerator; (c) one 3/4-inch plastic hose for Rhodamine B dye solution used in dispersion studies; (d) thermocouple wires and pressure leads of 1/4-inch plastic tubing to an orifice meter used for air flow measurements.

The entire river installation had to conform to two navigation restrictions--the space at the end of the pier had to be kept clear at all times for the sewage plant sludge barge, and the navigational anchorage area could not be infringed upon by any pilings or equipment.

Compressed air for the diffuser aerator was supplied from the pier by the same diesel-compressor unit used for the Passaic River Study in 1968 (see Ref. 1). This was a Fuller Company Sutorbilt rotary positive blower with silencer, driven by a 250 hp Cummins diesel engine, with muffler, through a clutch and reduction gear assembly. Pressures up to 25 psi were obtainable. The fuel tank was elevated on a steel framework so that its bottom was about two feet above the engine fuel intake. Air from the 12-inch supply pipe, metered by the orifice plate connected to an inclined manometer, was divided at the outward end into two 8-inch branches leading to the two 8-inch underwater headers with a total of 160 diffuser nozzles. Link-Belt 3/4-inch adjust-air diffuser nozzles, each having 12 openings 5/32 inches in diameter, were used.

The 75 horsepower Yeomans mechanical aerator was the same unit used in the Passaic River study in 1967 and 1968 (Ref. 1); electric power for it was supplied by a portable 200-kilowatt diesel-generator unit on the pier. Switchgear for the electrical output was mounted in a small existing shed near the outer end of the pier.

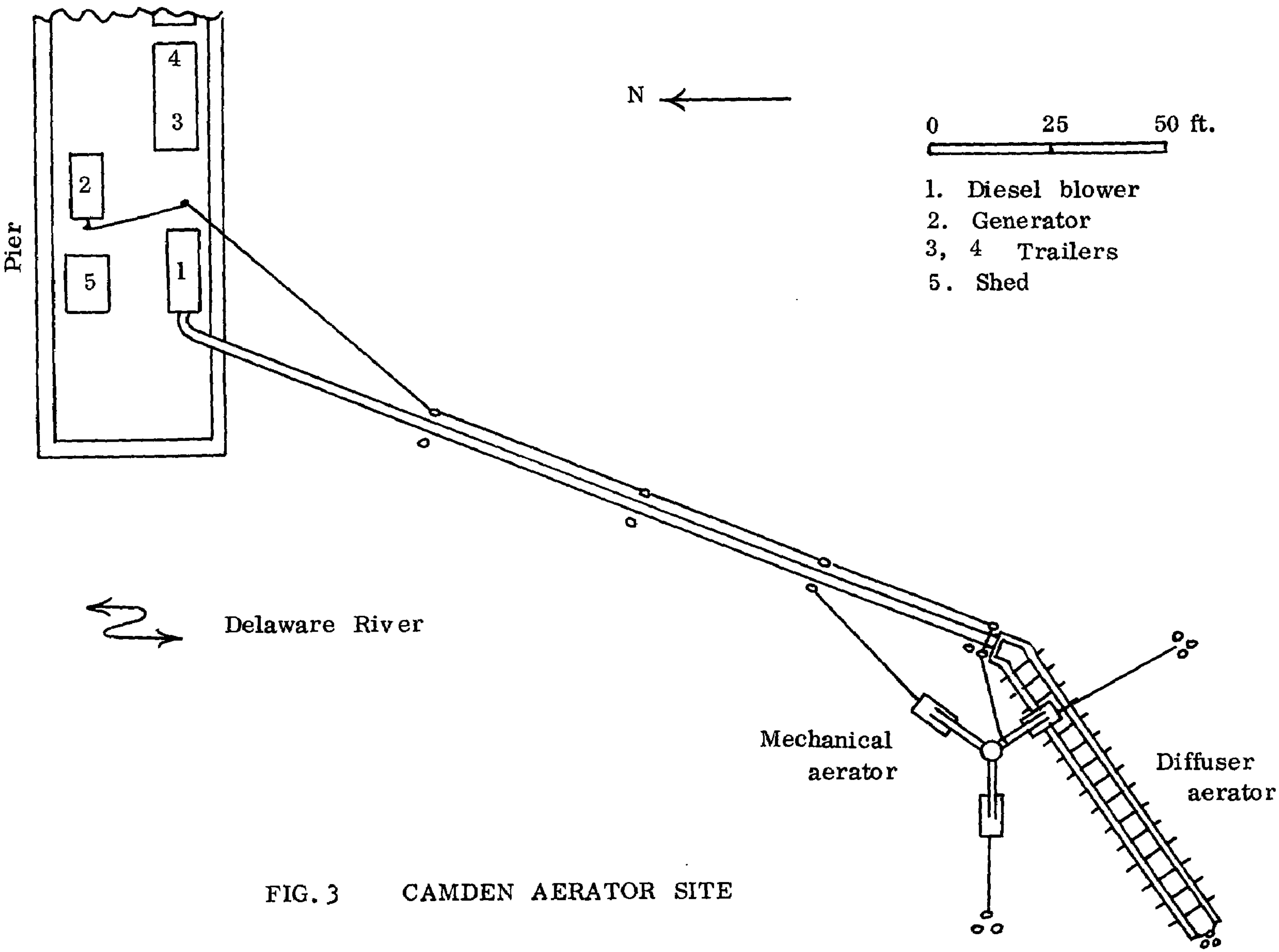

FIG. 3 CAMDEN AERATOR SITE

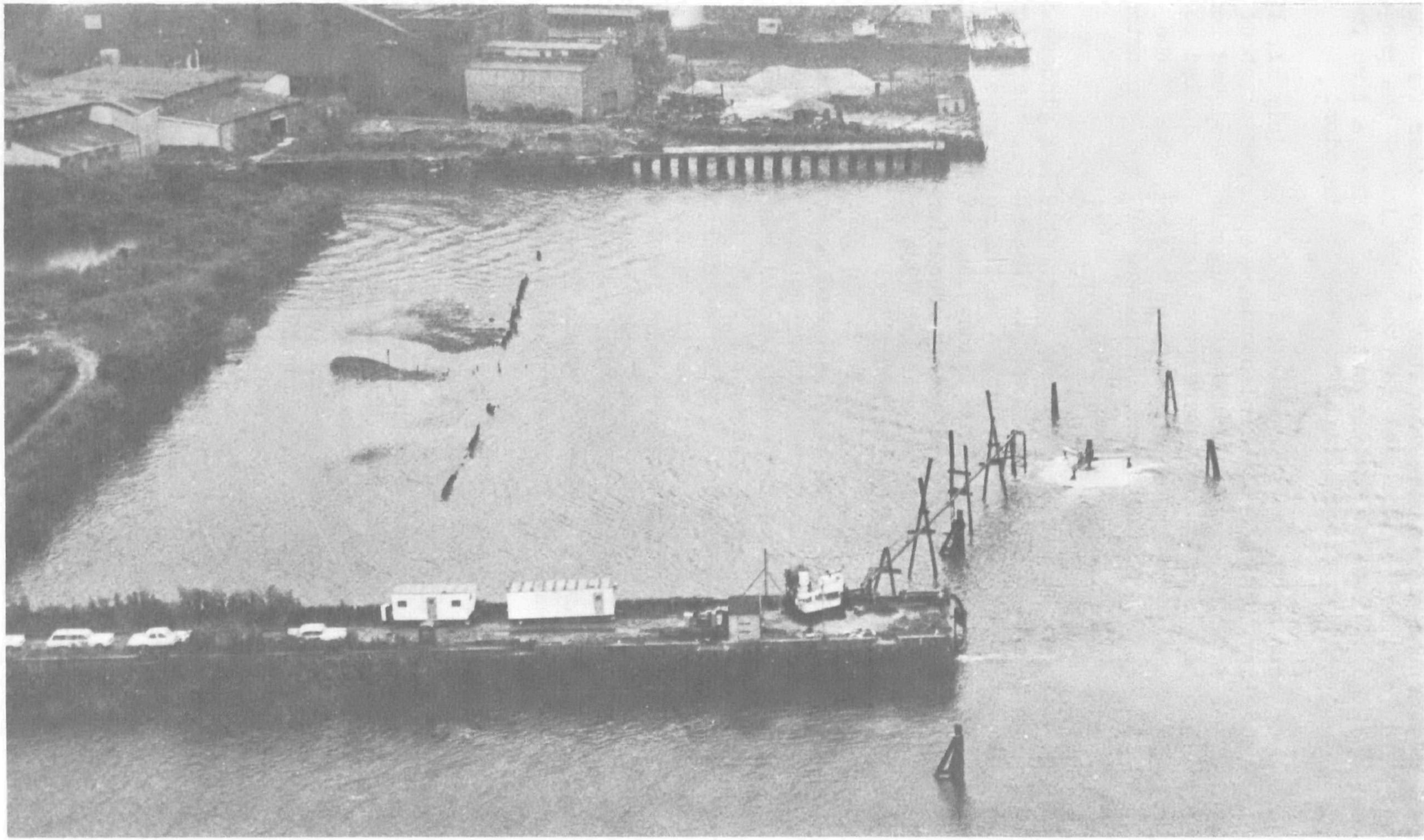

FIG. 4   AERIAL VIEW OF CAMDEN AERATOR SITE

Two trailers, one for the office and laboratory and the other for equipment storage, were installed on the pier for the duration of the project. 110-volt power for the office-lab trailer was supplied from a line previously installed to serve a floodlight at the end of the pier.

The installation of both aerators was completed on Friday, July 11, 1969. During the following day, a brief but violent storm occurred at about 6 pm; as a result of wave action, the mechanical aerator, designed for service in treatment plants or quiet waters, collapsed. It failed to sink only because its supporting pontoons were undamaged; two of the three radial pairs of steel channels were badly twisted, and the motor was damaged by water (see Figure 5).

A revised design was quickly developed, using fabricated box girders instead of simple channels for the radial members. Meanwhile, the motor was dried out and reconditioned. The installation of the redesigned and rebuilt mechanical aerator was completed on Friday, August 15. Initial operation occurred August 18, and satisfactory operation was achieved on August 21, after several problems were corrected (see Figure 6). The diffuser aerator was not affected by the storm.

Two 14-foot open boats with 10 horsepower outboard motors were used for direct instream measurements, for taking water samples, and for miscellaneous water transportation. Since the waters around the pier were completely unprotected against storms, ship wakes, and boat thieves, the boats were kept at the nearest marina, about 3 miles away, and were brought to the project daily. Additional boats and special equipment, used for a few days during the dye dispersion studies, were furnished by the U.S. Geological Survey office at Trenton. Their boats were stored temporarily at the Gloucester Coast Guard Base, immediately south of Camden. One boat each was also borrowed for dispersion tests from the Delaware River Basin Commission and the Corps of Engineers Philadelphia District.

The data taken from the boats on a daily basis included instream measurements of dissolved oxygen, temperature, velocity, depth, and boat position. Numerous water samples were also taken to check the dissolved oxygen meter readings against dissolved oxygen via Winkler titration. Samples of spent air from the diffuser were also taken. When an aerator was operating, two boats were used to make simultaneous cross-traverses, upstream and downstream of the aerators. Two men were needed in each boat to maneuver and position the boat, and then to take oxygen and velocity data (see Figures 7 and 8). Daily data taken on the pier included atmospheric temperture, pressure, and oxygen content, air flowmeter readings on the 12-inch supply line, electrical data on the mechanical aerator drive, and operating data on the two diesel engines. Also on the pier, Winkler samples previously fixed in the boats were titrated in the office-laboratory trailer.

One of the complications of data-taking in a tidal estuary is the diurnal tidal cycle; water is flowing upstream for about 12 hours of each 24. Random eddies, unpredictable mixing zones, and additional turbulence occur where the incoming tide meets the outgoing river water. The direction of

FIG. 5 SURFACE AERATOR DAMAGED BY STORM

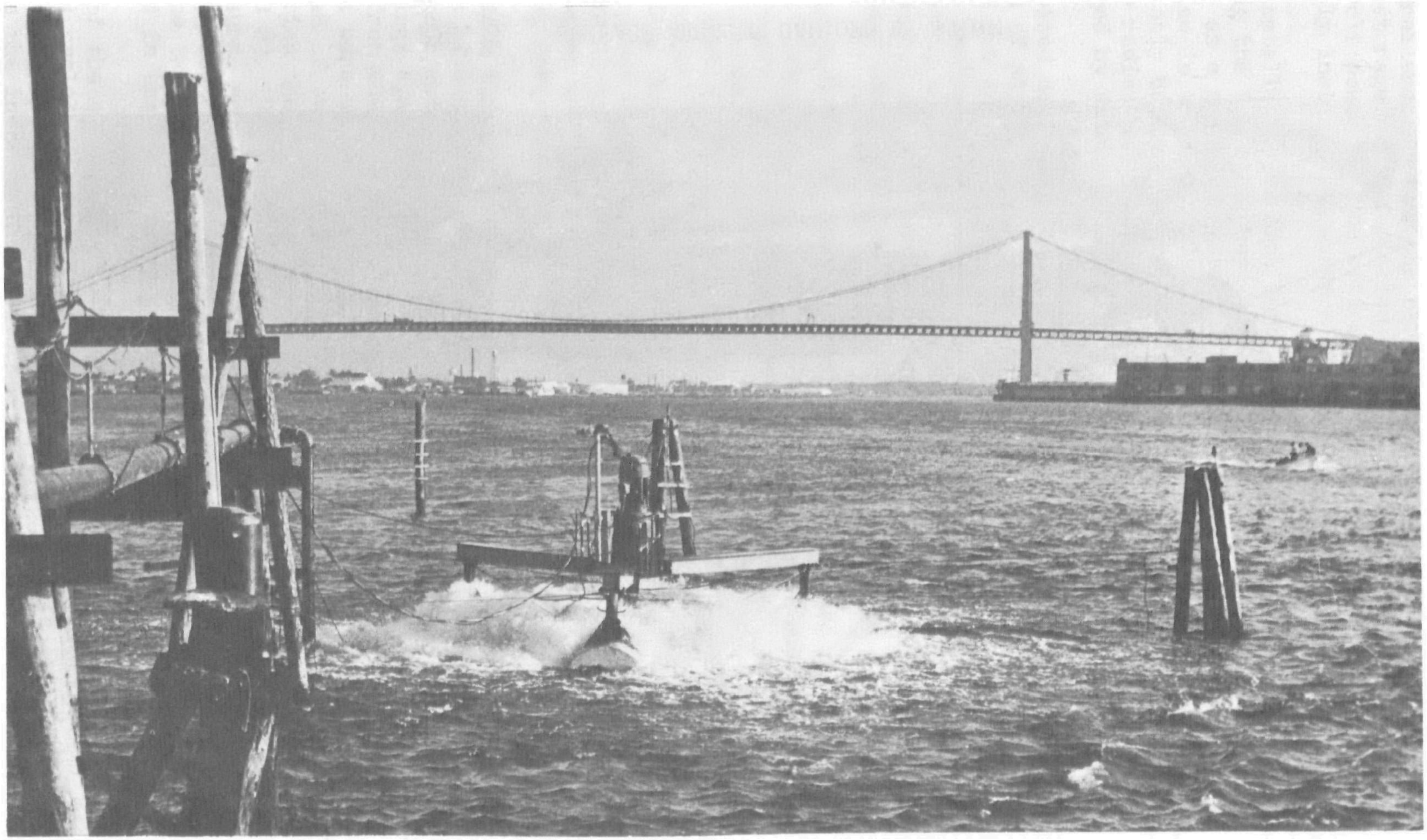

FIG. 6   REBUILT SURFACE AERATOR IN OPERATION

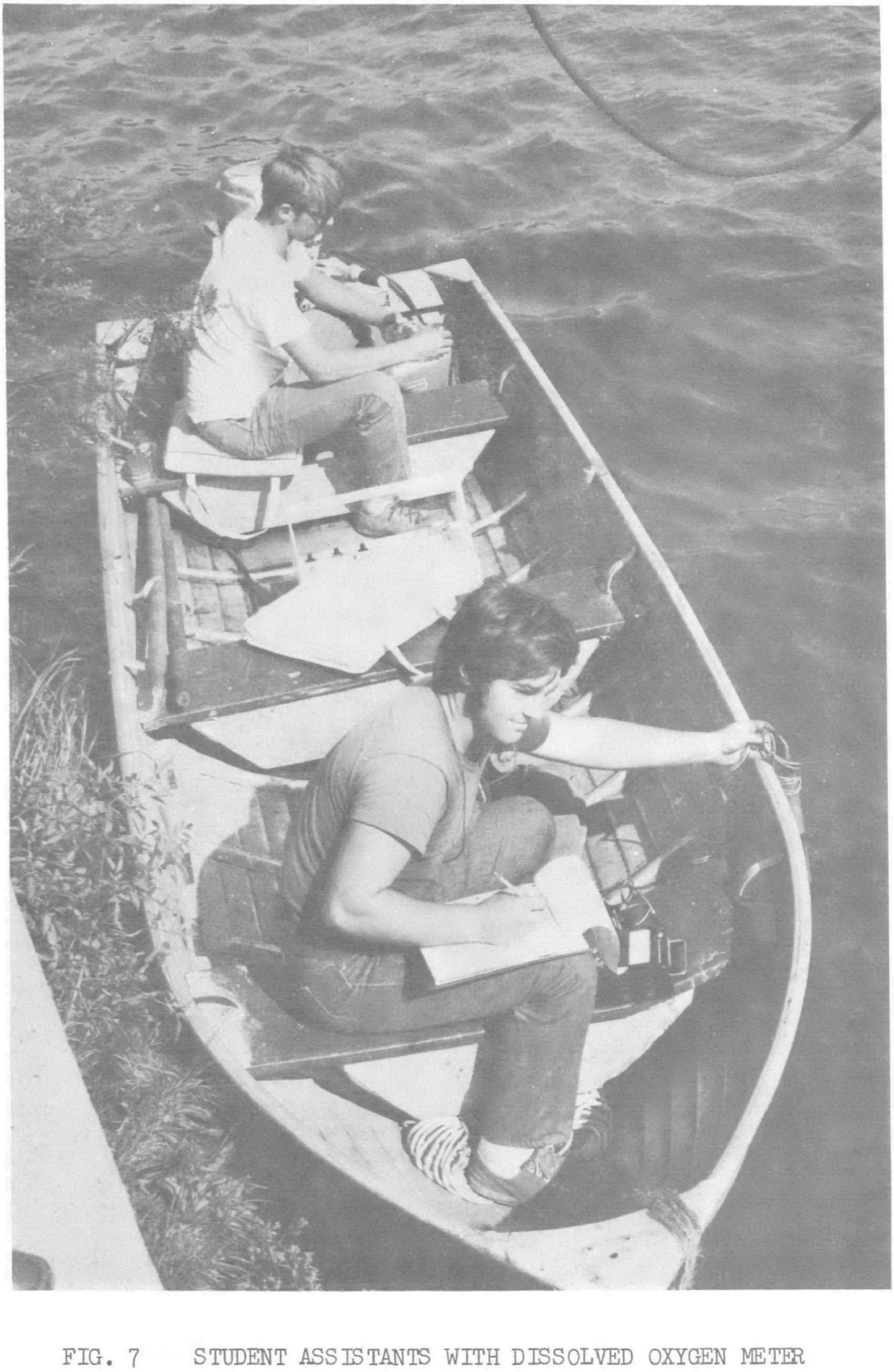

FIG. 7 STUDENT ASSISTANTS WITH DISSOLVED OXYGEN METER

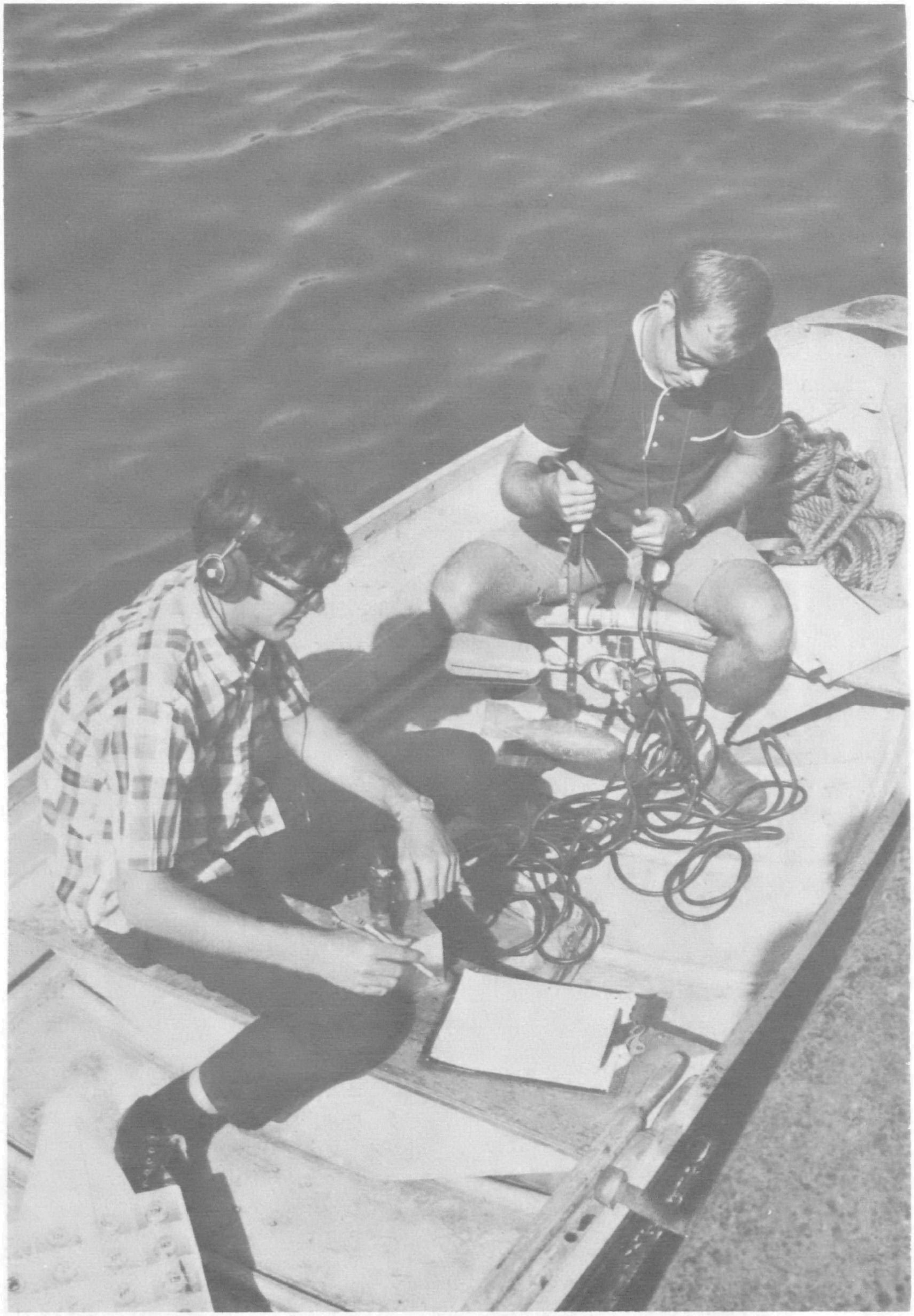

FIG. 8 STUDENT ASSISTANTS WITH CURRENT METER

the flow should not affect the performance of the aerators, but because of the mixing phenomena, it would affect the accuracy of our oxygen input calculations. For consistency, it was decided to operate the aerators and take data only during the periods of out-going tide. This decision, of course, required that data be taken at different time periods each day, using the tide tables as a guide. Most of the work could be done in daylight; on only a few occasions was there need to continue after sundown.

Two Delta Type 85 portable oxygen meters, previously used on the Passaic River project, were available for the work on the Delaware. Results with these portable instruments had been satisfactory, provided that they were calibrated by the Winkler method at the beginning of each data-taking period. These Type 85 meters, however, had cables only 6 to 8 feet long, which were not adequate for the Delaware. Therefore, while some data were taken with the Type 85 meters, portable polographic meters with cables about 45 feet long were obtained and used during most of the project--a Delta Type 75 from another OWRR project at Rutgers, and a Yellowsprings meter generously made available by the U.S. Geological Survey at Trenton. Meters were calibrated at the beginning of each data-taking run against the Winkler titration method, azide modification, using the same sample of river water for both measurements. The meters were adjusted to agree exactly with the Winkler method at the beginning of each run; data taken during the run usually indicated a maximum difference of ± 0.5 mg/l between the two methods. During July and August, 1969, the Delaware River at Camden usually contained 0.5 to 1.5 mg/l of oxygen except after heavy general rains, when it increased to a range of about 4 to 5 mg/l.

The measurement of water temperature at or very close to the oxygen probes is important for two reasons; it affects the meter readings, and it affects the saturation concentration of oxygen in water. The Delta 85 and Yellowsprings instruments are each equipped with a built-in thermistor close to the oxygen probe, plus a measuring circuit. The temperature is measured and recorded on the data sheet, and the temperature-compensating dial of the instrument is set accordingly, before the oxygen measurement is made. Since the Delta 75 lacks the temperature-measuring feature, but still requires the setting of a temperature-compensating dial, it was used in conjunction with a Model 380 electrical thermometer, made by RFL Industries of Boonton, N.J. This thermometer has a cable of about the same length as the Delta 75; in operation, the two cables were taped together.

Point values of river velocity to define the velocity profile were made at various depths and locations, using weighted current meters, made by Gurley Engineering Instruments of Troy, N.Y. These instruments had cables about 50 feet long, so that velocity could be measured at any desired depth. Prior to use on the project, these Gurley meters were recalibrated, using a moving boat technique in a swimming pool. Results agreed well with the manufacturer's calibration. The manufacturer's calibrations were used in making calculations from the data. The depth, at which each point measurement of temperature, velocity, and oxygen concentration was made, was obtained by means of red and black tapes fastened to the instruments' cables at 5-foot intervals.

The position of a given boat for a given measurement was determined by reference to a coordinate system based on distances from the pier and from various pilings or pile clusters. Distances of the boats from the reference points were obtained using calibrated ropes. Where possible, the ropes were stretched between pilings. When working on the outboard side of a single piling, the outboard motor had to be kept running to keep the boat in position at the end of the rope. This method was required because of the restriction against driving pilings in the navigational channel.

Ten to fifteen river water samples for Winkler analysis were taken as spot checks on the meters during each traverse, usually at 1-foot depths only. Standard 200-ml bottles with ground-glass stoppers were used. Samples were "fixed" in the boats immediately after being taken; that is, the oxygen content of the water in the bottle was converted to a chemically equivalent quantity of iodine (I_2) in solution. Back at the office-lab trailer, the iodine was titrated with standard $Na_2S_2O_3$ solution to determine the original oxygen content.

The diffuser manifold, 80 feet long, consisting of two headers 5 feet apart, was installed between two clumps of piles, supported so as to remain in a horizontal position, averaging about 13 feet below the surface. At this depth the operating characteristics were excellent. The 5-foot horizontal distance between the headers brought bubbles up in a fairly uniform pattern, with an upward velocity which seemed to be perhaps 1.0 to 1.5 ft/sec (see Figure 9).

In a permanent installation, the clumps of piles actually used would be objectionable to navigation interests. One of three alternatives would be used:

(a) Lay the diffuser on a sloping bottom and vary the size of diffuser apertures to correct (approximately) for the different depths.

(b) Use a support structure of some kind to hold the diffuser horizontal despite a sloping bottom.

(c) Lay the diffuser upon a bottom which was either already level, or was specially leveled prior to the installation.

It had been anticipated that the oxygen input to the Delaware in terms of pounds or tons per hour might not be calculable accurately if based on a small observed concentration rise multiplied by a large flow rate. Also, the exact quantity of water passing through the aeration zone is difficult to determine precisely when only part of the stream is being aerated. In the case of the mechanical aerator, there is no alternate simple, available way of verifying the oxygen input based on water analysis and flow rate. For the diffuser aerator, however, there is an available method, namely, to take samples of the spent air and analyze them for oxygen content. Then, knowing the flow rate and oxygen concentration of the inlet air, it should be possible to calculate the oxygen input to the water and the efficiency of absorption.

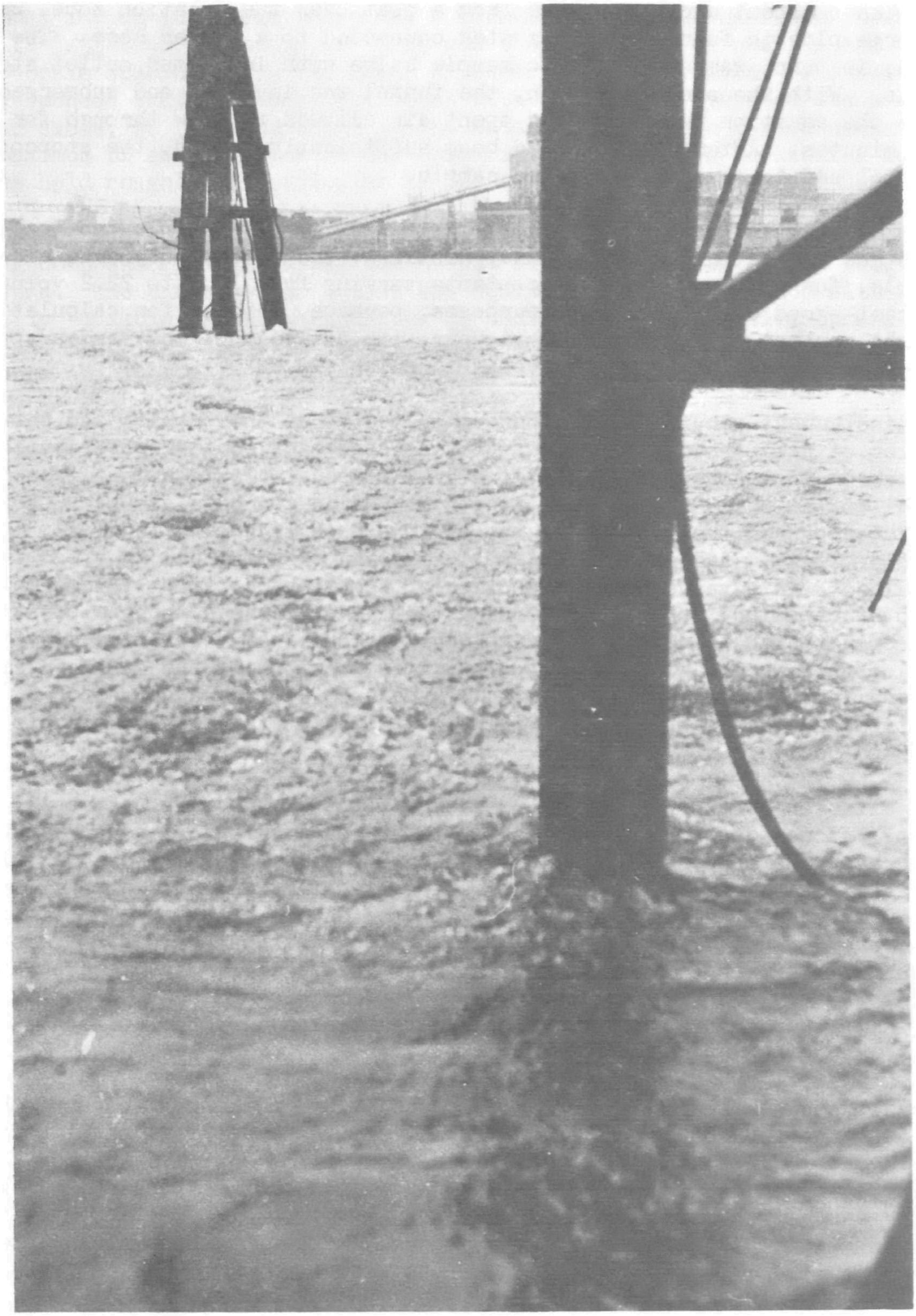

FIG. 9 OPERATION OF SUBMERGED DIFFUSER AERATOR

Samples of spent air were taken from a boat over the aeration zone, using a large plastic funnel with its stem connected to a rubber hose. The hose, in turn, was connected to sample bulbs with inlet and outlet stopcocks. With the stopcocks open, the funnel was inverted and submerged over the aeration zone, and the spent air allowed to flow through for a few minutes. After the bulb had been sufficiently purged, the stopcocks were closed to trap the required sample.

Initial results, using 5 to 10 ml portions of each sample in the Beckman GC-5 gas chromatograph, were disappointing. The same atmospheric air sample, for instance, gave O_2 contents varying from 19.5 to 22.2 volume percent--good enough for some purposes, perhaps, but not for calculation of the percent O_2 absorbed. Obviously, the analyses of the Camden spent air samples done in this way were not reliable.

The instrument manufacturer, when consulted about the problem and shown copies of data from several runs of this degree of scatter, attributed the error to unconscious variations in the operator's technique from one trial to the next. The variations occurred in the rate at which the operator pushed the plunger of the syringe when injecting the 1 ml sample of gas. A Beckman Gas Sampling Valve of the manual type was then obtained. This valve traps a portion of sample of constant volume in a loop of capillary tubing; by turning the valve to the alternate position, the operator then injects the sample at the same rate each time. By the use of this device, O_2 contents of various portions of the same air sample ranged from, for example, 20.9 to 21.5 percent O_2; the average for 5 portions of this sample was 21.1% O_2. Other air samples gave results as good or better.

The diffuser aerator at Camden operated at depths averaging about 13 feet. It was determined after analysis and discussion of aerator results with agencies concerned that the extensive pier and anchorage areas of the Philadelphia port and the navigation channels would not permit use of surface aerators; moreover that diffuser depths of up to 40 feet in some areas would be required. A search of the literature did not disclose any basis upon which the performance of these or any other aerators at depths of 30 to 40 feet could be predicted. Accordingly, a decision was made to carry on another set of tests using a diffuser aerator at various depths in June 1970.

These tests were performed at a deep water pier on the west bank of the Delaware River, about 3 miles upstream from the Camden test site, made available through the courtesy of Brig. Gen. Allen F. Clark (ret'd), director of the Philadelphia Port Corporation. At this pier a maximum water depth of 40 feet was available, so that if a variable depth diffuser with controllable air supply could be devised and spent air samples could be taken, a correlation of percent oxygen absorption with depth and air flow rate should be obtainable.

A 3-inch diameter steel pipe diffuser header, 6 feet long, was made up with a 3-inch cap at one end and a 1-inch hose connection at the other end. At 1-foot intervals there was a Link-Belt 3/4-inch Diffusair nozzle, with 12 5/32-inch air outlets. This was the same kind of nozzles and the same nozzle spacing as in the large diffuser previously used. The header was suspended from an improvised hoist with a manually operated winch and marked cable, so that the depth in the water could be controlled down to the maximum of about 40 feet. The axis of the header was horizontal and it was held roughly perpendicular to the current by the air supply hose.

The header was supplied with air from a Jaeger gasoline-driven reciprocating compressor having a maximum output flow of 125 SCFM at 100 psig pressure. The air receiver outlet was equipped for the occasion with a manually variable pressure regulator so that, while the receiver pressure rose and fell, and the compressor started and stopped automatically, the pressure and flow rate of the air supplied to the header remained constant.

From the pressure regulator, the air flowed through a Brooks rotameter with a maximum capacity of 70.8 SCFM; the meter outlet was equipped with calibrated temperature and pressure instruments and a sampling connection for collecting samples of the compressed air. The air then flowed through a standard 1-inch compressed air hose about 50 feet long to the air header in the water.

During the operation, 19 spent air samples and 4 compressed inlet air samples were taken over a 2-hour period. Three different header depths were used, and three different air flow rates were used at each depth. Data taken were as follows:

1. Time of day
2. Air rotameter scale reading
3. Air rotameter gauge pressure
4. Air rotameter temperature, ^{o}F
5. Atmospheric pressure, inches of mercury
6. Atmospheric dry bulb temperature, ^{o}F
7. Atmospheric wet bulb temperature, ^{o}F
8. Dissolved oxygen in water, mg/l
9. Dissolved oxygen sensor depth, ft.
10. Water temperature, ^{o}C
11. Spent air sample number
12. Compressed air sample number
13. Air header depth, feet.

Data items 2-7, 12, and 13 were taken by Observer No. 1, on shore. Items 8-11 were taken by Observer No. 2, in a boat over the zone of rising bubbles. Both Observer 1 and 2 recorded the time(data item 1) from synchronized watches. Observer No. 3, also in the boat, held the inverted funnel in the water over the rising bubbles and filled the sample bulbs, using a collecting period of 30 to 60 seconds for each sample. The weather was cloudy but there was no wind or rain. The only difficulties were caused by the wakes of passing tugs and boats.

The chromatographic analysis of these spent air samples and their correlation with depth and flow rate yielded interesting results, which are summarized in Table 1, and discussed in Section III.

A special feature of the 1969 project was the plotting of the dispersion pattern of the oxygenated water from the aerators by injecting Rhodamine B organic dye solution into the water at the point of aeration. Using a group of 3 small centrifugal pumps in series, with a capacity of 5 to 20 GPM, river water was pumped continuously up to the working level of the pier and mixed with dye solution in a jet mixer. The dye-water mixture was then sent through the 3/4-inch hose to a perforated spray hose within the turbulent mixing zone of whichever aerator was operating during the test.

For the mechanical aerator, the perforated hose was extended around a horizontal triangular pattern, just above the cascade created by the aerator. For the diffuser aerator, the perforated hose was underwater, parallel to the two 8-inch headers, just between and about 1 to 2 feet above them.

During each test, one of the aerators and the dye solution pumps ran continuously for several hours. Boats equipped with samplers and photoelectric colorimeters moved through the dispersion zone at various distances downstream from the aerator, measuring and plotting the dye concentration vs time at many known points. Measurements continued for one to two hours after the dye pumps and the aerator were shut down. In this way the dispersion pattern of the oxygenated water could be plotted much more accurately than would be possible by means of oxygen analysis.

For several reasons the dye solution is better than oxygen in this type of study. Dye analysis is quicker, more sensitive, and more accurate than oxygen analysis. There is only one source of dye, at a known location, and the dye concentration is not affected by the atmosphere or by variations in biochemical oxygen demand.

The dye dispersion studies were made possible by the cooperation of the U.S. Geological Survey of Trenton, N.J., under the leadership of Mr. John McCall. His staff worked closely with our project staff for several days to achieve results which constitute an unusually complete study of the dispersion pattern of the oxygenated water.

TABLE 1

TABULATION OF GAS SAMPLES
Taken July 2, 1970 in Philadelphia

Sample No.	Depth of Header	Corrected Flow Rate SCFM Air	% O_2 in Spent Air	% O_2 Absorbed
1	12'3"	93.0	20.8	1
2	12'3"	93.0	19.9	6.5
3	12'3"	44.0	20.06	5.6
4	12'3"	44.0	20.4	3.6
5	12'3"	16.3	19.9	6.5
6	12'3"	16.4	19.91	6.5
7	38'3"	19.7	20.7	1.8
8	38'3"	19.7	19.07	11.3
9				
10	38'3"	53.7	19.6	8.2
11	38'3"	53.5	18.9	$\approx$ 12.3
12	38'3"	99.4	19.3	10.0
13	38'3"	99.4	19.7	7.7
14	25'	17.9	20.1	5.3
15	25'	17.9	19.8	7.1
16	25'	49.6	19.6	8.2
17	25'	49.6	19.7	7.7
18	25'	49.6	19.7	7.7
19	25'	94.1	20.3	4.2
20	25'	92.9	19.4	6.0
A_1	Air Intake Samples		21.1	-
A_2	Air Intake Samples		21.0	-
A_3	Air Intake Samples		20.9	-
A_4	Air Intake Samples		20.83	-
	Sample bulbs filled with air;			
N_1	purged with N_2 15 seconds		$\approx$ 0.7	-
N_2	Purged with N_2 30 seconds		0.0	-

SECTION III

OXYGEN TRANSFER OF AERATORS

In this section the data on oxygen transfer for both diffuser and surface aerators are presented and the results discussed. Also comparisons are made with oxygen transfer efficiencies obtained from the same equipment on the Passaic River and other results reported in the literature.

Oxygen Transfer Rates

In the Passaic River aeration report (1) it was demonstrated that in a natural stream the rate of oxygen transfer for an aerator under steady-state conditions may be expressed as

$$R_t = \frac{.2246\ Q\ (C_d - C_u)}{P} \qquad (3\text{-}1)$$

in which

- R_t = oxygen transfer rate in pounds per hour per unit horsepower
- Q = river discharge in cubic feet per second
- C_d = DO concentration downstream of the aerator in milligrams per liter
- C_u = DO concentration upstream of the aerator in milligrams per liter
- P = aerator power consumption in shaft horsepower

Equation 3-1 implies that the amount of oxygen supplied by the aerator per hour is proportional to the difference between the concentrations of oxygen downstream and upstream of the aerator and to the river discharge. Also in this equation the contributions from other oxygen sources or sinks, such as BOD consumption and atmospheric reaeration, are considered negligible.

The applicability of Equation 3-1 depends mainly on the following assumptions:

(1) the dissolved oxygen concentrations within the upstream and downstream sampling cross-sections are uniform, that is, there is no significant DO concentration gradient across each of the river sections; and

(2) the capacity of the aerator is such that the entire downstream cross-section is affected by the aerator at the time DO samples are taken.

During the Passaic River aeration study, the aerators were placed in a relatively narrow (average width 100 feet) and shallow (average depth 7 feet near the aeration site during low flows) river. The above two conditions were generally satisfied (1) and Equation 3-1 was used to compute oxygen transfer rates for the aerators. For the Delaware River tests, however, the aerators were placed near the Camden side of the river, approximately 200 feet from the bank, as shown in Figure 3 in Section II. The width of the river at the aeration site is about half a mile, and the depth of water near the aerator about 30 feet. It is evident that only a small fraction of the river flow was affected by the aerator when DO samples were taken; also the DO concentrations were not uniform in the vicinity of the aerator. Hence in such cases the conditions for using Equation 3-1 are not satisfied. Therefore the following method derived from a mass balance concept is adopted as an approximation.

It is assumed that a "control section" could be located downstream of the aerator through which all or most of the aerated water passes. This control section can be determined by observing the flow pattern in the vicinity of the aerator in operation. For a small area, ΔA_i, the DO concentrations may be considered uniform and represented by C_i. If the velocity of flow for the small area, ΔA_i, is V_i, then the mass rate of oxygen passing through the area is $C_i V_i \Delta A_i$. The total mass rate for the control section, M, is then

$$M = \Sigma_i C_i V_i \Delta A_i \tag{3-2}$$

Let C_i be the DO concentration before and C'_i after the aerator was in operation. The oxygen uptake rate due to the aerator, U, can be computed by

$$U = \Sigma_i (C'_i - C_i) V_i \Delta A_i \tag{3-3}$$

under the assumption that there is no significant velocity change at the control section before and after the aerator is in operation.

The oxygen transfer rate for the aerator under test conditions, R_t, can then be determined by

$$R_t = U/P \tag{3-4}$$

Mechanisms of Oxygen Transfer

The mechanisms of oxygen transfer for the diffuser and the mechanical aerators are different. As shown by Bewtra and Nicholas (9), in the case of diffuser aeration the total rate of oxygen transfer constitutes the following three components, namely, bubble formation, bubble ascent, and bubble breaking at the water surface. For porous diffusers with small capillary openings and a small rate of air flow, the oxygen transfer during bubble formation is appreciable. However, for diffusers with large apertures, such as the one tested in this study, bubbles are formed while rising in the water and the amount of oxygen transfer during bubble formation is negligible. The aeration during bubble bursting at the water surface is related mainly to turbulence conditions. Although Carver (10) has shown that in conventional aeration tanks the amount of oxygen transfer in this phase of bubble aeration is small, other investigators, e.g., Barnhart (11), have observed that a substantial amount of oxygen is transferred at highly turbulent aeration tank surfaces. Therefore for duffusers with large apertures the total rate of oxygen transfer, N, can be written as the sum of two individual rates; namely, N_a, the rate during bubble ascent, and N_b, the rate during bubble bursting at the surface.

$$N = N_a + N_b \tag{3-5}$$

The oxygen transfer during bubble ascent, N_a, depends on such factors as the diffuser submergence, velocity of air bubbles, diameter of air bubbles, and so forth. On the other hand, N_b has been expressed as an exponential function of the water velocity at the surface (12). It is therefore expected that for a diffuser the efficiency of oxygen transfer would be proportional to the depth of submergence, the size of the bubbles, the air flow rate, and the surface turbulence, as described by Eckenfelder (13) and Eckenfelder and Ford (14).

In the case of the mechanical aerator, oxygen transfer to the water occurs both in the sprayed water and in the turbulent mixing zone (14). Carver (10) has investigated the process of spray aeration and found that oxygen transfer was correlated to the size of water droplets. Garland (15) reported that oxygen transfer efficiency for surface entrainment aerators generally decreases with increasing aeration basin volume, but increases with increasing water depth for basins of constant diameter. In an earlier study by Kaplovsky, et al (16), oxygen transfer was found to increase markedly in a certain velocity region. To date (1970), however, no information is available concerning the independent evaluation of the relative importance of each of the aforementioned two phases of oxygen transfer, i.e., the spray aeration and the turbulent mixing.

Procedures of Computation

As indicated in Section II, it was decided to operate the aerators and collect data only during the periods of outgoing tide in an attempt to minimize the mixing effects of the tidal currents on the DO distribution. For each test run, numerous samples were taken both upstream and downstream of the aerator. Details of the sampling procedures as well as the locations of the sampling sections are described in Section II. Figure 10 illustrates the results of a typical DO and velocity traverse.

To compute the oxygen uptake due to the aerator, the DO readings were first corrected against the Winkler readings. The average DO for a cross-section was then obtained by weighing the DO readings according to the velocities, and the uptake was determined by Equation 3-3. It should be noted that for several tests no DO data were taken at the downstream "control" section before the aerator was in operation. In these cases, the DO concentrations at the upstream sampling section were taken as approximations of the downstream readings.

As mentioned earlier, the downstream "control" section was located by examining the flow pattern of the oxygenated water in the vicinity of the aerator. To accomplish this, dye tests and floating object tests were conducted so that the paths of the aerated water could be determined.

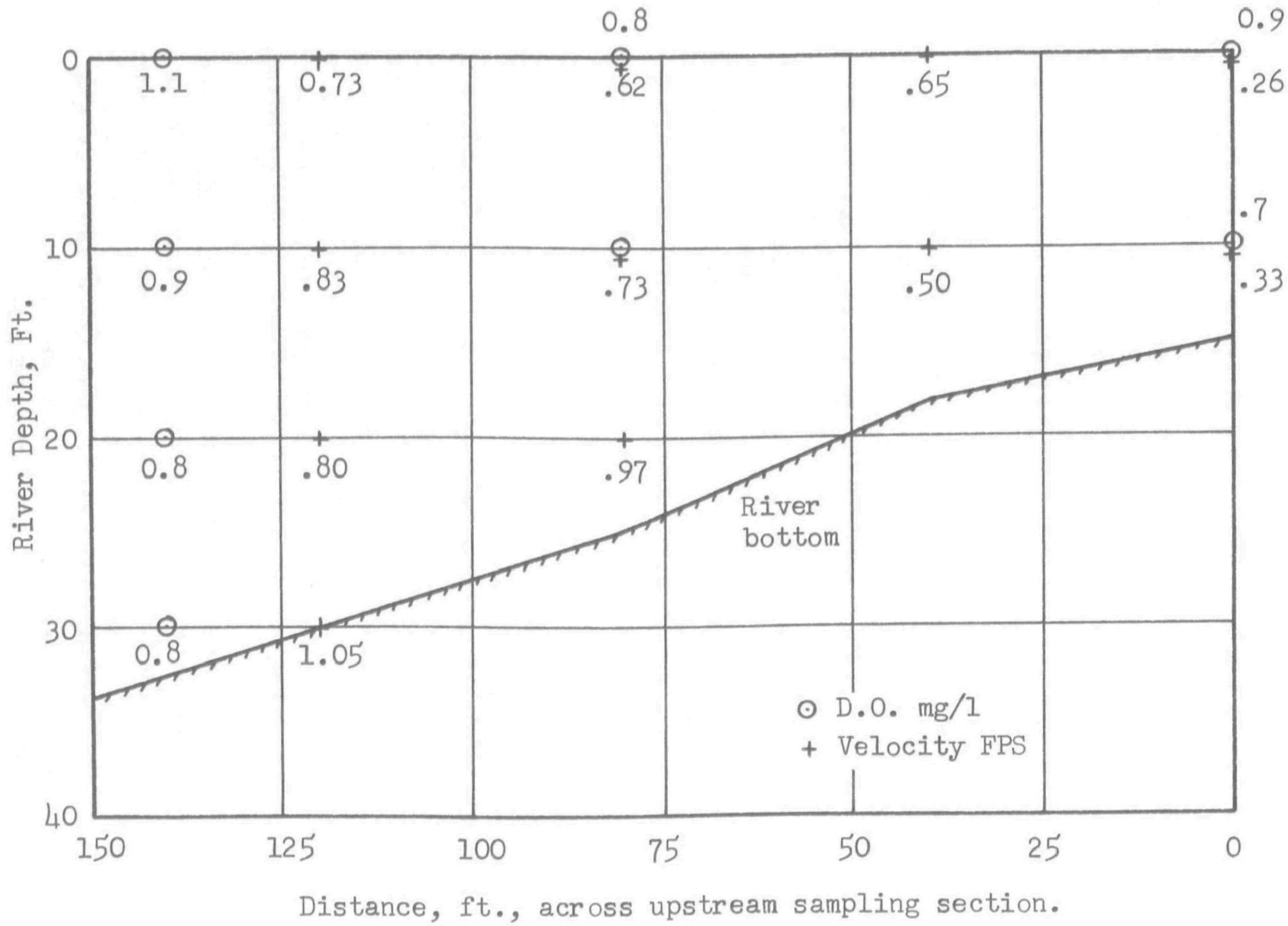

FIG. 10 DO AND VELOCITY TRAVERSE AT UPSTREAM SAMPLING SECTION

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These tests revealed that in general the aerated flows downstream of the aerator were divided. For the mechanical aerator, as shown in Figure 11, part of the flow passes riverward of pile BW, while the balance seems to pass landward of pile BE, leaving a section between them without aerated water. For the diffuser aerator the flow pattern is generally similar, with only a small portion of the flow also passing the section between piles BW and BE and some aerated flow going upstream and then turning back to downstream, as indicated in Figure 12. More detailed description of the oxygenated flow patterns is given in Section IV.

For the Philadelphia tests, only air samples were taken for the determination of percentage of oxygen absorption, as described in Section II. The oxygen uptake rates for these tests were computed by knowing the supply air flow rate, oxygen content in the air, percent absorption, and density of oxygen. The results so obtained in the Philadelphia tests for the diffuser with four nozzles were adjusted to compare with those for the manifold of 160 nozzles, at both Camden and the Passaic River, on the assumption that the oxygen transfer per nozzle remained the same. Equation 3-4 was then used to compute the oxygen transfer rates under test conditions. It should be mentioned that for the Philadelphia tests the power consumptions were obtained by extrapolating the manufacturer's calibration curves to the greater depth of submergence experienced during the experiments.

The oxygen transfer rates, R_t, were reduced to those under standard conditions, R_s, by the following relationship so that comparisons can be made with results elsewhere:

$$R_s = R_t \times F$$

$$F = \frac{(C_s)_{20}}{[(C_s)_T(\frac{P}{29.92})(\beta) - C_m](TF)(\alpha)} \qquad (3\text{-}6)$$

in which

$(C_s)_{20}$ = sautration DO concentration at 20°C
$(C_s)_T$ = saturation DO concentration at test water temperature, T
P = pressure in inches of mercury
β = "specific solubility" of oxygen
C_m = DO concentration at the aerator
TF = temperature correction factor = $(1.025)^{T-20}$
α = "specific oxygen transfer rate"
F = conversion factor

The saturation oxygen concentration, C_s, was computed by the SED/ASCE Equation (1). For the diffuser aerator C_s was corrected for pressure, which in turn was evaluated at the mid-point of the diffuser submergence. According to laboratory tests not yet reported on elsewhere, both α and β values were found to be 1.0. The analysis is as follows:

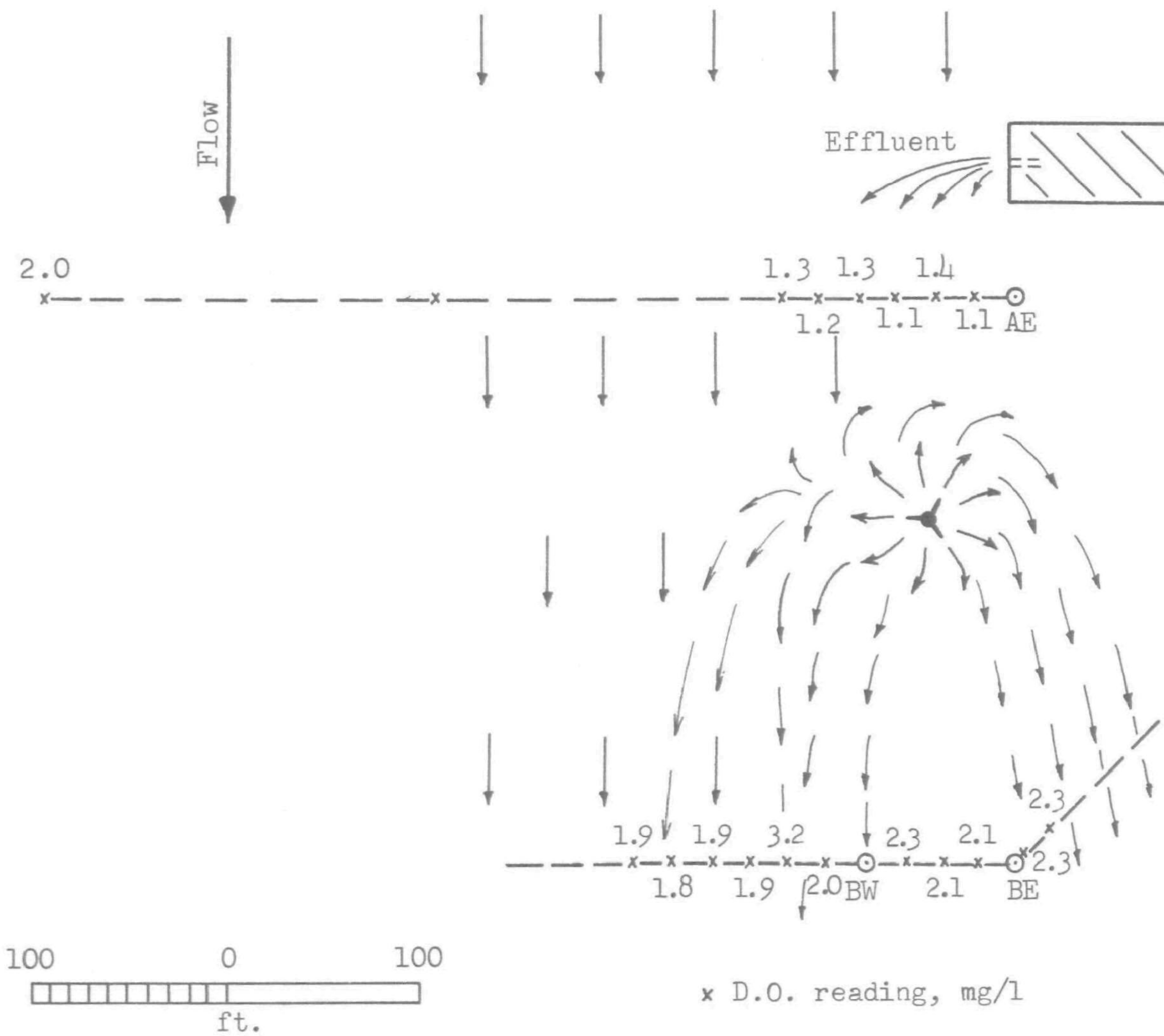


FIG. 11 TYPICAL FLOW PATTERN IN THE VICINITY OF MECHANICAL AERATOR

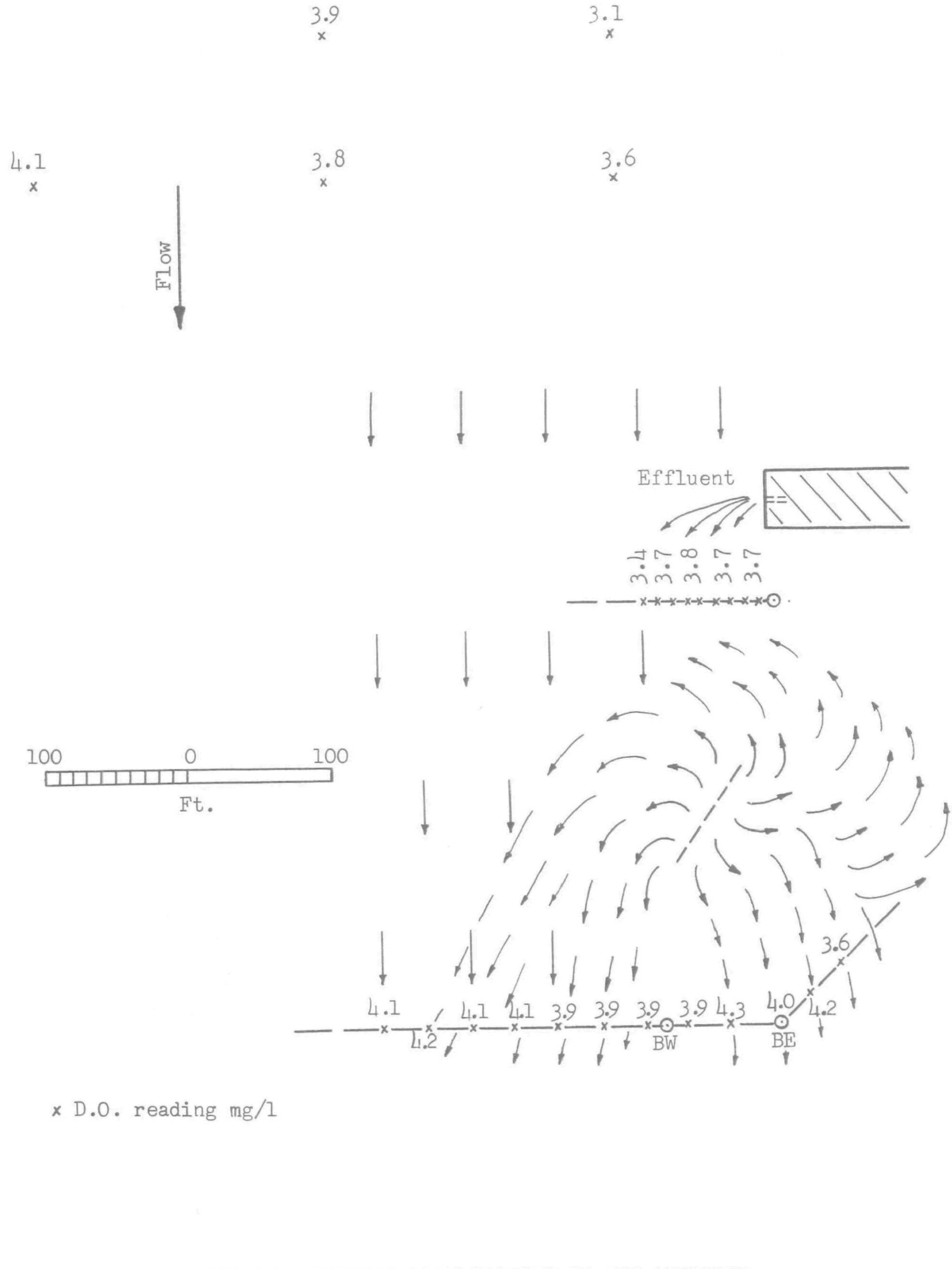


FIG.12 TYPICAL FLOW PATTERN IN THE VICINITY OF DIFFUSER AERATOR

Many environmental factors influence the reaeration characteristics of surface waters. One of the most general of these is the quality of the water itself. That is, the possible presence of constituents that will influence reaeration either through effects on the rate constant (transfer characteristics) or the saturation value above and beyond well defined influence of temperature and salinity.

To either substantiate or remove such possibilities, studies were carried out to determine any influences on either the saturation value or reaeration constants. Effects on the saturation value (C_s) were evaluated by deaerating six cylinders with nitrogen and measuring the dissolved oxygen levels after various time periods until the level remained constant. For 19°C, the DO levels ranged from 9.23 to 9.26 with an average of 9.25. This places the saturation value only slightly below that noted in Standard Methods for the Examination of Water and Waste Water.

Three systems were employed to evaluate effects on the rate of reaeration. These were slow stirred cylinders, high-speed mixing giving considerable turbulence and bubble aeration. In each case, the rate of aeration for river water was compared to that for New Brunswick tap water. For the slow stirred cylinders, the rates of reaeration of tap and river water were identified. For both the high turbulence mechanical and the bubble aerators, the river water values were 99% of the tap water values. As these latter two areas are directly analogous to actual methods employed in river aeration, it can be concluded that the rate of reaeration is not influenced by constituents present in the water at their actual concentration in the aquatic environment.

Mechanical Aerator Results

Due to the late start of tests and the storm accident described earlier in Section II, only four complete sets of observations were obtained. The field data, which include dates, water temperature, oxygen concentrations and uptake, and power consumptions are listed in Table 2. The results on oxygen transfer rates, both under test and standard conditions, are given in Table 3. Also Figure 13 illustrates the oxygen increase resulting from the aerator operation for the test on September 8, 1969. The stationing shown on the figure refers to arbitrarily chosen sampling section. It can be seen that the maximum oxygen increase at the downstream control section was close to 1.0 mg/l, and the net increase in oxygen content is well indicated. The upstream variation of DO concentration does not seem to be significant.

The computed oxygen transfer rates show a large variation in the efficiencies, probably partly due to approximations inherent in the methods of measurement. The transfer rates varied from 1.18 lbs O_2/hp-hr to 3.78 lbs O_2/hp-hr with an average of 2.56 lbs O_2/hp-hr. When converted to standard conditions, the range became 1.29 lbs O_2/hp-hr to 4.50 O_2/hp-hr and the average 3.06 lbs O_2/hp-hr.

The Delaware results indicated substantially higher average transfer rates for the mechanical aerator than the Passaic River tests, both for

TABLE 2

SUMMARY OF FIELD TEST DATA FOR MECHANICAL AERATOR

Date	Water Temp. °C	d.o. concentrations Before (mg/l)	After	Uptake lbs O_2/hr	Power Shaft hp
8/21/69	25.0	1.23	2.14	377.1	99.8
8/25	27.7	0.95	1.13	172.4	98.0
9/2	27.4	1.79	2.02	351.7	100.0
9/8	26.8	0.78	1.02	118.9	101.4

TABLE 3

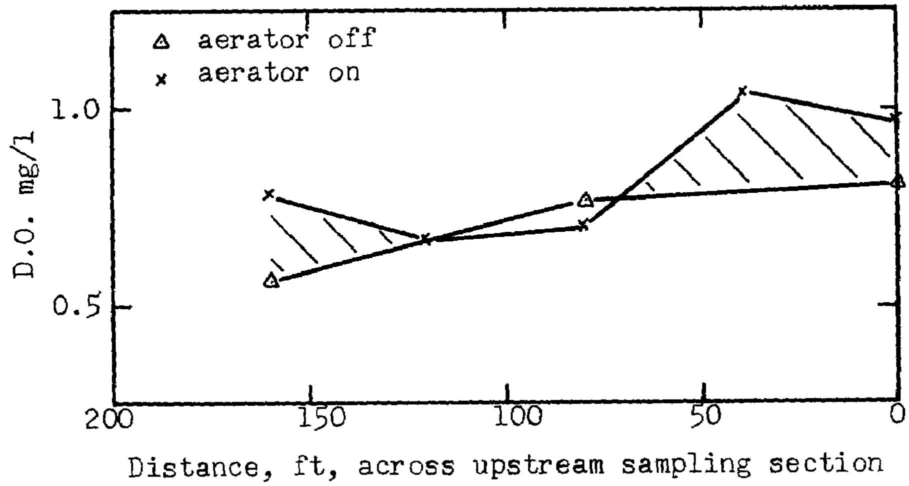
SUMMARY OF OXYGEN TRANSFER RESULTS, MECHANICAL AERATOR

Date	Uptake lbs O_2/hr	R_t Oxygen transfer rate under test conditions lbs O_2/hp hr	R_s Oxygen transfer rate under standard conditions, lbs O_2/hp hr
8/21/69	377.1	3.78	4.50
8/25	172.4	1.76	1.94
9/2	351.7	3.52	4.49
9/8	118.9	1.17	1.29
			Ave. 3.06

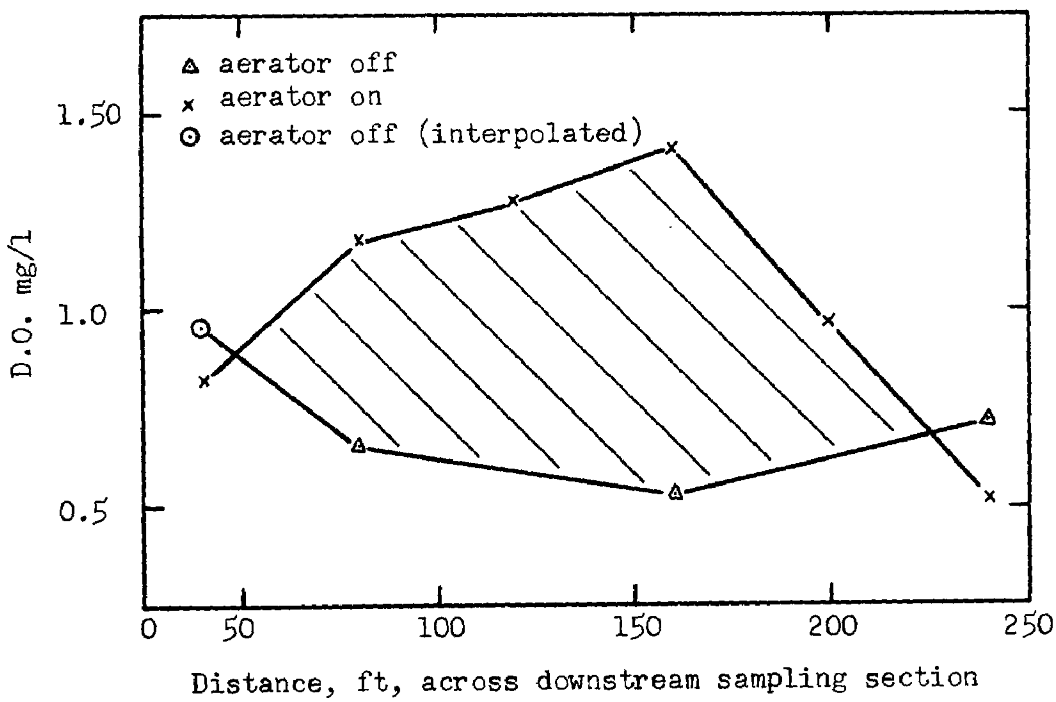
TABLE 4

SUMMARY OF FIELD TEST DATA AT CAMDEN, N.J. DIFFUSER AERATOR

Date	Water Temp. °C	d.o. concentrations Before (mg/l)	After	Uptake lbs O_2/hr	Brake hp
8/1/69	23.1	4.52	4.64	103.5	108.0
8/7	24.2	3.67	4.07	90.5	83.5
8/8	24.5	3.13	3.35	118.9	92.5
8/18	26.2	1.47	1.82	105.4	76.5
8/22	26.0	0.75	0.82	109.2	90.0
8/27	27.0	1.51	1.92	141.9	94.0
9/5	27.4	0.63	0.92	146.4	77.0



Upstream Section



Downstream Section

FIG. 13 OXYGEN INCREASE RESULTING FROM MECHANICAL AERATOR OPERATION

9/8/69

field conditions (2.56 lbs O_2/hp-hr compared to 1.04 lbs O_2/hp-hr) and under standard conditions (3.06 lbs O_2/hp-hr compared to 2.12 lbs O_2/hp-hr).

Compared with most of the transfer rates reported in the literature, even the results for the Delaware are a little low. Eckenfelder and Ford (14) reported a transfer rate between 3.2 and 3.8 lbs O_2/hp-hr in activated sludge plants and aerated lagoons; Susag, et al (17), reported a 4 lbs O_2/hp-hr in laboratory channels; Cleary (18) an 11.05 lbs O_2/hp-hr and Kaplovsky (16) a range of 1.5 to 4.5 lbs O_2/hp-hr in the Chicago canal; all referred to standard conditions. However, the average uptake rate of 210 lbs O_2/hp-hr under standard conditions on the Delaware is higher than the 180 lbs O_2/hp-hr reported by Imhoff (19) on the lower Ruhr River in West Germany.

In summary, the Delaware results seem to fall within the range of values reported in the literature, the difficulties of measurement and number of tests were such that the determination is not considered conclusive.

Diffuser Aerator Results

Compared with the Passaic River study, much more data were obtained for the diffuser aerator on the Delaware River. As described earlier in Section II, the diffuser aerator was tested under various depths of submergence ranging from 11.0 feet to 16.9 feet at Camden, N.J., and a short replica of the diffuser was tested later at Philadelphia under depths of 12.3 feet, 25 feet, and 38.3 feet. A summary of the Camden tests data, including date, water temperature, DO concentrations, power consumption, and uptake rates is given in Table 4, and the Philadelphia data are listed in Table 5.

The oxygen increase due to diffuser aeration is illustrated in Figure 14, using data of September 5, 1969. It can be seen that the DO increase is approximately uniform along the vertical direction, but less so horizontally.

The oxygen transfer results for the diffuser aerator are given in Table 6, together with some Passaic River results for comparison purposes.

The observed power consumption data for the Camden tests and for the Passaic River tests are plotted against the diffuser submergence for various engine speeds, as shown in Figure 15. It is observed that for a certain engine speed, the brake horsepower varies linearly with the water depth. Consequently, power consumptions for greater depth could be estimated by extrapolation, as was carried out in this study.

Upon examining the results for diffuser aerators given in Table 6, the following are noted: (1) The amount of oxygen absorption increases substantially as the depth of submergence increases. Under standard conditions, for an average depth of 7.2 feet, the oxygen absorption averages 3.1 percent, as experienced on the Passaic River. On the Delaware, the absorption increases to 5.0 percent for an average depth of 13.2 feet; to

TABLE 5

SUMMARY OF FIELD TEST DATA AT PHILADELPHIA,* DIFFUSER AERATOR
July 2, 1970 Water Temp. = 25.5°C

Diffuser submergence, ft.	Air flow rate SCFM/Nozzle	Percent Absorption	Uptake lbs O_2/hr	Brake hp
12.3	11.0	5.6	102.7	65
12.3	11.0	3.6	66.0	65
25.0	12.4	8.2	169.6	140
25.0	12.4	7.7	159.2	140
38.3	13.4	8.2	183.2	230
38.3	13.4	12.3	274.8	232

* Include only the portion of the data for which the air flow rates are comparable with the Passaic and Camden tests.

TABLE 6

SUMMARY OF OXYGEN TRANSFER RESULTS, DIFFUSER AERATOR

Study	Depth of submergence, ft.	Air flow rate-SCFM/Nozzle	Percent absorption standard conditions	R_t Oxygen transfer rate test conditions lbs O_2/hp-hr	R_s Oxygen transfer rate, standard conditions lbs O_2/hp-hr
Passaic	7.0	9.1	3.8	1.33	1.44
	7.7	15.8	2.7	0.92	1.16
	7.9	17.1	3.2	0.95	1.50
	6.5	12.6	2.6	0.95	1.05
Del. at Camden, N.J.	11.0	15.4	4.1	1.35	1.38
	11.2	13.6	5.4	1.21	1.59
	12.8	14.3	5.0	1.08	1.43
	14.2	14.0	6.0	1.29	1.51
	14.2	11.7	5.0	0.94	1.08
	14.4	14.7	5.4	1.23	1.41
	16.9	15.9	5.3	0.96	1.30
Del. at Phil., Pa.	12.3	11.0	5.5	1.58	1.55
	12.3	11.0	3.5	1.02	0.99
	25.0	12.4	6.5	1.21	0.96
	25.0	12.4	6.1	1.14	0.90
	38.3	13.4	8.4	1.18	0.81
	38.3	13.4	5.6	0.80	0.54

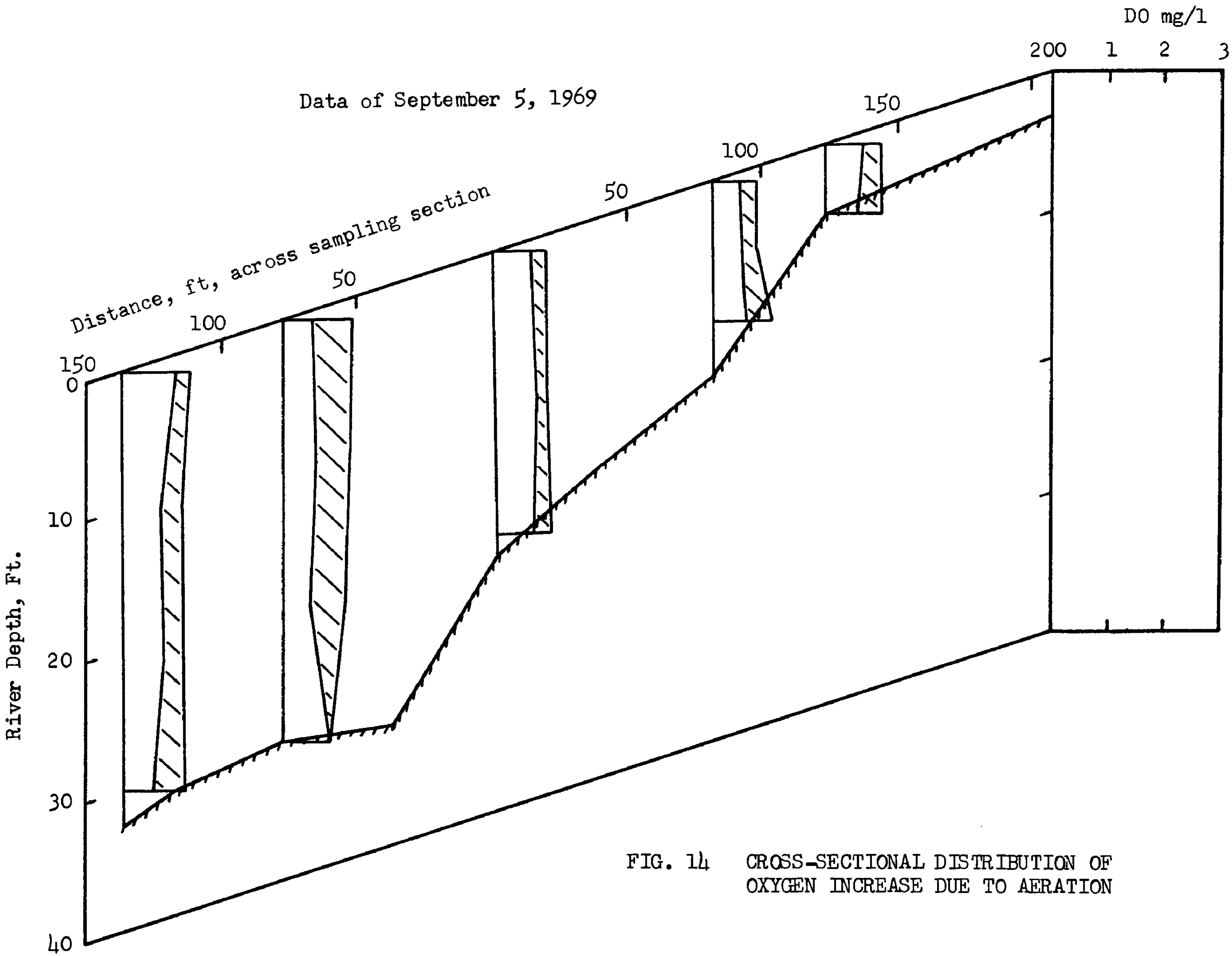


FIG. 14 CROSS-SECTIONAL DISTRIBUTION OF OXYGEN INCREASE DUE TO AERATION

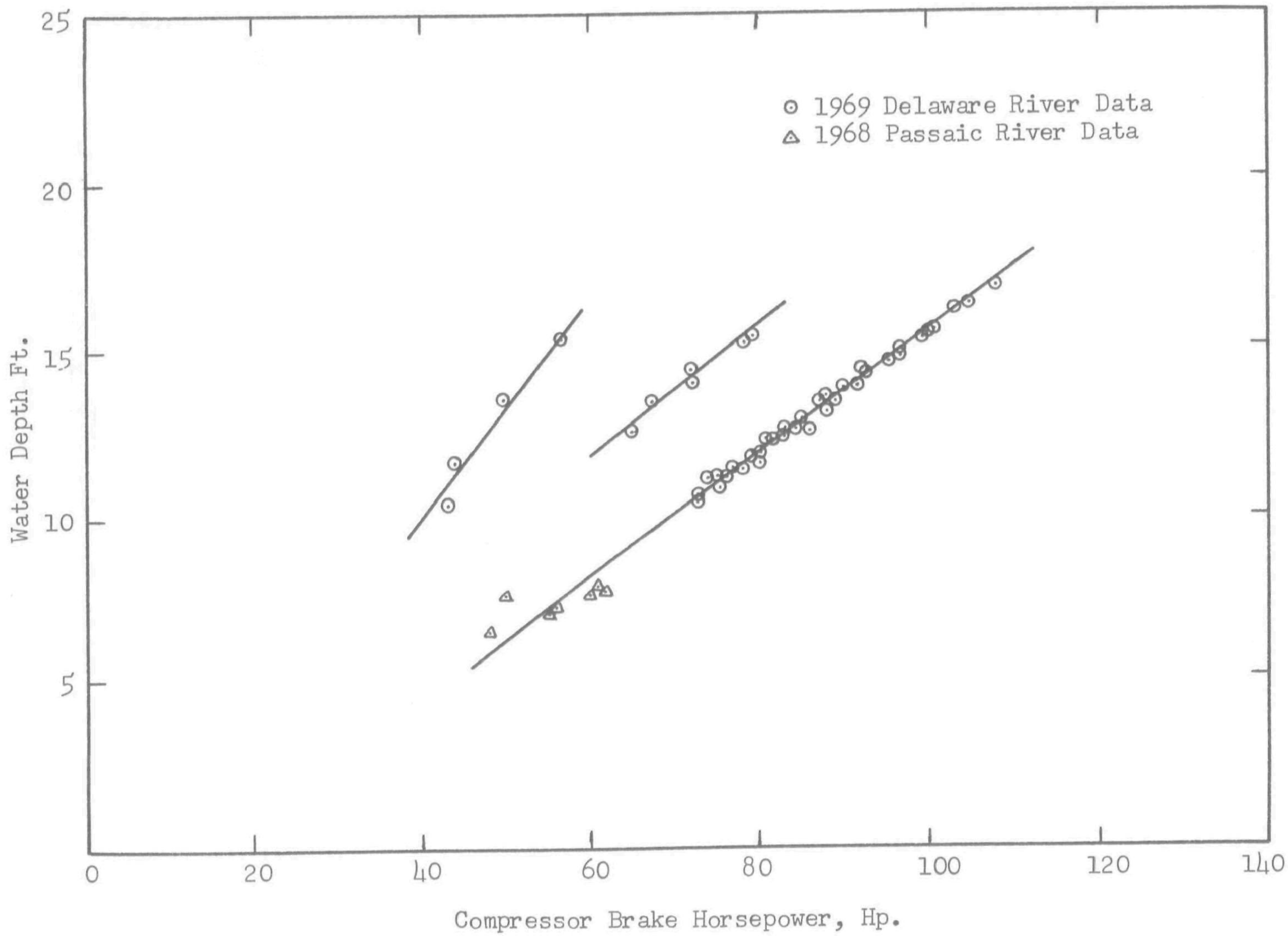


FIG. 15 COMPRESSOR BRAKE HORSEPOWER VS SUBMERGENCE DEPTH FOR DIFFERENT ENGINE SPEED

6.3 percent for a depth of 25 feet; and to 7.0 percent for a depth of 38.3 feet. (2) The variation in oxygen uptake with depth of submergence can be summarized as follows: 68.8 lbs O_2/hr at 7.2 feet; 113.6 lbs O_2/hr at 13.2 feet; 130.3 lbs O_2/hr at 25 feet; and 156.4 lbs O_2/hr at 38.3 feet, all under standard conditions. (3) The power consumption varies linearly with the depth of submergence, with a range of 52 hp at a depth of 6.5 feet, to 232 hp at 38.3 feet. (4) The oxygen transfer rate, R_s, in pounds of oxygen per hp-hr seems to increase somewhat between depths 7 and 15 feet, but decreases materially with further increase in depth. The average transfer rates at various depths are: 1.29 lbs O_2/hp-hr at 7.2 feet; 1.36 lbs O_2/hp-hr at 13.2 feet; 0.93 lbs O_2/hp-hr at 25 feet, and 0.68 lbs O_2/hp-hr at 38.3 feet. Figure 16 illustrates this variation with the depth of submergence.

The oxygen absorption results for diffusers also were compared with results of other studies. Bewtra and Nicholas (9) reported aeration data for both the saran tube and the sparger type diffusers operating in aeration tanks. Their data, for air flow rates ranging between 10 and 15 SCFM per unit, are plotted on Figure 17 against diffuser submergence. The relationship between percent absorption and depth appears to be linear on the log-log paper. For the saran tubes, which have very fine bubbles, the absorption reaches 11% at a depth of 12 feet, while for the spargers, with larger openings, the absorption is 7.5% for the same depth. Also Imhoff (19) used hoses with very fine orifices (between 0.5 and 0.7 mm in diameter) on the lower Ruhr River in West Germany and obtained high absorption rates for depths of 8, 16, and 20 feet. These results are also plotted on Figure 17. To compare the above findings with results of the present study, the Passaic and the Delaware aeration results are plotted on the same figure, and an eye-fit line is drawn to represent the approximate relationship. It is noted that the absorption rates for the Passaic and the Delaware studies are lower than both of the aforementioned two sets of results (see Figure 17). This may be due partly to the larger bubble sizes as a result of the larger openings of the nozzles (5/32 inch) used in the present study, and the fact that most of the tests were conducted in tanks, which would materially reduce the upward velocity of the bubbles.

According to Eckenfelder (13), and Bewtra and Nicholas (9), oxygen absorption is also correlated with the supply air flow rate. However, no apparent relationship was found with the present data. It may be possible that, although the rate of absorption increases with increasing air flow rate, the velocity of the rising bubbles may also increase, resulting in a shorter detention time, and hence less absorption.

Conclusions

1) For the mechanical aerator, an average oxygen transfer rate of 3.06 lbs O_2/hp-hr was obtained on the Delaware River, while for the Passaic River a 2.12 lbs O_2/hp-hr was obtained. The Delaware results, however, should not be considered conclusive due to certain difficulties in taking measurements and small number of experiments.

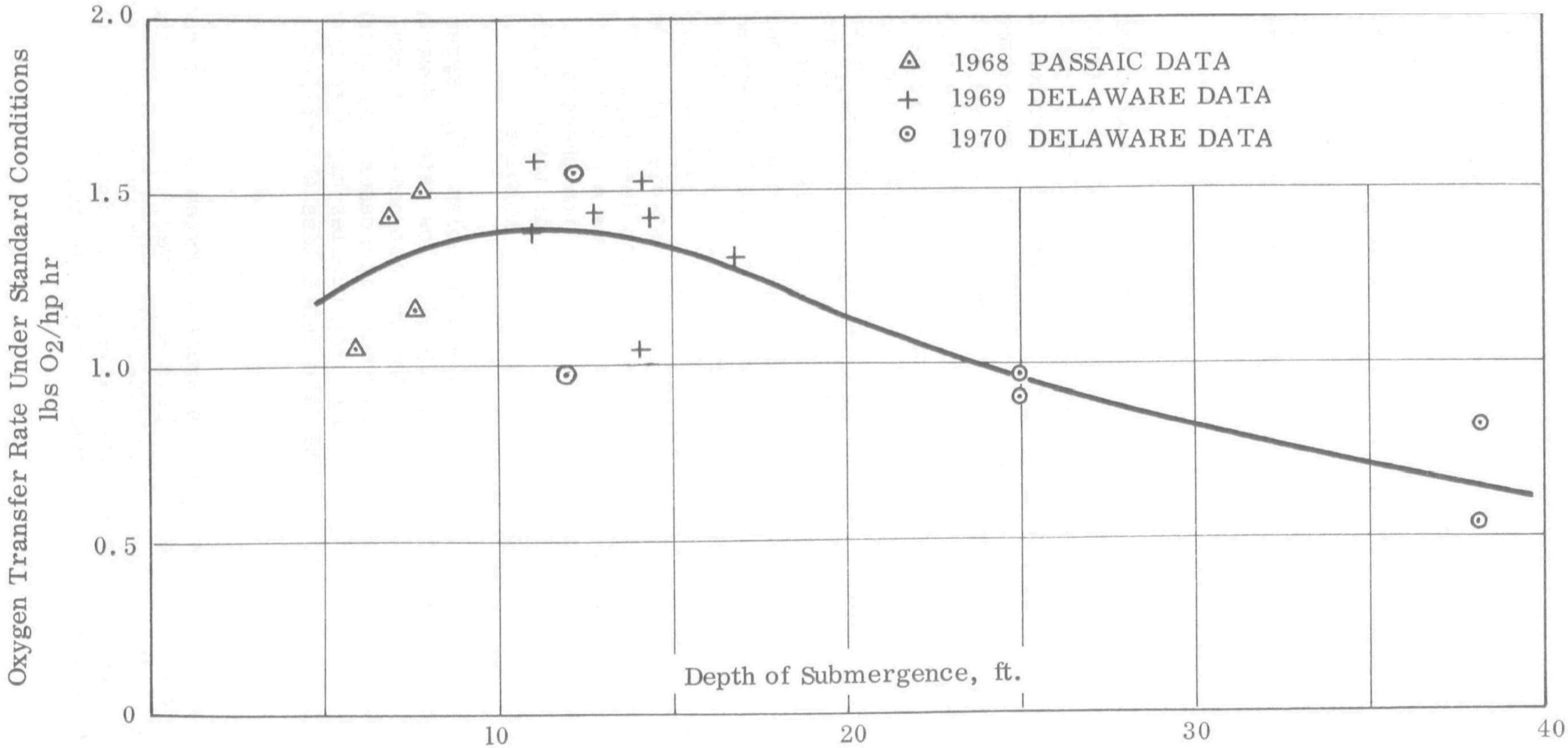


FIG. 16 OXYGEN TRANSFER RATES VS DIFFUSER SUBMERGENCE

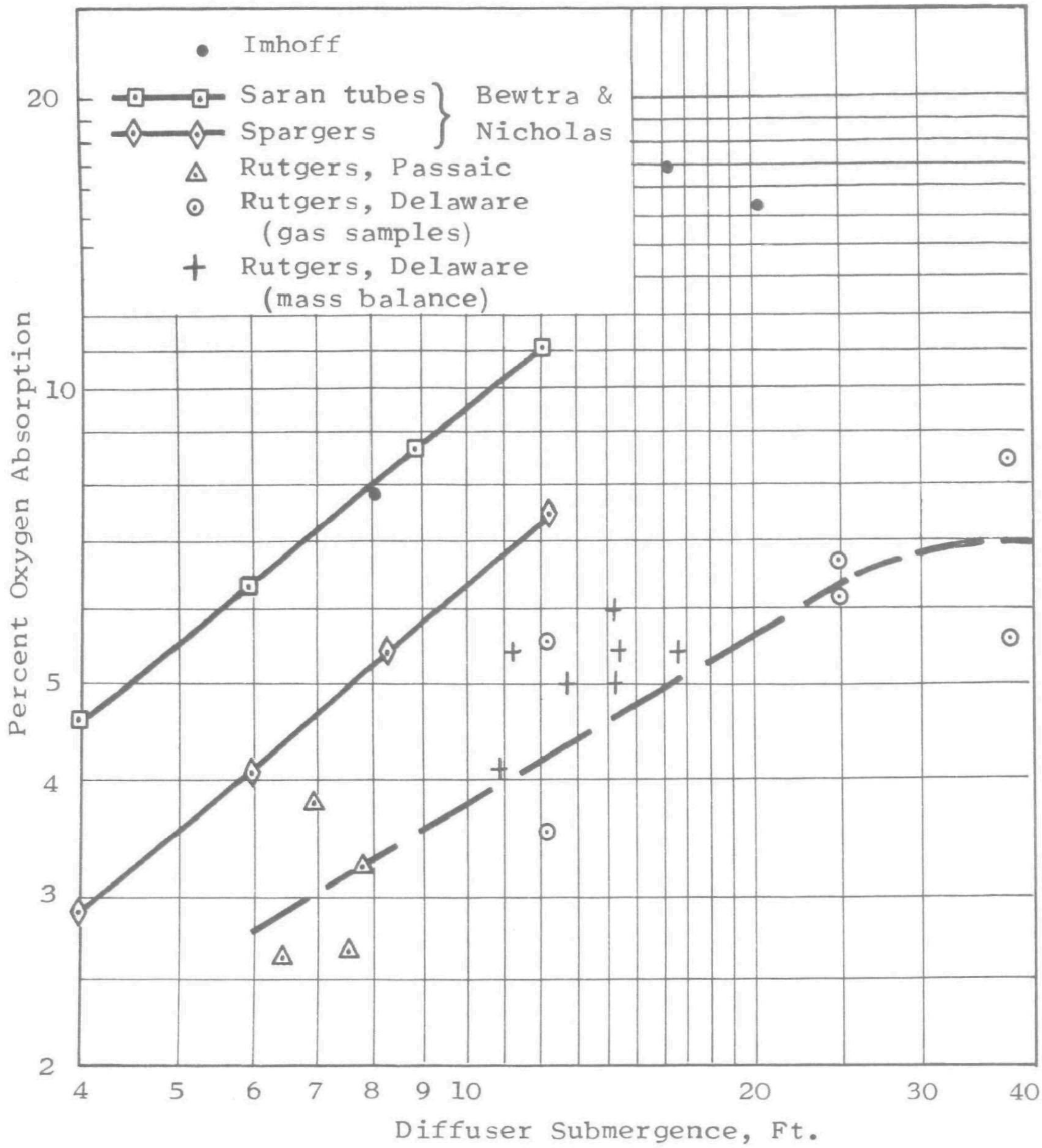


FIG. 17 OXYGEN ABSORPTION VS DIFFUSER SUBMERGENCE
COMPARISON OF RESULTS

2) For the diffuser aerator, the percent oxygen absorption was found to increase significantly with increasing depth of submergence, though not as rapidly as results reported elsewhere for aeration tanks with fine bubble diffusers. The average oxygen absorption increases from 3.8 percent at a depth of 10 feet to 7.0 percent at a depth of 38.3 feet.

3) The oxygen transfer rate for the diffuser aerator was found to decrease generally with increasing water depth, though a slight increase in efficiency appeared to occur between depths of 7 and 16 feet. The transfer rates average about 1.4 lbs O_2/hp-hr at 10 feet depth and about 0.65 lbs O_2/hp-hr at 40 feet depth.

4) The diffuser results indicated generally lower absorption rates than most of those reported in the literature, probably due mainly to the larger bubble sizes, and the free circulation provided by the river.

SECTION IV

DISPERSION ANALYSIS

Introduction

The purpose of the dispersion test was to determine quantitatively the geometry of the aerated plume spreading downstream from the aerator. The importance of this plume geometry becomes apparent when several aerators are to be installed in the same river. Optimal placement of these aerators is dependent upon the dispersion characteristics of the individual aerators. Consequently, to avoid repetitious reaeration of the same slug of river water, it is appropriate to know the aerator dispersion characteristics.

Aeration installations may be subdivided into two categories: (a) aeration from a line source and (b) from a point source. In the first group would exist such schemes as bank-to-bank aeration, wherein the entire width of a stream is aerated. Here, at least initially, the dispersion of the plume is in two spatial dimensions, i.e., the vertical or with depth and the streamwise direction. The second aeration category is exemplified by a single, relatively small aerator unit installed in a much larger river. In this case, the initial stages of dispersion take place spatially in three dimensions, i.e., in the vertical, in the stream direction and in the cross-stream or lateral direction. When, in both of the above instances, the dispersion phenomenon has succeeded in spreading throughout one or more spatial directions, the stages that follow take place in the remaining dimensions. That is, in the first case of line source aeration when the aerated plume has spread throughout the vertical so as to permeate uniformly the entire depth of a stream, the remaining stages of dispersion occur only in the stream direction. This then diminishes the concentration with downstream distance only, all extraneous effects neglected. In the second case, when the aerated plume has spread throughout the depth, the dispersion process occurs in both the streamwise and cross-stream directions. After the cross-stream mixing has been completed, the dispersion process then takes place only in the stream direction.

The dispersion phenomenon is further complicated in the following manner. Immediately after the injection of a dispersing quantity into a stream, the spreading process is dominated by what is termed convective transport phenomena. During this convective period the concentration distributions take on a conspicuous skewness that will be discussed further in the following. This skewness, which initially is quite severe, diminishes until at the end of the convective regime the symmetrical distributions pertaining to one-dimensional diffusion prevail. Once the concentration distributions attain this symmetrical character, their behavior is predicted by the one-dimensional dispersion dispersion model. The different dispersion regimes are illustrated as follows. Consider a stream in which a vertical cross-sectional plane of water oriented perpendicular to the stream direction is instantaneously colored red. Immediately after this injection, the one-dimensional concentration distribution exhibits a decided skewness as shown by Figure 18. In (a) the view is that of a vertical plane parallel to the stream direction; in (b) is pictured the corresponding concentration distributions where $\bar{c}$ is the dye concentration averaged over the cross section of the stream. Ultimately, the concentration distribution exhibits the gaussian shapes predicted by the simple model. Until this occurs, however, the dye cloud spreading phenomenon is convective, and following this interval it becomes dispersive. It is therefore important to arrange the data taking procedures to record the symmetrical gaussian concentration distributions.

Several schemes (see references) have been devised through which the longitudinal dispersion coefficient may be determined. The one employed in the present study is the change of moment method. The results of experiment will determine both quantitatively and qualitatively the dispersion characteristics downstream from aerators in river conditions similar to those encountered in the Delaware River.

Theory for One Dimensional Dispersion Model

The three-dimensional, unsteady conservation-of-mass equation for the dispersion of a conserved quantity will be developed. This is found by decomposing the velocity field and the concentration of our conserved quantity into a time averaged and the fluctuating quantity. Assuming conservation of mass for the mean velocity field, we obtain, in Cartesian form (see Daily & Harlemann, 1966)

$$\frac{\partial \bar{c}}{\partial t} + \bar{u}\frac{\partial \bar{c}}{\partial x} + \bar{v}\frac{\partial \bar{c}}{\partial y} + \bar{w}\frac{\partial \bar{c}}{\partial z} = -\frac{\partial}{\partial x}(\overline{u'c'}) - \frac{\partial}{\partial y}(\overline{v'c'}) - \frac{\partial}{\partial z}(\overline{w'c'}) + D_{AB}\left[\frac{\partial^2 \bar{c}}{\partial x^2} + \frac{\partial^2 \bar{c}}{\partial y^2} + \frac{\partial^2 \bar{c}}{\partial z^2}\right] \tag{1}$$

where $\bar{u}$, $\bar{v}$, $\bar{w}$ are the usual time averaged velocities. The quantity $\bar{c}$ is the time-averaged concentration and D_{AB} is a molecular dispersion coefficient that is assumed uniform and isotropic. Invoking the Fickian dispersion relations:

$$\begin{aligned} \overline{u'c'} &= -E_x\frac{\partial \bar{c}}{\partial x} \\ \overline{v'c'} &= -E_y\frac{\partial \bar{c}}{\partial y} \\ \overline{w'c'} &= -E_z\frac{\partial \bar{c}}{\partial z} \end{aligned} \tag{2}$$

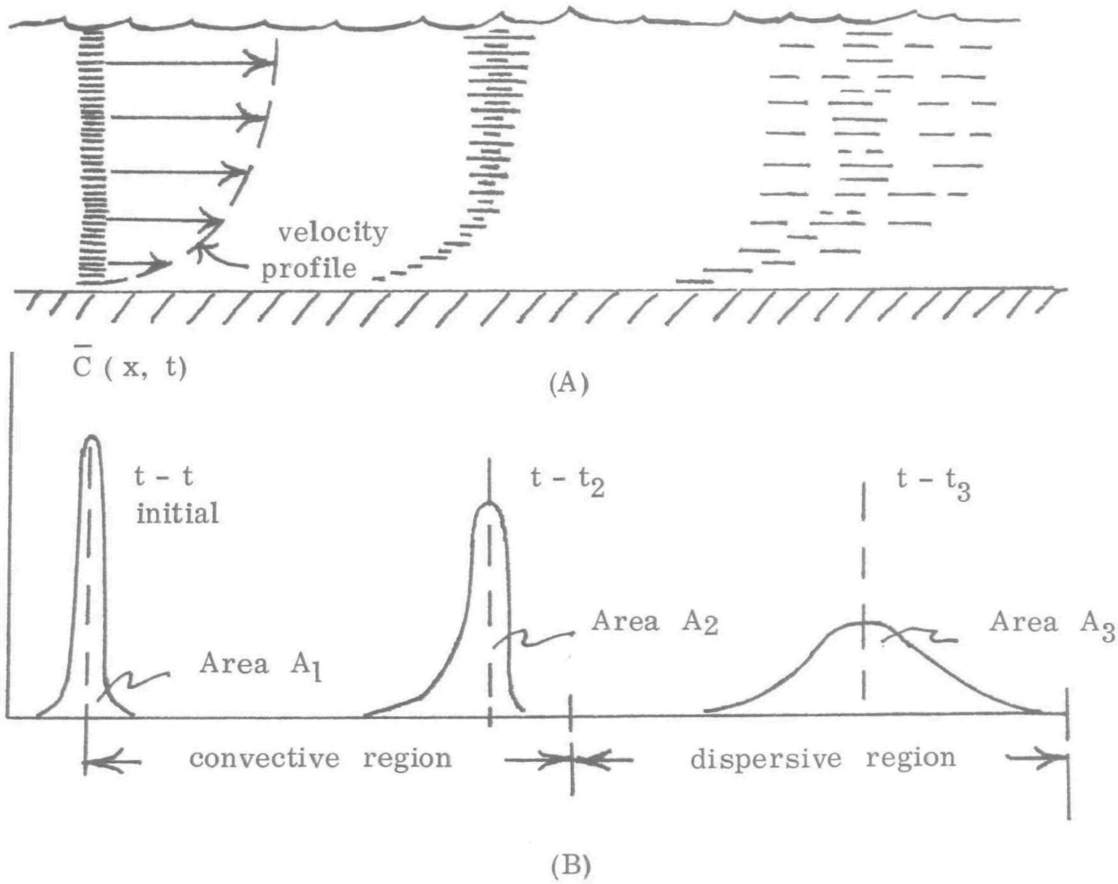


FIG. 18 (A) SKETCH OF DYE PATTERNS IN A STREAM

(B) PLOT OF ONE-DIMENSIONAL UNSTEADY DYE CONCENTRATIONS VS DOWNSTREAM DISTANCE the above equation, dropping the molecular dispersion terms which are dominated by their turbulent dispersion counterparts, becomes

$$\frac{\partial \bar{c}}{\partial t} + u\frac{\partial \bar{c}}{\partial x} + v\frac{\partial \bar{c}}{\partial y} + w\frac{\partial \bar{c}}{\partial z} = \frac{\partial}{\partial x}(E_x\frac{\partial \bar{c}}{\partial x}) + \frac{\partial}{\partial y}(E_y\frac{\partial \bar{c}}{\partial y}) + \frac{\partial}{\partial z}(E_z\frac{\partial \bar{c}}{\partial z}) \tag{3}$$

When $\bar{v} = \bar{w} = 0$ and the turbulent dispersion is characterized solely by the uniform coefficient, E_x, we obtain our one-dimensional model

$$\frac{\partial \bar{c}}{\partial t} + \bar{u}\frac{\partial \bar{c}}{\partial x} = E_x\frac{\partial^2 \bar{c}}{\partial x^2} \tag{4}$$

Boundary conditions for the above equation depend upon the type of injection of the conserved quantity. If, as in the case of the dispersion tests conducted in the present work, the quantity Rhodamine B dye is steadily injected at a prescribed rate the conditions are

$$\int_{-\infty}^{+\infty} \bar{c}(x,t)dx = \int_{-\infty}^{\infty} \bar{c}(x,o)dx = \frac{M}{\rho A}$$

$$\bar{c}(\pm\infty,t) = 0; \; t \geq 0 \tag{5}$$

$$Q_{inject} = \frac{dM}{dt}$$

Solutions to the one-dimensional dispersion model, satisfying the above boundary conditions are given by:

$$\bar{c} = \frac{Q_{inj}}{A\rho(4\pi E_x)^{\frac{1}{2}}} \int_0^t \frac{1}{\sqrt{t-\tau}} e^{\frac{-[x-\bar{U}(t-\tau)]^2}{4E_x(t-\tau)}} d\tau \tag{6}$$

Experimental determination of the coefficient E_x via the method of moments (see H.B. Fischer, 1966) utilizes the transformation:

$$\xi = x - \bar{u}t \tag{7}$$

Substituting this into equation (1) and taking the partial derivative with respect to time, we get

$$\frac{\partial^2 \bar{c}}{\partial t^2} = E_x \frac{\partial^3 \bar{c}}{\partial \xi^2 \partial t} \tag{8}$$

Multiplying by ξ^2 and integrating over all values of ξ produces

$$\int_{-\infty}^{\infty} \frac{\partial^2 \bar{c}}{\partial t^2} \xi^2 d\xi = E_x \int_{-\infty}^{\infty} \frac{\partial^3 \bar{c}}{\partial \xi^2 \partial t} \xi^2 d\xi \tag{9}$$

for constant E_x. Switching the order of operations on the left hand side gives

$$\frac{d}{dt} \int_{-\infty}^{\infty} \frac{\partial \bar{c}}{\partial t} \xi^2 d\xi = 2E_x \int_{-\infty}^{\infty} \frac{\partial \bar{c}}{\partial t} \, d\xi \tag{10}$$

Defining the variance by

$$\sigma_\xi^{\ 2} = \frac{\int_{-\infty}^{\infty} \frac{\partial \bar{c}}{\partial t}\, \xi^2 d\xi}{\int_{-\infty}^{\infty} \frac{\partial \bar{c}}{\partial t}\, d\xi} \tag{11}$$

we obtain the following relationship for E_x:

$$E_x = \frac{1}{2}\,\frac{\Delta\, \tau_\xi^{\ 2}}{\Delta t} \tag{12}$$

Equation (11) may be transformed

$$\sigma_t^{\ 2} = \frac{\int_0^{\infty} t^2\, \frac{d\bar{c}}{dt} dt}{\int_0^{\infty} \frac{d\bar{c}}{dt}\, dt} - \bar{t}^2 \tag{13}$$

where $\bar{t}$ is the mean time:

$$\bar{t} = \frac{\int_0^{\infty} t \frac{d\bar{c}}{dt} dt}{\int_0^{\infty} \frac{d\bar{c}}{dt} dt} \tag{14}$$

The longitudinal dispersion coefficient, E_x will be determined using the relations (12) through (14).

Longitudinal Dispersion

The concentration distributions moving through two stream stations are presented in Figure 19. Differentiating these distributions produces the curves shown in Figure 20. These curves pertain only to the diffuser aerator, as similar data for the mechanical aerator were found to be incomplete due to equipment failures.

Using a computerized moment method, the value of E_x for the diffuser aerator found between the two stream stations in the Delaware River is 8.5×10^6 ft^2/min. While it is true that this value is characteristic of the aerator in the reach of the river under consideration, it is felt that it constitutes a decent first approximation to other reaches in similar rivers.

It is significant to note from Figure 19 and 20 that the concentration levels at the front of the dye cloud move downstream ahead of the mean stream velocity of the cloud. When the dye cloud is assumed to approach the behavior of an aerated plume, it is concluded that the dissolved oxygen level behaves similarly. Hence, an amount of river greater than the mean slug quantity has experienced an increased DO.

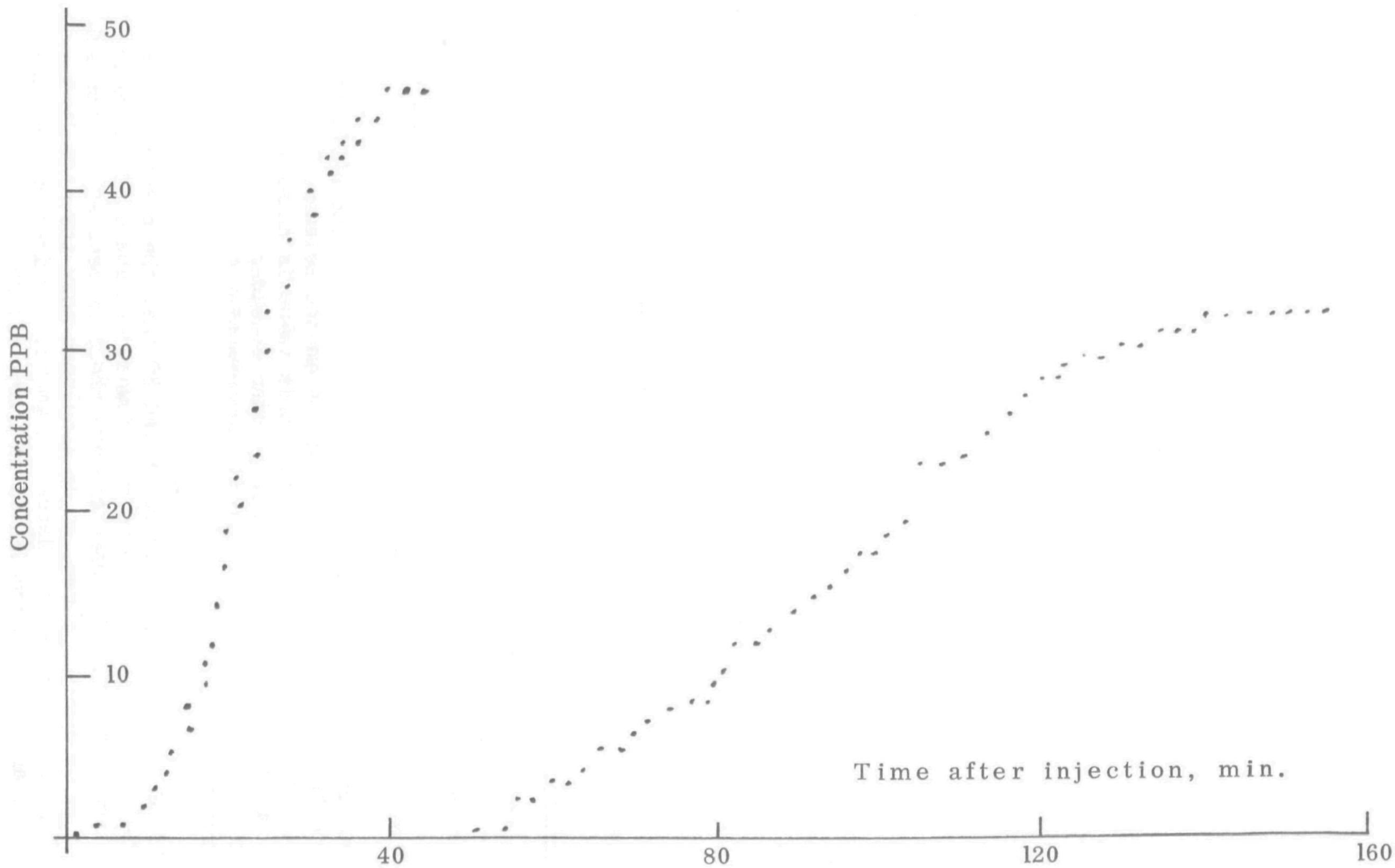


FIG. 19 DYE CLOUD FRONTAL STRUCTURE VS TIME AFTER INJECTION AT TWO STREAM STATIONS

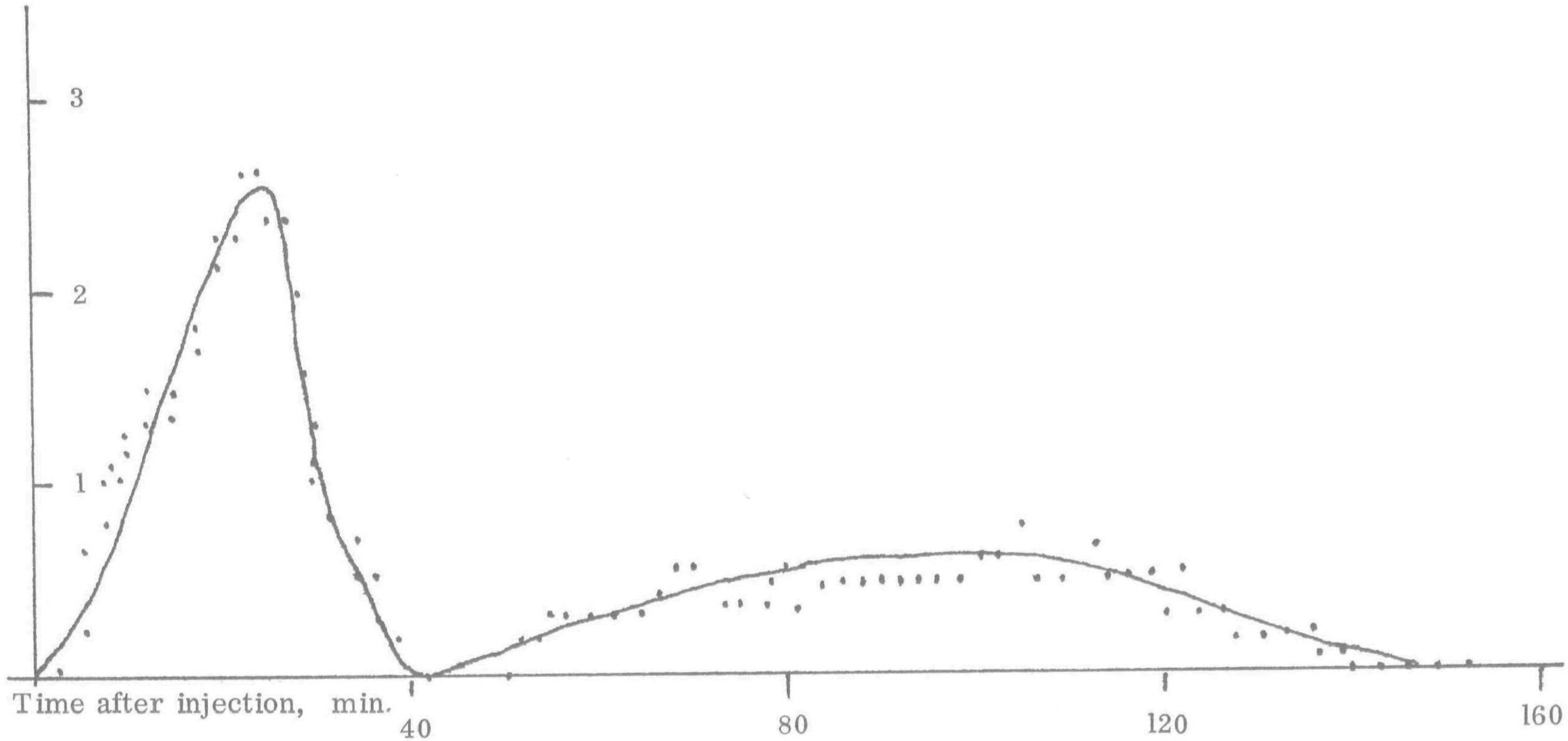


FIG. 20 DIFFERENTIATED DYE CLOUD FRONTAL STRUCTURE VS TIME AFTER INJECTION AT TWO STREAM STATIONS

Considering travel times, specifically, Figure 19 shows that the leading edge precedes the mean of the front by 40% at the upstream station. At the station downstream, the travel time of the leading edge is approximately 25% of the mean travel time.

The magnitude of the longitudinal dispersion coefficient is significant. Previous values available in the literature (Yotsukura, et al, 1970) (32) indicate that naturally a value of 9.6×10^5 $ft^2/min.$, which is the largest yet determined, has been measured in the Missouri River flowing at 33,000 cfs. A value for the Delaware estuary of approximately 160,000 ft^2/min has been determined by Paulson (1969) (28).

That the longitudinal dispersion coefficient determined in the present study is an order of magnitude larger than that which occurs naturally in similar rivers becomes more apparent from the photographs, shown elsewhere in this volume, of the turbulent mixing visible at the river surface over this submerged aerator. It is to be noted that the diffuser aerator installed in the present Delaware test was oriented at an angle of about 45° with the New Jersey shore. In this configuration it presented a projected length of only 40 feet normal to the flow of the river. The speculation is therefore put forth that were it oriented normal to the river flow, the longitudinal dispersion phenomena would have been even more pronounced. Such a violent turbulent mixing is of course associated with the large air bubbles emitted by the diffuser nozzles. A small bubble diffuser, therefore, might not give rise to dispersion coefficients of the size presently determined. However, the smaller bubbles would rise more slowly to the surface and hence would enable an increased DO to be attained by the affected river water. Obviously, both bubble size, oxygen transfer, and dispersion characteristics have to be considered together in the final analysis of river aeration.

Transverse Dispersion

Because it is important for the optimal installation of multiple aerators in the same river, an estimate is obtained for the extent of transverse mixing downstream of the diffuser aerator. With the collected data for the dye cloud geometry, a curve-fitting technique is employed wherein the cross-stream dispersion is predicted as a function of downstream distance. However, based upon visual observation of the spreading dye, the lateral dispersion of the two types of aerator may be considered approximately the same.

It is assumed here that complete vertical mixing has taken place and that further mixing occurs only in the cross-stream direction and longitudinally. Furthermore, it is assumed that cross-stream mixing occurs monotonically in the downstream direction. To insure this monotonicity, an exponential relationship of the following form is assumed:

$$A = a + b(1 - e^{-x}) + c(1 - e^{-x})^2 \qquad (15)$$

where A and x are the non-dimensionalized, cross-sectional area normal to the stream direction, and the downstream direction, respectively. The normalizing quantities are $A_o = 12{,}000$ ft^2 and $x_o = 1000$ ft. The coefficients a, b, and c are non-dimensional constants evaluated using cross-sectional areas depicted by the dye cloud at three downstream stations. These are shown in Figure 21. Numerically, the constants are found to be

$$a = 0.0666$$
$$b = 1.1993$$
$$c = -0.2756$$

These values enable the calculation of the graphical results presented in Figure 22. From these results a percentage of reaeration can be obtained which is hyperbolic in nature. Using this as an estimate one is able to determine the amount of aerated water that is reaerated downstream by subsequent aerators. Specifically, if two diffuser aerators were aligned one directly upstream of the other at 400 feet distance, it may be estimated that 16% of the aerated water from the first would pass through the second. At greater distances the percentage would be less.

Conclusions

The results of the dispersion experiment conducted for the diffuser aerator in the Delaware River verify the highly dispersive effects that exist downstream of this type of device. Quantitatively, the longitudinal dispersion coefficient determined using a one-dimensional moment method is 8.5×10^6 ft^2/min. This value is an order of magnitude larger than the largest "natural" coefficient measured to date. It is apparent that the violent, turbulent, mixing motions initiated in this river by this type of artificial aeration are responsible for this large value. In addition, judging by the relatively symmetric concentration distribution shown in Figure 20 at the upstream station, the convective regime behind this aerator is quite short. The convective region which occurs naturally is much longer, and in Ref. (32) stated to be of the order of tens of miles.

In view of this large dispersion coefficient found downstream of this diffuser it is felt that a smaller bubble diffuser might well have a smaller longitudinal dispersion coefficient. However, it is also felt that the small bubble diffuser would inject an increased amount of oxygen per hp-hr into the river. As a result, it is concluded that future analyses pertaining to varying bubble size include both of these factors. Undoubtedly, the violent turbulent mixing motions which exist downstream of the diffuser aerator are due to the circulatory fluid dynamics produced by the rising bubbles interacting with the river velocities. Needless to add, this is an extremely complicated phenomenon to document in detail. The present results pertain specifically to time and space averaged ramification of these detailed features. As a consequence, the extrapolation of the present to other situations should be done with care and consideration of these factors.

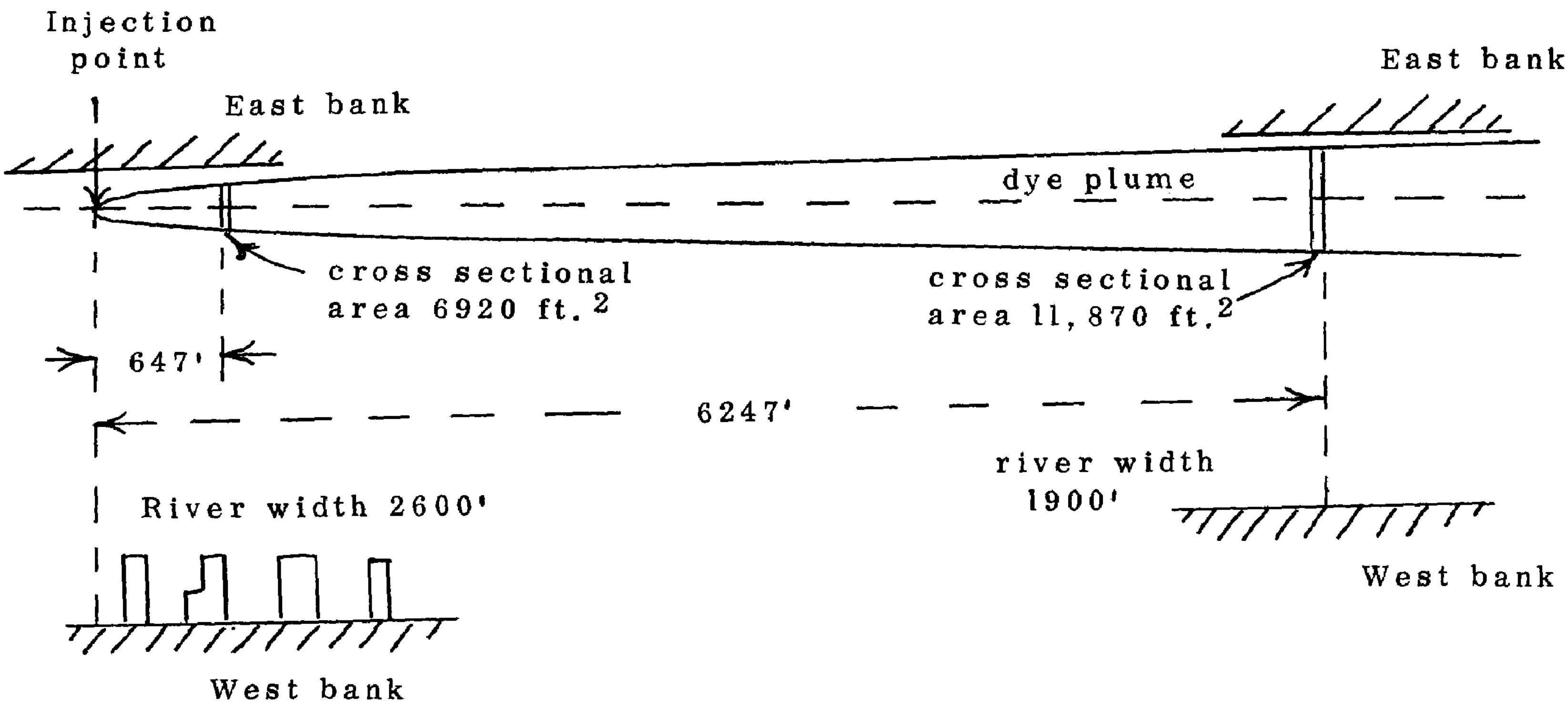


FIG. 21 STREAM CROSS - SECTIONAL AREA AFFECTED BY THE DIFFUSION AERATOR VS DOWNSTREAM DISTANCE

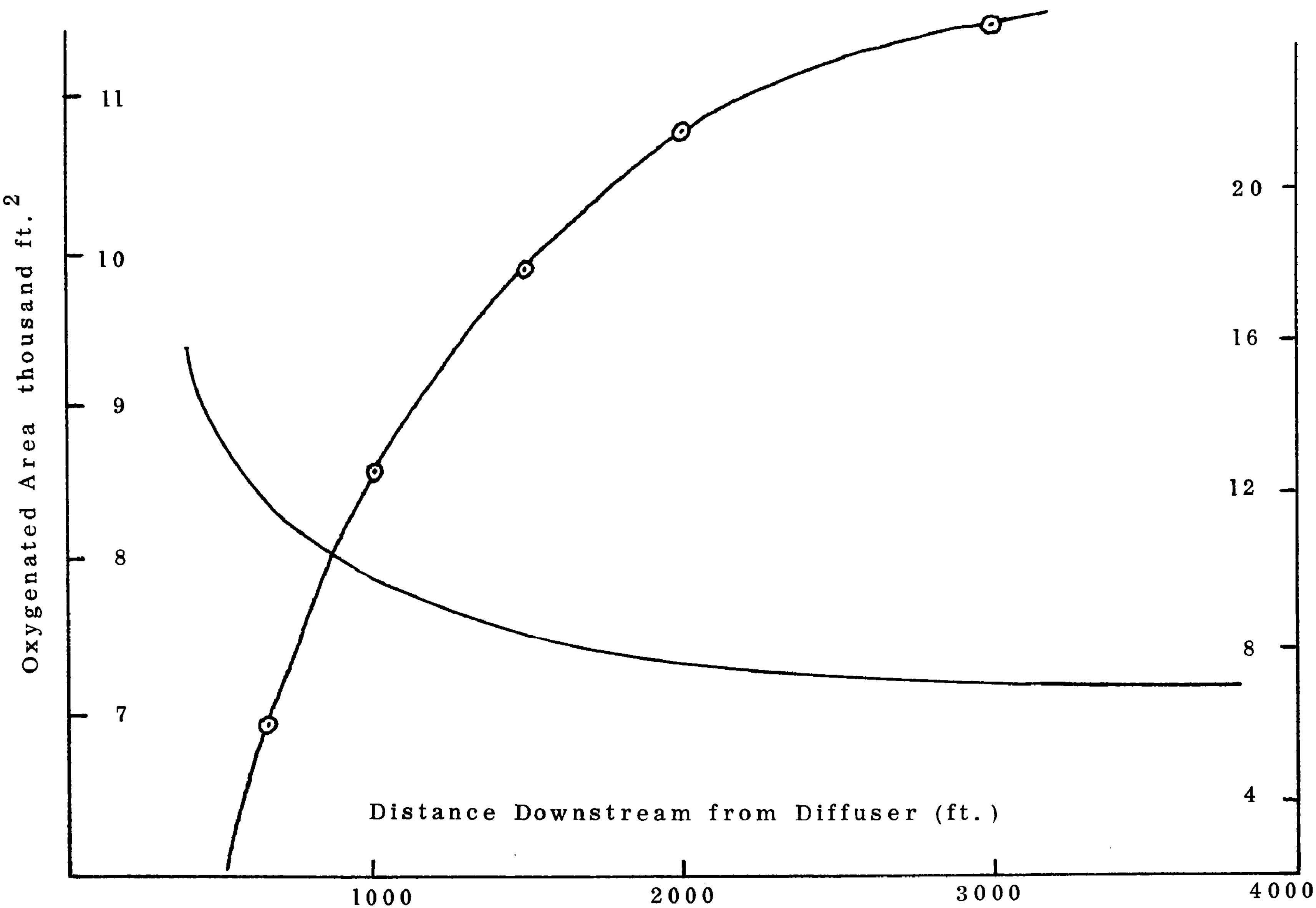


FIG. 22 GRAPHICAL RESULTS OF CROSS-SECTIONAL AREA DISTRIBUTION AND REAERATION PERCENTAGE VS DOWNSTREAM DIRECTION

Because of the large longitudinal dispersion coefficient, the diffuser aerator actually supplies dissolved oxygen to a segment of river larger than the slug described by the mean river velocity. With regard to the times of travel at the two stream stations, the leading edge of the dye cloud exceeds the mean travel time by 40% and 25%, respectively.

The cross-stream dispersion that occurs downstream of the diffuser aerator is approximated from the available dye data. Intuitively assuming a monotonically increasing distribution with downstream direction, the dependence of aerated cross-sectional area upon distance is

$$A = a + b(1 - e^{-x}) + c(1 - e^{-x})^2 \qquad (16)$$

where

$$a = 0.0666$$
$$b = 1.1993$$
$$c = -0.2756$$

Using this result the amount of reaeration which occurs with aerators placed in the aerated plumes of upstream aerators may be predicted using the results presented in Figure 22. The distribution found is hyperbolic. This leads to the conclusion that the time required to increase the DO level above that of the ambient at the outer edge of the plume at the downstream station may now be estimated. However, this equation should not be used to extrapolate dispersion results beyond the reach actually measured.

To approximate the distance required for the dye to spread throughout the width of the stream, we assume that natural dispersion processes prevail below the 6247 foot station. From reference 23, the downstream distance estimated for the beginning of the dispersive region (see Figure 18)

$$x \leq 1.8 \frac{\bar{u}}{u_*} \frac{B^2}{Y_n}$$

The distance required is x; $\bar{u}$ is the average velocity; u_* is the frictional velocity; B is the transverse width of spreading; and Y_n is the average channel depth. Substituting the values for the Delaware: $\bar{u}$ = 1.27 ft/sec; $u_* = \sqrt{gY_nS}$ = 1.86 ft/sec where g = 32.2 ft/sec; Y_n = 40 ft; S the slope determined from discharge, area, and hydraulic radius; and B = 1500 ft, which is transverse distance from the west edge of the plume to the west shore. The above equations produce

$$x \leq 12.8 \text{ miles}$$

This is the approximate distance from the 6247 foot station required for non-tidal natural dispersion to spread the cloud of dye across the width of the river. However, when tidal effects are incorporated, this distance decreases. Through a simple proportion, the distance required for the cloud to spread to the center of the river would be $x_{1/2}$ = 4.5

miles (see Figure 21). Both distances, x and $x_{1/2}$, are relative to the 6247 foot stream station. As a result, the distance downstream of the aerator required for the dye cloud to reach the west shore is 14.0 miles assuming that only natural non-tidal dispersion takes place below the 6247 foot station. The distance required for the dye to reach the stream center would be 5.7 miles given the same assumptions.

SECTION V

DELAWARE AERATION SYSTEM ANALYSIS

Objectives

The feasibility of the application of instream aeration to meet dissolved oxygen standards on the Delaware Estuary is examined in Sections V and VI. In this section a systems analysis is carried out to estimate the amount of oxygen input required to raise the existing DO level to a specific, desired level.

Various desired DO levels have been suggested for the Delaware Estuary (7). In this analysis it is assumed that the present DO level will be maintained at no less than 3 mg/l by treatment, and that a further improvement to a minimum level of 4 mg/l is to be achieved by instream aeration.

The Delaware Estuary has been intensively studied by the Environmental Protection Agency, the Delaware River Basin Commission and others; and reference has been made to various published and unpublished results in order to relate the present analysis to what has been done previously.

The Critical Region

The estuary between Trenton and Liston Point is divided into 30 sections, the length of which being either 10,000 feet or 20,000 feet, except section one, which is assumed to be 21,000 feet long, as described by Pence *et al* (35).

The critical region is designated as the region in which the present DO levels are below 3 mg/l. The region was determined by using the isovariate plot of dissolved oxygen for 1964 loading conditions. Two critical fresh water flows were investigated; namely, a 1-in-25 year low flow and a 6000 cfs minimum flow assumed to be provided by an upstream reservoir system. For details, see Pence *et al* (35).

Composite DO profiles for the months June through September, derived from these figures are plotted in Figure 23. For the 1-in-25 year low flow, the critical region includes Sections 10 through 20, while for the 6000 cfs minimum flow it includes Sections 12 through 21. To obtain a conservative estimate of the oxygen input required, it was decided to consider Sections 10 through 21 as the critical region that required instream aeration. As can be seen in Figure 23, the present DO levels in Sections 9, 22, and 23 are lower than the desired 4 mg/l, and thus require aeration. However, the actual DO profile to be raised by advanced treatment will undoubtedly extend beyond the critical region making it unnecessary to add oxygen to those sections.

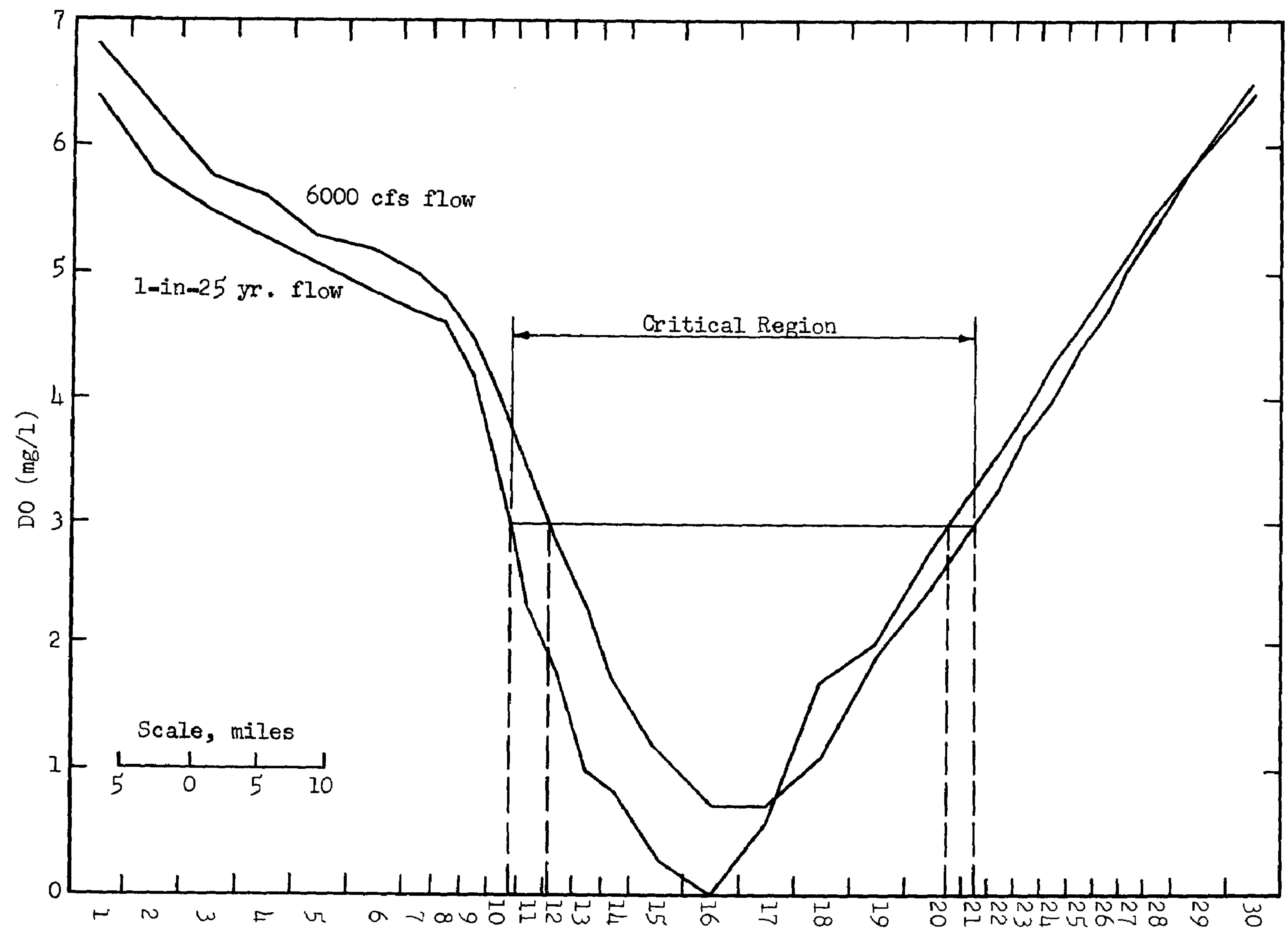


FIG. 23 ESTUARY SECTIONS, COMPOSITE D.O. PROFILE
June Through September, Delaware River
Based on 1-in-25 Year and 6,000 CFS Minimum Flow at Trenton

Oxygen Mass Balance in a Section

Following procedures of Pence et al (35), any section i can be represented by a free body, as shown in Figure 24. Mathematically, the oxygen mass balance in the section can be expressed as (35):

$$\underbrace{Q_{i-1,i}[\xi_{i-1,i}C_{i-1} + (1-\xi_{i-1,i})C_i] + E_{i-1,i}(C_{i-1}-C_i) + E_{i,i+1}(C_{i+1}-C_i)}_{\text{oxygen entering section}}$$

$$+ \underbrace{r_i\overline{V}_i(C_s-C_i)}_{\text{natural aeration}} \underbrace{-d_iL_i}_{\text{BOD consumption}} = \underbrace{Q_{i,i+1}[\xi_{i,i+1}C_i + (1-\xi_{i,i+1})C_{i+1}] \pm S_i}_{\text{oxygen leaving section}}$$

in which

- i = 1, 2, 3....n and i-1 = upstream, i+1 = downstream
- L = ultimate carbonaceous BOD demand
- Q = net flow from section to section
- $\overline{V}$ = volume of section
- ξ = an advection coefficient due to tidal motion
- E = an eddy exchange coefficient
- d = the decay rate of BOD
- C_s = saturation DO concentration
- C_i = DO concentration in section i
- r = atmospheric reaeration coefficient; and
- S = other sources or sinks of oxygen.

In this analysis the following assumptions were made to obtain approximate estimates of oxygen required:

1) $Q_{i-1,i} = Q_{i,\ i+1}$, i.e. constant flow

2) $C_{i-1} = C_{i+1} = C_i$, i.e. uniform DO level

3) $\xi_{i-1,\ i} = \xi_{i,\ i+1}$, i.e. constant advective coefficient

Equation 1 is then simplified to:

$$r_i\overline{V}_i(C_s - C_i) = d_iL_i \pm S_i \qquad (2)$$

Now if the DO level is to be raised artificially from 3 mg/l to 4 mg/l in the critical region, the reduction in natural reaeration must be supplemented by instream aeration in order to maintain the higher DO level.

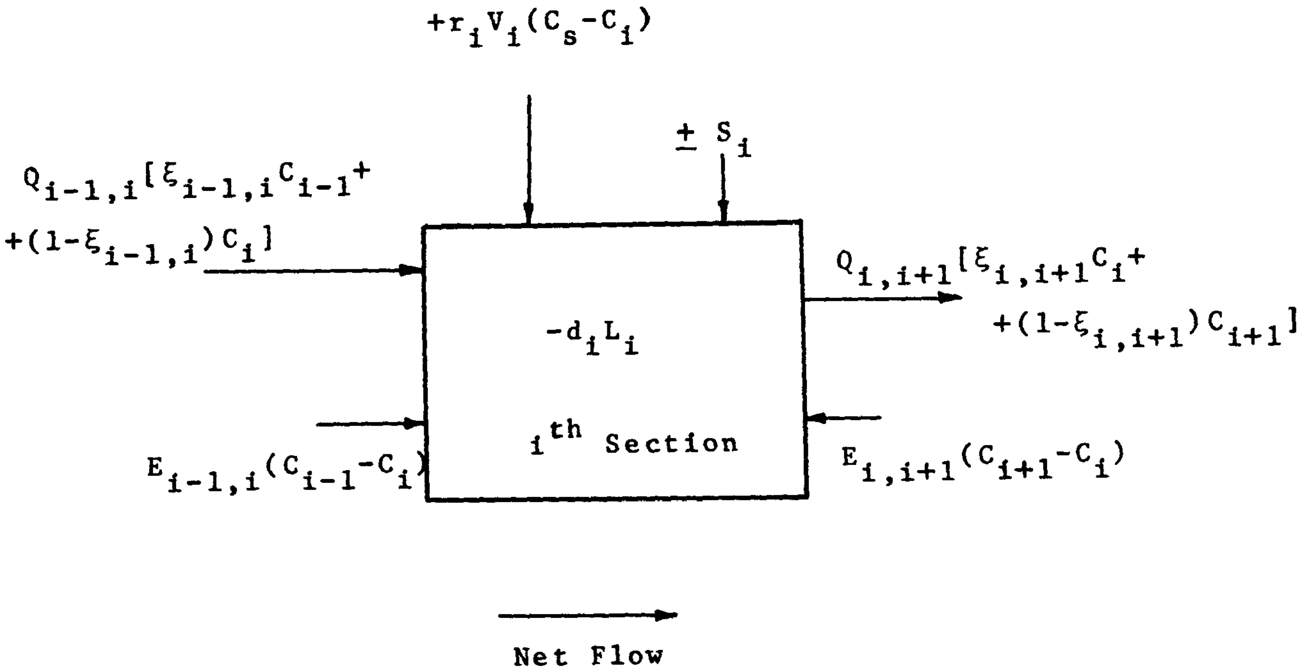


FIG. 24 OXYGEN MASS BALANCE ON SECTION i
(After Pence *et al.*)

But S_i remains unchanged.

Therefore

$$r_i\overline{V}_i(C_s - 3) - r_i\overline{V}_i(C_s - 4) = N_i \quad (3)$$

where

N_i = oxygen required from instream aeration.

Thus

$$N_i = B\overline{V}_i(1)r_i \quad (4)$$

where

B = a units conversion constant.

In order to allow a DO sag after the oxygen level is raised to 4 mg/l, and also to account for the effect of dispersion, the oxygen required, N_i, was computed for a DO raise from 3 mg/l to 4½ mg/l, by the following equation:

$$N_i = B\overline{V}_i(1.5)r_i \quad (5)$$

where

N_i is in lbs O_2/day

$\overline{V}_i$ in liters, and

$B = 2.2046 \times 10^{-6}$

Data for the hydraulic geometry and atmospheric reaeration coefficient were obtained from the EPA office in Metuchen, N.J. The results as to oxygen required are listed in Table 7. The computation gave a total required oxygen input of 304,869 lbs/day for sections 10 through 21. Since the Delaware Estuary is tidal, with tidal flows far in excess of flows due to net discharge, additional net discharges up to 6000 cfs do not correspond to materially increased BOD loads or oxygen requirements, and, from Figure 23, it appears that the critical period is the period of extreme low flow. For purposes of computation the total area affected by either period was included.

As described earlier in Section III of this report, Table 2, the actual oxygen transfer rates of the diffuser aerator for raising DO from 3.0 to 4.5 mg/l are as follows:

At 20 ft	3240 lbs O_2/day
25 ft	3530 lbs O_2/day
40 ft	4580 lbs O_2/day

TABLE 7

COMPUTATION OF OXYGEN REQUIRED TO MAINTAIN A 4 MG/L D.O. LEVEL IN THE CRITICAL REGION

i Section	r 1/day	Volume liters x 10^6	N* lbs O_2/day
10	.14	20,700	9,581
11	.14	19,794	9,161
12	.10	19,057	6,300
13	.10	17,642	5,832
14	.16	21,606	11,429
15	.16	56,209	29,732
16	.23	58,446	44,441
17	.16	70,566	37,327
18	.15	84,866	42,085
19	.15	90,728	44,992
20	.11	108,992	39,636
21	.16	56,039	24,353
		Total	304,869

* $N = 2.2046 \times 10^{-6}(V)(1.5)r$

This diffuser is 80 feet long, with 160 nozzles. Based on the above efficiencies, the number of the diffusers required to supply the oxygen demand was computed for each section for the three depths of submergence. The results are given in Table 8.

Comparison with DECS Report

In a tidal estuary, the effect of adding oxygen at one section will not be confined to the section volume alone, but will spread to both upstream and downstream sections due to tidal mixing and dispersion. The DECS Report (6) has presented a "response matrix," which gives the responses in DO increase in all the sections due to an input of 10,000 lbs/day of oxygen at any section. Since the DECS model was based on the general equation of the form of Equation 1, it was intended to compare the results of this study with those computed by the DECS model. If placed at 25 foot depth, a total of 91 such diffusers would be required. However, as is brought out in the next section, design considerations will vary the type of aerator used, so that this result is only illustrative.

To compare the above results with those computed by the DECS model (36), the actual oxygen input at each section was first calculated, based on the number of aerators placed at 20 foot depth as indicated in Table 8. The oxygen input vector was then multiplied with the DECS response matrix, to give the actual DO increase in each section. The results are listed in Table 9.

The system results based upon the present approach (treating each section separately) are not much different from those of the DECS model. The latter shows a considerable dispersion of oxygenation effects to adjacent sections, which is undoubtedly realistic, about 16% less aggregate dissolved oxygen response, which is presumably due to differences in the approach used. The total additional oxygen demand obtained by the methods of this study should be conservative, since it provides enough oxygen to maintain a mean level of 4.5 mg/l throughout the entire critical regions, which would correspond to local levels of over 5 mg/l at aerators and minimums of 4 mg/l in the middle of the stream. There seems no reason to believe that the aeration process itself would accentuate either the normal or benthic BOD demands, under situations given. If natural aeration is affected at all, other than by the reduction of the oxygen deficit, it would be increased.

As will be discussed in the next section, it is unlikely that such a large difference as 1.0 mg/l will be required. Small indicated deficiencies of the DO level below the required norm towards the ends of the critical region are not of significance, because a treatment program which establishes minimum levels of 3 mg/l in that part of the river would not result in a quantum jump at the ends of the critical region but in a gradual slope or sag curve. The results of the aeration program could more easily be adjusted to such a sag curve than to the assumed step profile.

TABLE 8

DIFFUSER AERATION SYSTEM DESIGN - AN EXAMPLE

Section	Oxygen required to maintain 4 mg/l lbs/day	Number of 80' diffusers needed			Remarks
		If placed at 20' depth	If placed at 25' depth	If placed at 40' depth	
10	9,581	3	3	3	(1) At 20' the diffuser transfers 1.09 lbs O_2/hp hr at a brake hp of 124 hp; this gives 3240 lbs O_2/day.
11	9,161	3	3	2	
12	6,300	2	2	2	
13	5,832	2	2	2	
14	11,429	4	4	3	
15	29,732	10	9	7	(2) At 25' the diffuser transfers 0.98 lbs O_2/hp hr at a brake hp of 150 hp; this gives 3530 lbs O_2/day.
16	44,441	14	13	10	
17	37,327	12	11	9	
18	42,085	13	12	10	
19	44,992	14	13	10	
20	39,636	13	12	9	(3) At 40' the diffuser transfers 0.83 lbs O_2/hp hr at a brake hp of 230 hp; this gives 4580 lbs O_2/day.
21	24,353	8	7	6	
	Total	98	91	73	(4) All for a temp. of $25^{o}C$ and average d.o. 375 mg/l.

TABLE 9

COMPARISON OF THE OXYGEN INCREASE DUE TO THE PRESENT DESIGN AND THAT BASED ON DECS D.O. RESPONSE MATRIX

Section	Number of diffusers	Oxygen input lbs O2/day	Oxygen increase mg/l	Oxygen increase based on DECS response matrix mg/l
1 - 6	---	---	---	---
7	---	---	---	0.01
8	---	---	---	0.07
9	---	---	---	0.23
10	3	9,720	1.52	0.56
11	3	9,720	1.59	0.77
12	2	6,480	1.54	0.90
13	2	6,480	1.67	1.00
14	4	12,960	1.70	1.10
15	10	32,400	1.63	1.23
16	14	45,360	1.53	1.34
17	12	38,880	1.56	1.43
18	13	42,120	1.50	1.48
19	14	45,360	1.51	1.41
20	13	42,120	1.59	1.21
21	8	25,920	1.60	0.87
22	---	---	---	0.65
23	---	---	---	0.49
24	---	---	---	0.37
25	---	---	---	0.28
26	---	---	---	0.21
27	---	---	---	0.15
28	---	---	---	0.11
29	---	---	---	0.06
30	---	---	---	0.02

SECTION VI

DESIGN AND COST CONSIDERATIONS

The area of oxygen deficiency on the Delaware River, extends over a distance of about 40 miles, including extensive port area developments, heavy industrial sites, the Philadelphia Navy Yard and other developed water front. The river is generally from 2000 feet to 2500 feet wide above the confluence with the Schuylkill, and wider below this point; and it has been extensively dredged, with a 40-foot main channel and 30-foot anchorage areas.

Since passage of anadromous fish is an important consideration on the Delaware, consideration was given initially to the possibility of providing adequate oxygen only along the lesser developed New Jersey shore, in order to provide for assured fish passage at minimum cost. However, experiments with the young of shad and striped bass have now shown that these fish do not immediately perceive water of deficient oxygen; and when suffocation begins they react randomly, being as likely as not to swim deeper into the oxygen-deficient area (37). Moreover, legally adopted water quality standards apply to the river as a whole. Accordingly, it is accepted as basic that supplemental oxygenation must be effective throughout the entire river cross-section.

Spacing of Aerators

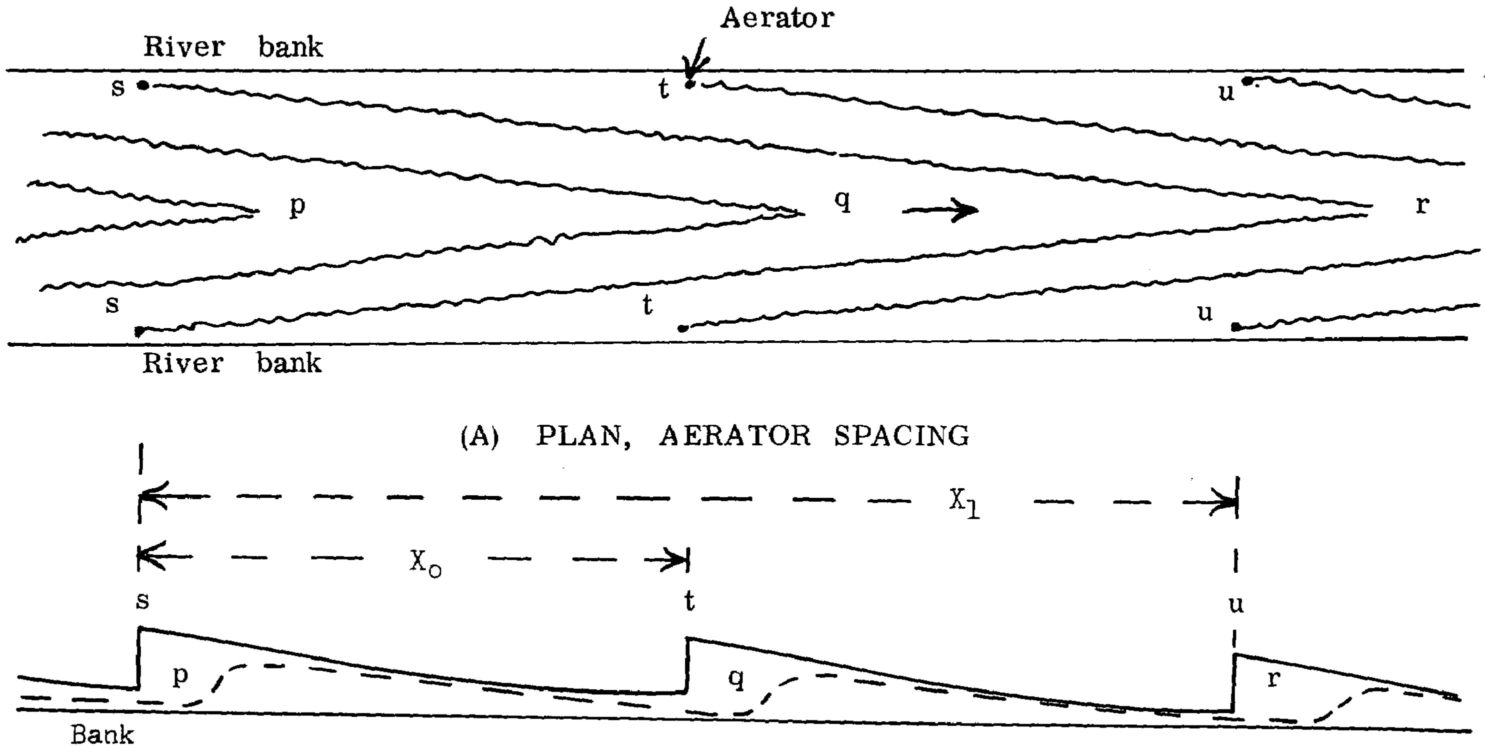
Figure 25 shows schematically a system of aerator sites evenly spaced on each side of a river. Five-day BOD values during summer periods are currently about 5 mg/l, and dissolved oxygen falls at times to below 1.0 mg/l. However, it is not intended that oxygenation be applied to present conditions, but be used in combination with added effluent treatment, which will reduce prevailing levels of BOD from the present values of about 5.0 mg/l (5 day) to perhaps 4.0 mg/l. If the influence of various sources and sinks of aeration is assumed unchanged by river aeration or degree of effluent treatment, the steady-state condition to be satisfied in a section where DO level remains level, based upon the usual first order relationship, is the following

$$K_2 \, (C_s - C) = K_1 L \qquad (1)$$

where K_2 is aeration coefficient, C_s is oxygen saturation of water, C is actual DO level, K_1 is BOD removal coefficient and L is BOD (ultimate). If aeration raises DO level C temporarily to C', mg/l, a corresponding expression will be

$$dc/dt = K_2 \, (C_s - C') - K_1 L \qquad (2)$$

$$\text{or} \quad K_2 \, (C_s - C') = K_1 L - dc/dt \qquad (3)$$



(A) PLAN, AERATOR SPACING

(B) DISSOLVED OXYGEN PROFILE

FIG. 25 DISSOLVED OXYGEN DISPERSION

Dividing Eq. (3) by Eq. (1) we obtain

$$\frac{C_S - C'}{C_S - C} = \frac{K_1 L - dc/dt}{K_1 L} \qquad (4)$$

Substituting values of $C_S = 8.17$, $C' = 4.5$, $C = 3.0$, $K_1 = 0.37$, and $L = 1.5 \times$ 5-day BOD $= 6.0$

Eq. (4) may be reduced to give

$$dc/dt = 0.645 \text{ mg/l} \quad 1 \text{ day}$$

Therefore the rate at which DO will decline after the aeration to 4.5 mg/l will be 0.645 mg/l per day. The aeration of water at the aerator site to a DO of 4.5 mg/l, at a time when the river as a whole was slightly above 4.0, would be immediately subject to dilution effects during the dispersion process. The actual reduction in DO concentration would be a complex variable depending upon dilution as well as natural aeration and biochemical action. As an approximation it may be assumed that the process is represented by a dilution reducing the DO immediately to 4.25 mg/l, followed by reduction by aeration and biochemical processes only, at the rate of 0.645 mg/l/day.

If spacing of aerator sites is assumed to be not over 2.0 miles, the basic design condition will be an oxygenated plume from one site dispersing to the center of the river, a distance of 5.45 miles, at a rate of 1.27 ft/sec, and thereafter flowing another 2.0 miles until the next oxygenated plume arrived. Application of Eq. (4) indicates that DO would decline by 0.24 mg/l during this movement. An alternative assumption is that flow near the bank, during periods of low tide, might be only one half of that actually observed, or 0.63 ft/sec, and that it might circulate under tidal influence from one site almost to the other, and then return, a distance approaching 4.0 miles. The computed reduction of DO during this cycle would be 0.25 mg/l. Therefore it may be seen that, under the assumptions made, a spacing of aerator stations of 2.0 miles will be satisfactory, and this spacing is assumed for design purposes. Where particular circumstances warranted it, spacing closer than two miles would be operationally acceptable, down to as little as 400 feet for 25-foot diffusers. Below this interval, as shown in Section IV, such an aerator would be likely to rehandle a substantial proportion of aerated water from a site immediately upstream, and thus lose efficiency. Larger aerators would require further spacing.

For all types of aerators considered, an increase in number of aerator sites would add to total cost, primarily on account of cost of electrical connections and electric service. Accordingly, based upon general design considerations, aerators may be tentatively considered to be spaced about two miles apart, down each side of the river. The sites would handle unequal quantities of oxygenation, depending upon a BOD systems analysis to determine the requirements of each section.

Aerator Type

Unlike the case for small rivers such as the Passaic, oxygen transfer efficiency is not the determining factor in selection of aerator type. In this important port area the requirements of navigation greatly limit use of mechanical aerators, since their pile moorings would greatly interfere with navigation in the main port and anchorage areas. They can be used outside of port activity and anchorage areas; but the site must have water of sufficient depth and current to carry away the aerated mass and disperse it into the main flow of the stream.

Surface Aerator Sites

The layout of a suitable surface aerator site should be governed as far as practicable by the following criteria.

- (a) Not more than two aerators along a stream line
- (b) As close to the main channel as possible
- (c) Layout as compact as possible
- (d) Layout such that any one aerator can be removed individually.

Two suggested layouts are outlined in Figure 26, one with one aerator and the other with two. The twin aerator layout could easily be expanded to take a third aerator shoreward of the two shown. Such sites would require submarine cable connections to shore, and a source of electric power. Cost estimates are indicated in Table 10. These estimates are on a similar basis to estimates previously reported (1), modified to provide for creosoted piling, submarine cable, and navigation lights. They are based upon electric drive, 75 hp surface aerators, with frames specially reinforced, and upon installation of a number of facilities in one contract. Figure 27 shows the mooring of a surface aerator between pile clusters.

As shown in Section III, the surface aerators have a transfer rate of 3.06 lbs/hp-hr at standard conditions. This amounts to 1.70 lbs/hp-hr field output at 25°C and a mean DO level of 3.75 mg/l. Therefore, the field output of the three-aerator site in pounds per day would be $3 \times 75 \times 24 \times 1.70 = 9150$ lbs/day.

Annual costs computed as indicated in the paragraph following are $49,200. With a 135-day operating period annually, this would amount to 4.0 cents per pound of oxygen utilized. Corresponding figures for

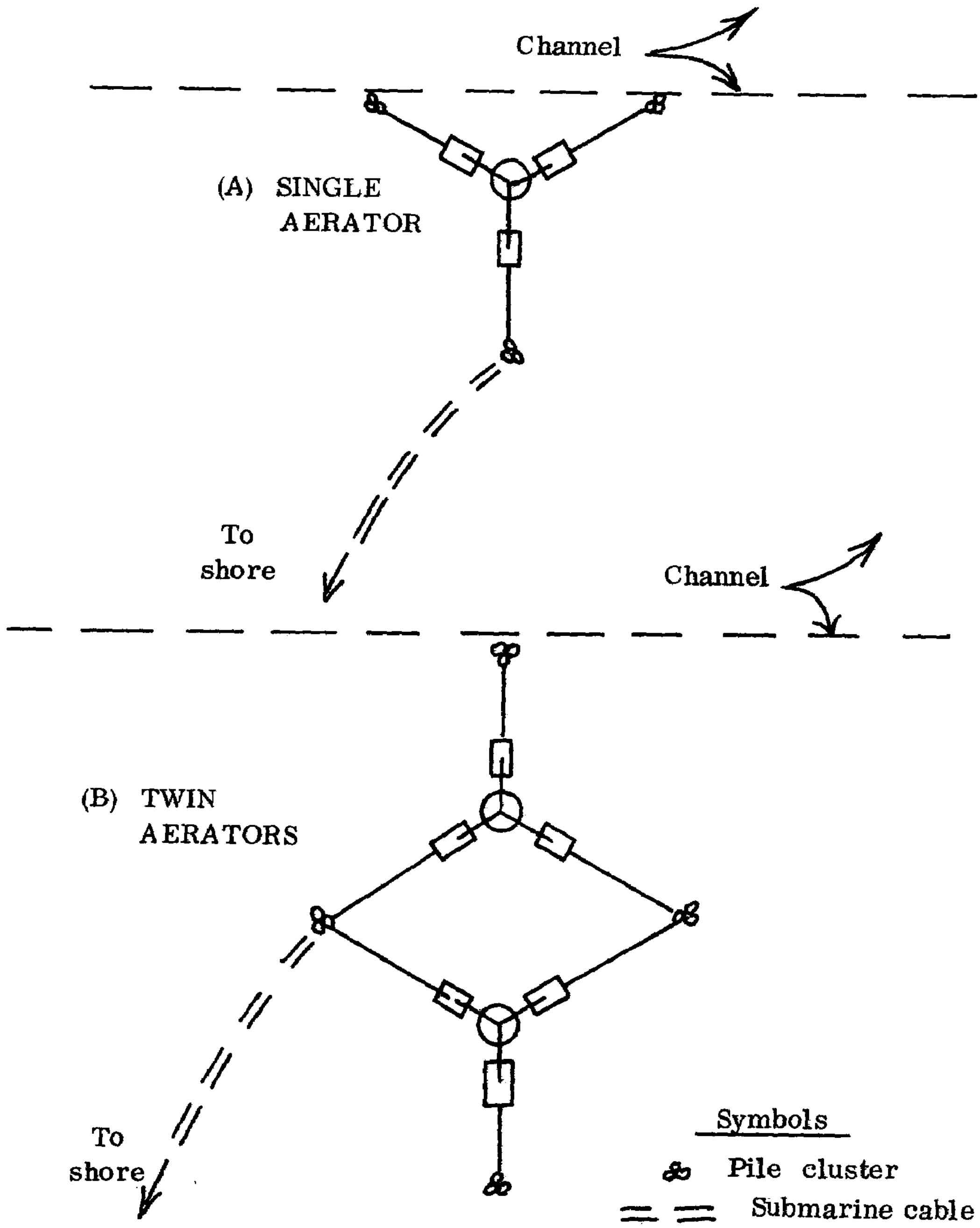


FIG. 26 SINGLE AND TWIN AERATOR FACILITIES

Table 10

COST ESTIMATE

SURFACE AERATOR SITES

	Single Aerator	Two Aerators	Three Aerators
Installed horsepower	75	150	225
Equipment and Construction Items	$57,000	$92,700	$130,500
Engineering and Contingencies	11,400	18,500	26,100
Total Construction Cost	$68,400	$111,200	$156,600
Operation and Maintenance	$20,000	$ 26,500	$ 33,000
Interest and Amortization at 15 years 6% basis (10.3%)	7,000	11,500	16,200
Total Annual Costs	$27,000	$38,000	$49,200

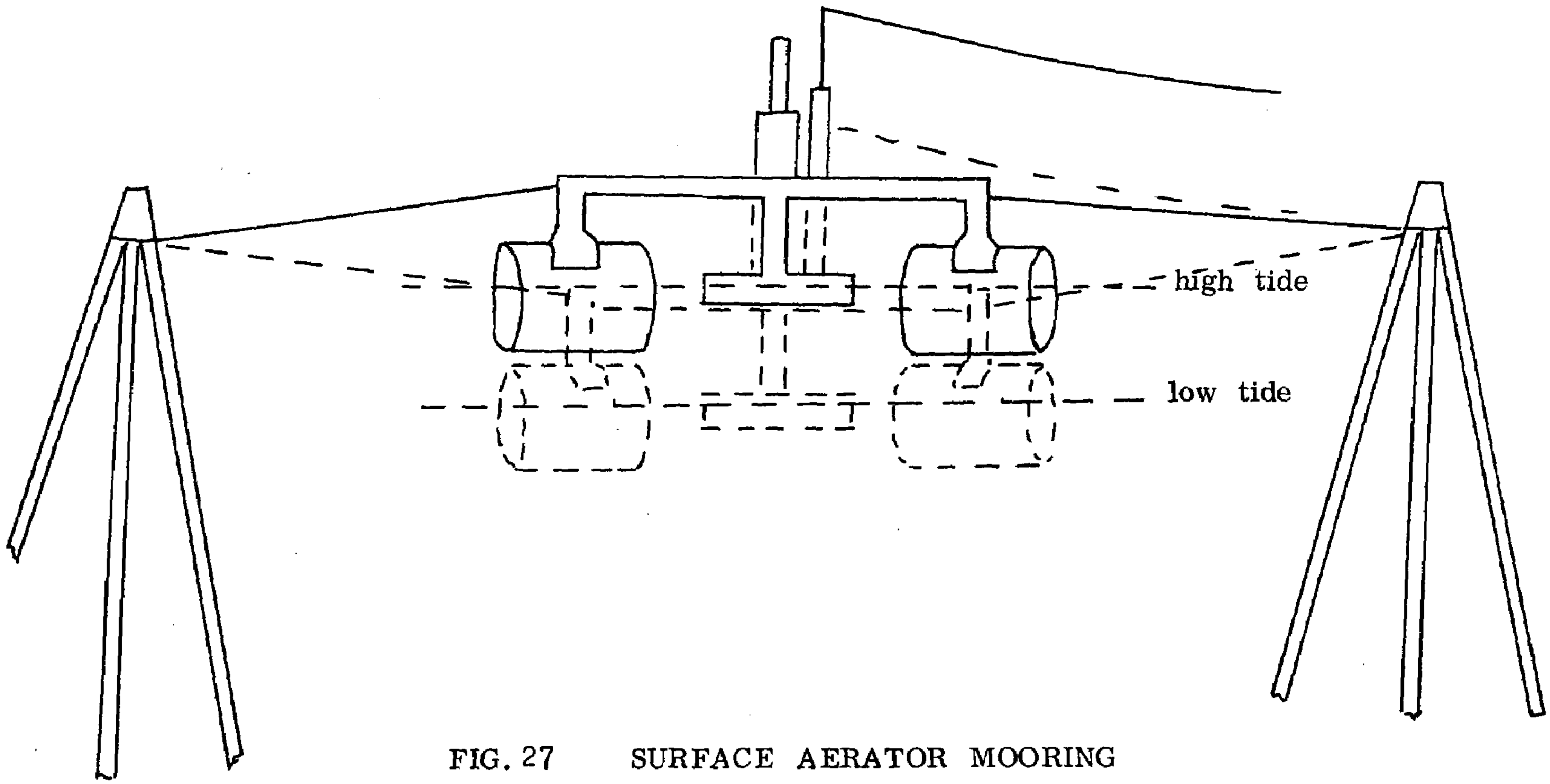


FIG. 27 SURFACE AERATOR MOORING

the two aerator sites are 4.6 cents and for the single aerator site 6.6 cents per pound of oxygen utilized.

Equivalent Annual Costs

The costs in Table 10 are reduced to equivalent total annual costs per unit of oxygen transferred, for comparison with other types of aerator, in the following manner.

The social discount rate for economic comparison of one government investment with another may be approximated as the long-term U.S. bond yield rate, less an allowance for the inflation increment in the current rates, and plus an increment for risk not borne by the bond holder (38). In November 1970, U.S. bonds of maturity exceeding ten years had an average interest rate of 6.7%. Allowing for a depreciation component of 1.7% and a risk component of 1.0%, the costs of alternatives may be compared on the basis of an economic interest/discount rate of 6% annually. With an economic life of 15 years, this corresponds to a combined rate of 10.3% annually for both interest and amortization of the original investment.

Diffuser Aerator Facilities

The costs of providing a diffuser aeration facility depends very largely upon distance of the diffusers from the shore, since underwater pipelines are very expensive. The distance between the blower and the manifold is assumed to be 1000 feet; and the resulting estimated pipeline cost is more than half the entire construction cost in each case. Installation nearer shore would be less expensive, although on-shore pipelines would be required in most such cases.

Another very important design condition is the question of whether the diffusers are capable of operation for long periods of time without clogging or obstruction by sediment. One unpublished study of river aeration potential (preliminary by others) eliminated diffuser aerators from consideration because of this question. However, the diffuser aerators tested have holes of 5/32-inch diameter, with a ball valve which at least partly seals off the manifold when not in use. It is assumed that these diffusers would remain operable over a period of four years, on the average, and would then require to be removed and serviced. Much greater efficiency could be obtained by fine bubble aerators, but because of this question of clogging, the coarse bubble aerator has been retained as a basis for comparison. If necessary, devices could be provided to seal off the orifices of the diffuser when not in use.

A third important consideration in design is the relationship of the equipment to navigation requirements, in the areas in which the pierhead line and channel line are closely adjacent. According to discussions with the Philadelphia District, Corps of Engineers, it must be accepted as a constraint that there can be no diffusers laid in the channel and anchorage areas on account of potential interference with mooring or with maintenance dredging. On the other hand, placing of diffusers back of the pierhead line might leave them in slack water or eddy conditions during portions of the tidal cycle, such as to detract seriously from their effectiveness. Accordingly, in areas where navigation requirements preclude the use of surface aerators, there are three possible solutions, as follows. First, in open water, use single long diffusers, as illustrated in Figure 28B and cases a, b, and c in Table 11. Second, where the pierhead line is close to the channel line, the necessary diffuser capacity could be provided by one or more short (25) diffusers perpendicular to the line of stream flow, successive diffusers being separated by at least 400 feet along the stream line, in order to avoid reprocessing the aerated water a second time. These short multiple diffusers illustrated in Figure 28 (A) and cases d and e of Table 11, would be comparatively expensive, on account of the underwater pipelines. Third, where piers exist, the outer ends of which are not used for mooring purposes, a good solution would be a diffuser laid parallel to the line of stream flow, close to the pier, as illustrated in Figure 29 and with costs as shown in case f, Table 11. Judging from the flow characteristics shown by diffusers in the tests, the surface water would flow away from the pier at a fairly rapid rate, as shown by solid lines on the figure, while water from lower levels would flow in towards the diffuser as shown by dotted lines. It is believed that such a design, if not over 80 feet long, would function satisfactorily, except briefly at slack tide. At such periods all types of aerators would probably recirculate some of the aerated water. An examination of the map shows that there are a great number of finger piers in the Philadelphia area, many of which would undoubtedly be adaptable to such an installation.

The following design assumptions were made for the diffuser aerators by consulting engineers Hazen and Sawyer, in preparing the cost estimates.

1. In relating air flows to estimated shaft horsepower, average blower efficiency was assumed at 80% and a discharge pressure was estimated to overcome the depth plus 25% for losses. These values were checked against the maximum allowable presure drop in the diffuser nozzles when located one foot on center, with 12 orifices "open" and a discharge air flow of 15 scfm per diffuser nozzle.

2. An optimum air velocity of 50 to 60 feet per second was used to size the main and diffuser header pipes.

3. No excavation of the river bottom is included in these costs. The diffuser would lie directly on the bottom.

4. Current market prices (material only) were used for the air

Table 11

COST ESTIMATES

DIFFUSION AERATION FACILITIES

Case Designation	a	b	c	d	e	f
Manifold Systems	1-80'	1-160'	1-80'	1-25'	3-25'	1-80'*
River Depth, ft.	20	20	30	40	40	30
SCFM	2620	5240	2790	1000	3000	2790
Equipment and Construction	$101,000	$128,000	$110,000	$ 84,000	$176,000	$ 77,500
Contingencies and Engineering at 20%	20,000	26,000	22,000	17,000	35,000	15,500
Total	$121,000	$154,000	$132,000	$101,000	$211,000	$ 93,000
Annual Operation and Maintenance Costs	$ 18,000	$ 26,000	$ 22,000	$ 15,000	$ 34,000	$ 19,000
Interest and Amortization at 15 years 6% basis (10.3%)	12,500	15,900	13,700	10,400	21,800	9,600
Total Annual Cost	$30,500	$41,900	$35,700	$25,400	$55,800	$28,600

* Installed at pier end

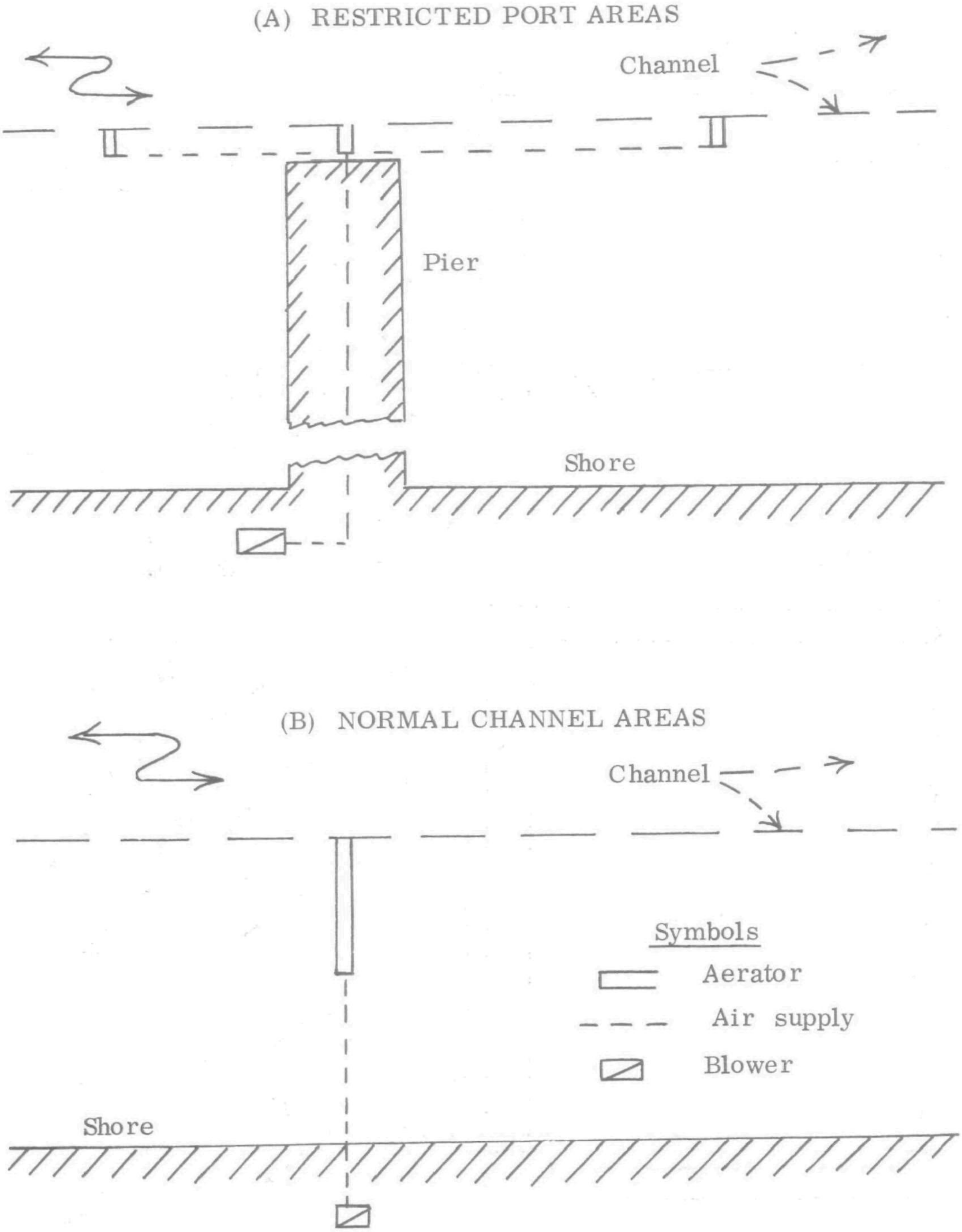


FIG. 28 DIFFUSER AERATOR LAYOUTS

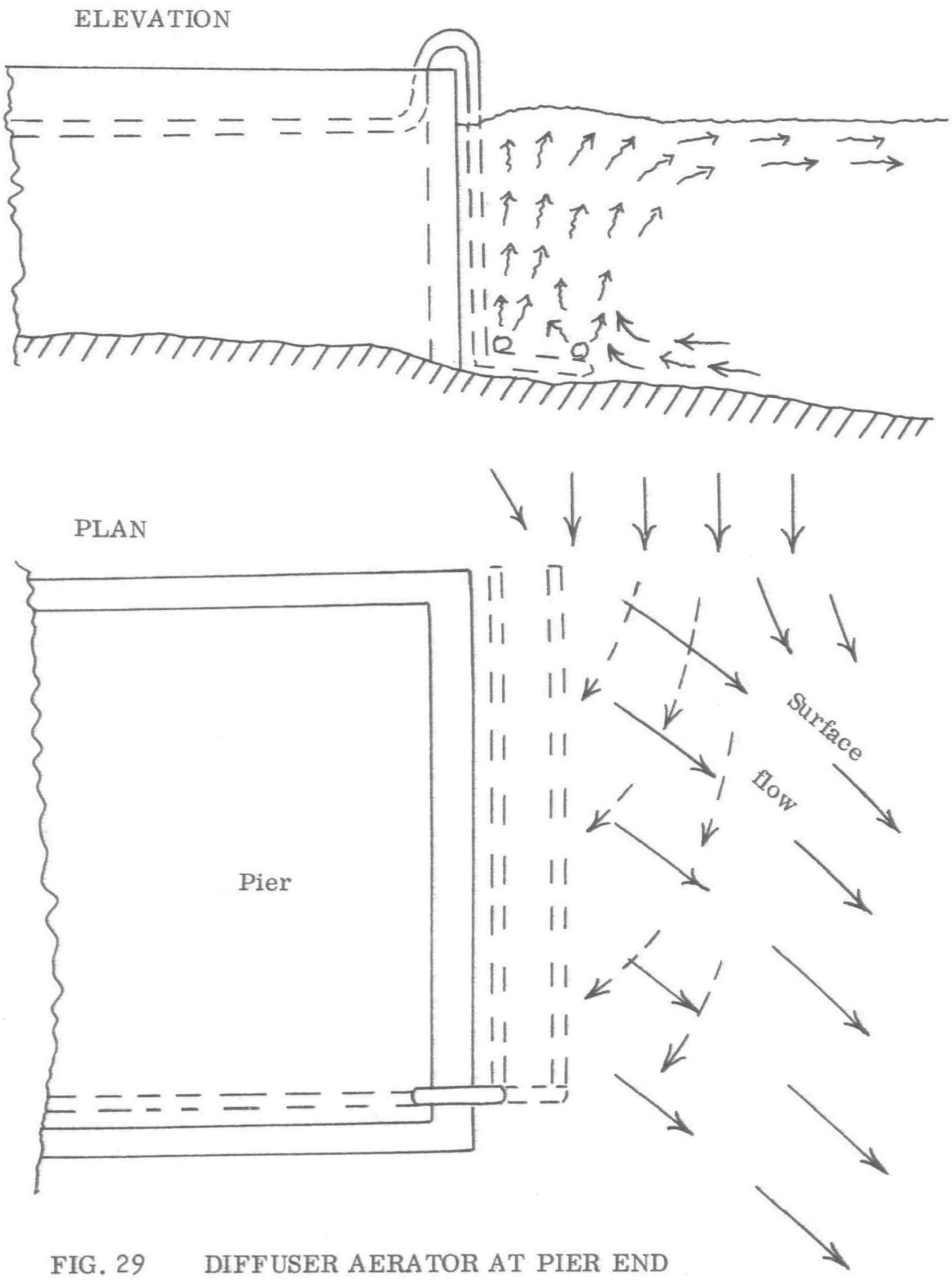


FIG. 29 DIFFUSER AERATOR AT PIER END

blower with its accompanying electric drive motor, with an allowance of 30% for installation. The estimates of horsepower were generally increased to account for economic equipment sizes.

5. The blower assembly was assumed to include the following:

   a. Purchase of blower unit and accessories--one or two stage blower, V-belt drive or reduction gear, electric drive motor, starter, base, coupling guard, relief and unloading valve, inter-stage piping, inlet filter silencer, discharge silencer and wiring.

   b. Installation of blower with electric drive motor complete with timber or concrete foundation, and

   c. Assistance in intial start-up operation.

6. The air piping system includes the following:

   a. Preliminary river soundings.

   b. Purchase, erection and installation of 1000 ft. of Schedule 40 steel pipe (main header) and various lengths of diffuser piping.

   c. Valves, fittings and flexible couplings.

   d. Purchase and installation of proper anchorage and supports.

   e. Purchase and installation of diffuser nozzles similar to previously purchased.

   f. Assistance in initial start-up operation.

7. Electrical costs were estimated based on a source of electric power approximately 1,000 ft. from the site. Among the principal items included are the following: 1,000 ft. conduit, 3,000 ft. of cable sized for motor load, lighting transformer feeder breaker, lighting transformer, lighting panel, two floodlights, and six incandescent fixtures. In addition, 250 ft. of service cable from the service pole is included. The cost of the poles was assumed backcharged by the utility.

8. Each piping is planned to be removed for cleaning and repair and reinstalled once every four years.

9. The following schedule of equipment operation was used:

Number of Months/Year	Hours of Operation (all cases)
6	No operation
3	Full (24 hr/day) continuous operation
3	Half-day (12 hr/day) operation

10. Annual costs of removal from river were estimated as 50% of the original installation cost, prorated over four years.

11. During a daily visit to each of approximately ten sites, one serviceman can inspect, repair and maintain equipment.

12. Electric power costs based on Public Service Gas and Electric Company of New Jersey rate schedule for large power and light users.

13. Annual maintenance costs estimated as 3% of total equipment costs.

The transfer efficiency of diffusers varies with depth, and must be adjusted to field conditons. In this case, field conditions are calculated as a mean DO value of 3.75 mg/l and temperature of 25°C, and also pressure corresponding to the mean depth of water during rise of bubbles. A change in oxygen saturation value appropriate to that depth must be allowed for. Values for the diffuser tested are as follows:

Depth	Percent Absorption	
	Standard Conditions	Field Conditions
20	5.6	4.8
30	6.8	6.9
40	7.0	8.1

Applying these percentages to the various cases outlined in Table 11, the costs per pound of oxygen used during an assumed 135 day annual operational period may be computed.

The diffuser aerator with lowest unit cost is case f, a large pier-end installation (80' unit) which would provide oxygen at 4.4¢/lb.O_2 in 30' water. Case c, a similar installation in open river without a pier, assuming a 1000' underwater pipeline, would have costs of 5.5¢/lb.O_2. If the water were only 20 ft. deep (case a) costs would rise to 7.2¢. Smaller installations would be more expensive. For example, a single 25-foot diffuser in 40 feet of water, in the open river (case d), would have costs of 9.3¢

When a comparison is made as to costs between diffuser and mechanical aerators, account must be taken of volume of output, since, for both classes of aerator, unit costs for the smaller units rise rapidly. When compared on the basis of equivalent outputs, the diffuser aerators appear somewhat more costly than the surface aerators, except for case f, the pier-end aerator, which is less costly.

Based upon these results, the surface aerators appear to be the more economical for reaches of the river where they do not interfere with navigation. In port areas and other developed waterfronts where surface installations would not be acceptable, the diffusers would be used, installed preferably upon pier ends or other favorable points where underwater pipeline construction would be minimized.

Possibilities of Oxygenation

There are also possibilities of raising DO level by diffusion of pure oxygen, which have been reported on both for rivers (39,40) and in much more detail, for waste treatment plants (41). Although investigation of such possiblilities was not within the scope of the demonstration project, other studies underway indicate that oxygen diffusion offers possibilities of providing an economical alternative to air diffusion under conditions assumed. This is particularly true for water of 30-40 feet deep. There are two reasons for this: (a) the oxygen supply lines, being much smaller, can utilize flexible plastic tubing rather than steel pipe, and (b) the oxygen diffusers function at 40 feet depth as well or better than at lesser depths, with added cost only for initial installation. The cost of the oxygen is a considerable item, of course, but for installations of the larger sizes in particular, oxygen diffusion appears considerably more economical. These conclusions are based upon estimates of cost of diffusers provided by the Martin Marietta Corporation, and provision for construction cost, provision of oxygen, and annual removal and cleaning of diffusers. The annual removal of diffusers would be much simpler for the small oxygen diffusers and flexible supply lines than with the heavy steel aeration pipe lines and diffusers. However, further work will be required to determine various design aspects since there are several alternative methods of oxygenation. Also it will be necessary to make an entirely different dispersion analysis since the dispersion analysis of the present report will not be applicable.

Overall Economy of Induced Oxygenation

An accurate cost estimate for adding oxygen to a major river cannot be be made without further research and design studies, particularly to determine which areas in the river can be oxygenated with surface aerators and which of the remainder can be served by pierhead installations. Also, possibilities of further economies by use of pure oxygen should be developed. However, some very rough approximations can be made. It is shown in Section V that the total additional oxygen requirement on the Delaware amounts to about 305,000 lbs/day (Table 7).

Allowing extra for irregularities in spacing and sizing, this might amount to about 48 million pounds of oxygen annually provided by a minimum of perhaps 50 sites, an average of 960,000 lbs O_2 annually per site. Such an input would require two of the 8 foot pier-end diffusers (case f) or intermediate between two and three surface aerators. Since the distribution of added oxygen to obtain the desired oxygen distribution would be somewhat irregular (as shown in Section IV), and the size of diffuser facilities will usually be limited by practical considerations, there will undoubtedly be a considerably larger number of sites required. Some sites will undoubtedly be required of size much less than the mean, with corresponding increase in unit price. It appears likely that the mean unit cost of raising the minimum average DO level from 3.0 to 4.0 mg/l by means of induced aeration would cost about 5¢ per pound of oxygen added during the critical period. This would correspond to total cost, including amortization of $4,800,000 annually. Since this is much less than the costs of achieving the same results by treatment alone, it appears that the instream aeration should be adopted in planning as an alternative to advanced degrees of waste treatment, where the main objective is the maintenance of satisfactory dissolved oxygen levels.

SECTION VII

ACKNOWLEDGEMENTS

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1 Accession Number	2 Subject Field & Group	
W	5G	**SELECTED WATER RESOURCES ABSTRACTS** **INPUT TRANSACTION FORM**

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6 Title

Oxygen Regeneration of Polluted Rivers: The Delaware River

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27 Abstract

Tests of surface instream aerators and of bottom diffuser aerators were conducted on the Delaware River near Philadelphia in order to determine the practicability of induced oxygenation of deep navigable rivers. The diffuser was tested at various depths up to 38 feet, but its performance in pounds of oxygen per horsepower hour decreased markedly in the deeper water. Performance of the surface aerator appeared to be somewhat improved over results previously found in a shallower river. Cost estimates and systems analysis led to the conclusion that induced oxygenation by aerators appears to constitute an economical alternative to advanced waste treatment on the Delaware River. This would require structurally reinforced surface aerators in some areas, and bottom diffuser aerators where the surface aerators would interfere with navigation. However, oxygen diffusers developed by others may provide an even more economical means of induced oxygenation for such rivers.

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