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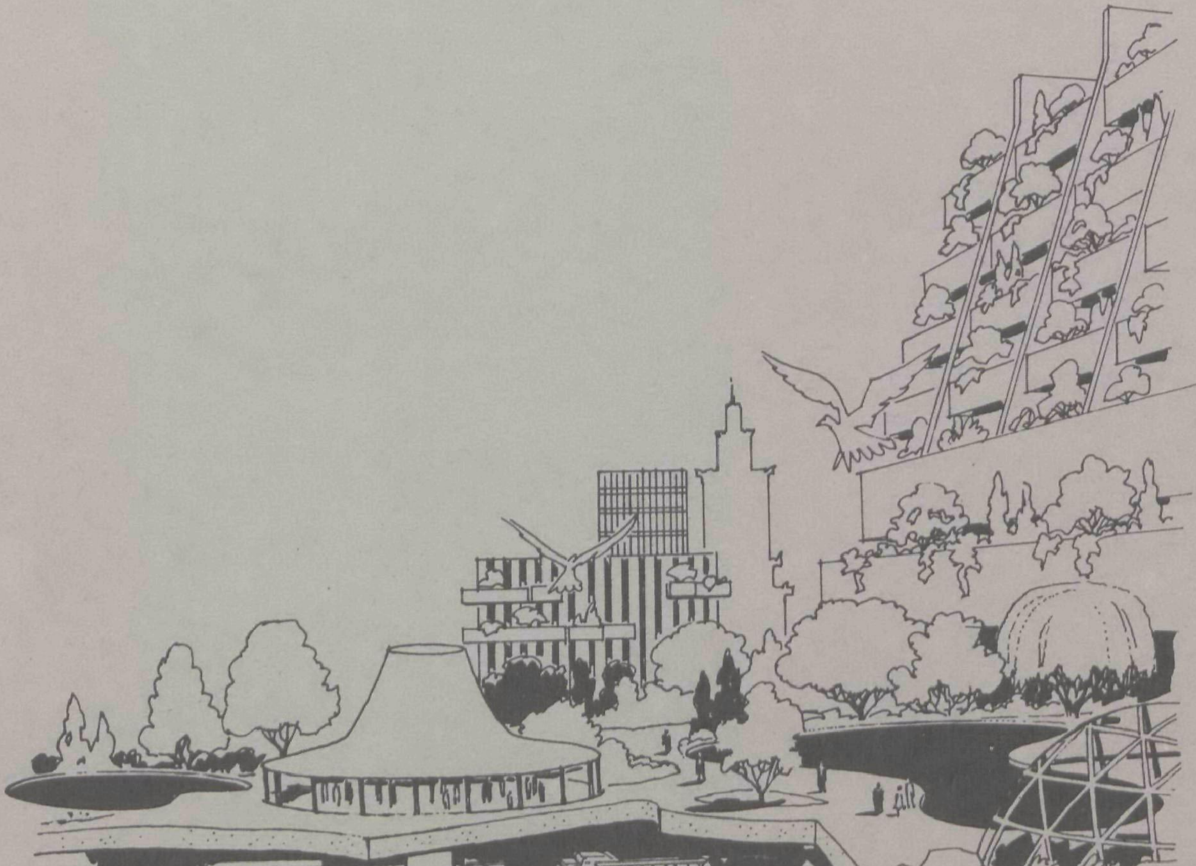
OXYGEN REGENERATION OF POLLUTED RIVERS: THE PASSAIC RIVER



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OXYGEN REGENERATION OF POLLUTED RIVERS: THE PASSAIC RIVER

by

Water Resources Research Institute
Rutgers University
New Brunswick, New Jersey

for the

WATER QUALITY OFFICE
ENVIRONMENTAL PROTECTION AGENCY

Project #16080 FYA

March 1971

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ABSTRACT

Field tests were made of a mechanical surface aerator and of pure oxygen diffusers in a small polluted river, the upper Passaic. Results generally corroborated results of previous test, as to performance of surface aerators on such rivers, in excavated pools. A somewhat higher oxygen transfer rate was obtained with a flow concentration device, which, in a permanent installation, would take the form of low rock spur dikes, one extending from each bank, or flow concentration groins. Tests in shallower water, about 7 feet deep, were inconclusive. Tests of oxygen diffusers were fragmentary, due to mechanical difficulties with the equipment; but it was demonstrated that the very fine bubbles used were very largely absorbed in the water. A dye dispersion test gave a very high longitudinal dispersion coefficient downstream of the aerator. Mathematical modelling indicated that during the test period, parameters of biochemical deoxygenation were not changed by the artificial aeration process.

This report was submitted in fulfillment of Project Number 16080 FYA, under the partial sponsorship of the Water Quality Office, Environmental Protection Agency.

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SECTION I

CONCLUSIONS

The field tests of the mechanical surface aerator reinforced previous conclusions as to the suitability of this equipment for raising dissolved oxygen levels in small polluted rivers. Results as to oxygen transfer rate were generally consistent with those obtained during tests of previous years. Correlation appeared to exist between the oxygen transfer rate and the river discharge for the observed flow range, as had been noted in previous tests. A somewhat higher oxygen transfer rate was obtained by using a flow concentration device, which represented a pair of flow concentration groins or low spur dikes employed with surface aerators in a permanent installation. Tests in shallow water (about 7 feet) were insufficient to indicate a change in effectiveness as compared with deeper water. Tests of oxygen diffusers were carried out only to a limited extent due to mechanical difficulties encountered by the Martin Marietta Corporation in the installation and initial operation. No useful data were obtained for the dynamic oxygen diffuser. The static oxygen diffuser tests, carried out with only a few diffuser plates in operation, indicated that most of the fine-bubble oxygen produced was being absorbed by the river. The spent gas rising to the surface had as much as 51% nitrogen in it, reflecting the high degree of absorption of the oxygen and the stripping of nitrogen from the water during the process.

A dispersion test, carried out with fluorescent dye, verified the highly dispersive action of the mechanical surface aerator in the relatively slow, shallow Passaic River. The turbulence generated by this aerator resulted in a longitudinal dispersion coefficient of 5.4×10^6 ft^2/min, which exceeds by a factor of five the largest "natural" coefficient yet reported. On account of this high dispersion, the leading edge travel distances were found to exceed the mean values by 50% at the upper of the two stations and by 30% at the lower.

The data obtained from the 1970 tests were used to recheck previously mathematical modelling of the Passaic River. In particular, analysis was directed at determining whether the operation of the mechanical aerator had any effect upon deoxygenation parameters, as had appeared to be the case in tests made during 1968. For 1970, there does not appear to have been any such relationship. Special attention was also given to nitrification effects. Based upon statistical indications only, it would appear that appreciable nitrification was occurring during the tests; but nitrogen balances indicated that this was not the case. These questions as to nitrogenous BOD and deoxygenation parameters in an artificially aerated stream are being studied further in connection with continuing research projects.

SECTION II

RECOMMENDATIONS

After consideration of results obtained, it is recommended:

That consideration be given to use of flow concentration groins or low rock spur dikes for use with any future permanent mechanical aeration installation in small polluted rivers.

That further research be conducted into the practicability and feasibility of adding gaseous oxygen to polluted rivers, as an alternative to artificial aeration.

That research be continued as to influences, including mechanical aeration, which my affect the parameters of biochemical oxygen demand.

SECTION III

INTRODUCTION

The Water Resources Research Institute of Rutgers University has been engaged upon research and testing of means of instream aeration for several years, with financial support from the Environmental Protection Agency, the Office of Water Resources Research and the State of New Jersey. The first phase of this work indicated that mechanical aeration of small rivers would provide an economical alternative to advanced waste treatment for obtaining desired dissolved oxygen standards. This work has been fully reported upon (1)(2)(3)(4)(5).

The second phase of testing, carried on in 1969 and 1970 on the Delaware River, resulted in development of design considerations for instream aeration on large, navigable rivers, and showed that, for the critical area of the Delaware Estuary, instream aeration would provide a viable solution to supplement secondary treatment of wastes. A report covering this phase of the work has been forwarded to the Environmental Protection Agency (6).

The present report covers Phase II of the project "Oxygen Regeneration of Polluted Rivers." This phase of work was planned (a) to test performance of aerators with flow concentration devices, and in shallow water, (b) to facilitate research concerning certain phenomena of deoxygenation rate which had previously been observed downstream of river aerators, and (c) to test surface aerators on a comparative basis with diffusers of pure oxygen.

The testing of flow concentration devices with mechanical aerators was suggested after tests in 1967 and 1968, from which it was observed that surface aerator had considerably greater oxygen transfer rates at higher river velocities. A research project has been carried out, which has demonstrated by hydraulic model tests that higher river velocities can be created at midstream at an aeration site by low rock spur dikes, or flow concentration groins, extending out from the bank at each side (7). For the present project, the permanent rock dikes were simulated by a long canvas strip, weighted at the bottom, and with a gap in the center. This arrangement is referred to as a flow concentration device.

Research concerning the parameter of deoxygenation rate in artificially aerated rivers is being conducted under Project B-027-N.J. of the Office of Water Resources Research, "Instream Aeration and Parameters of Nitrogenous BOD." The operation of surface aerators under the present project was essential to provide test facilities for the first phase of that research. The research activity will continue for two more years, and the aspects of parameter variation and mathematical modelling covered in this report are of an interim nature. In connection with the analysis of effects of the aerators, dispersion tests were made, using fluorescent dye, and a dispersion coefficient computed.

Field tests were conducted during the summer of 1970 at the previously used test site on the upper Passaic River, and the same mechanical aerator was installed. Arrangements were made for the necessary water quality observations, for the installation of the flow concentration device, and the shifting of the aerator to shallow water. The weather was fovorable, and some excellent results were obtained for the aerator. There was an interruption in the tests, due to an unknown object, probably a floating log, which entered the impeller, seriously damaging it, and causing a delay for repairs.

Meanwhile, as planned, the Martin Marietta Corporation brought to the test site the supplies and equipment for installing two types of oxygen diffusers, and provided a large liquid oxygen reservoir, with a heat exchanger and other necessary controls. A schedule was worked out to test the oxygen diffusers alternately with the aerators, in order to obtain comparable results. Certain of the results are of considerable interest; but, unfortunately, mechanical difficulties in the course of installation of the oxygen diffusers precluded obtaining sufficient data for a meaningful comparison of transfer rate with that of aerators.

The test results for both aerators and oxygen diffusers were analyzed by Rutgers personnel and are summarized in this report.

SECTION IV

FIELD OPERATIONS

The location chosen for the field operations is about 100 yards below the point where U.S. Highway 46 crosses the Passaic River, in the village of Pine Brook, Montville Township, Morris County, New Jersey. It is the site designated as No. 1 in the previous report (1).

At this site, two rental trailers were installed by the Rutgers research team, an 8' x 20' office and laboratory trailer, and an 8' x 40' storage trailer. The office and laboratory trailer were connected to electrical and telephone lines, and had a refrigerator for the storage of BOD samples. The storage trailer was without power but had ample space for the storage of tools, equipment, and outboard motors. Both trailers were used in common by Rutgers and Martin Marietta personnel.

Three different aerators were installed at the site for study and comparison: (a) the same Yeomans mechanical aerator used by the Rutgers research team during the summers of 1967, 68 and 69; and (b), (c), two different oxygen diffuser-type aerators by the Martin Marietta team.

River Bottom Conditions

The 10 foot deep basin, about 100' x 100' in area, excavated for the surface aerator in 1967 and 1968 was partly filled by sediments. Most of the excavation work done in 1970 was required for a 12 foot deep trench for the Martin Marietta aerators, about 10' wide (measured in the downstream direction), dug transversely just downstream of the 100' x 100' basin. A contour survey of the bottom after completion of excavation is shown in Figure 1. This shows depths at a stage of 221 cfs. The surface aerator site is shown by a cross, the diffuser site by a dotted line.

Yeomans Aerator Installation

The Yeomans mechanical aerator was installed as nearly as possible at the same location as in 1967 and 1968.

This aerator (Figure 2) has 35 vertical spade-like steel blades attached to a circular impeller rotating horizontally in the water at an elevation such that the blades are partially submerged when stationary. The impeller is supported and driven at a speed of 30 revolutions per minute by a vertical shaft running up to a 75 horsepower speed reducer and electric meter. When the machine is operating, the continuous movement of the blades in their circular path throws up and outwards a heavy cascade of water, greatly increasing both the surface available for oxygen transfer and the turbulence of the water.

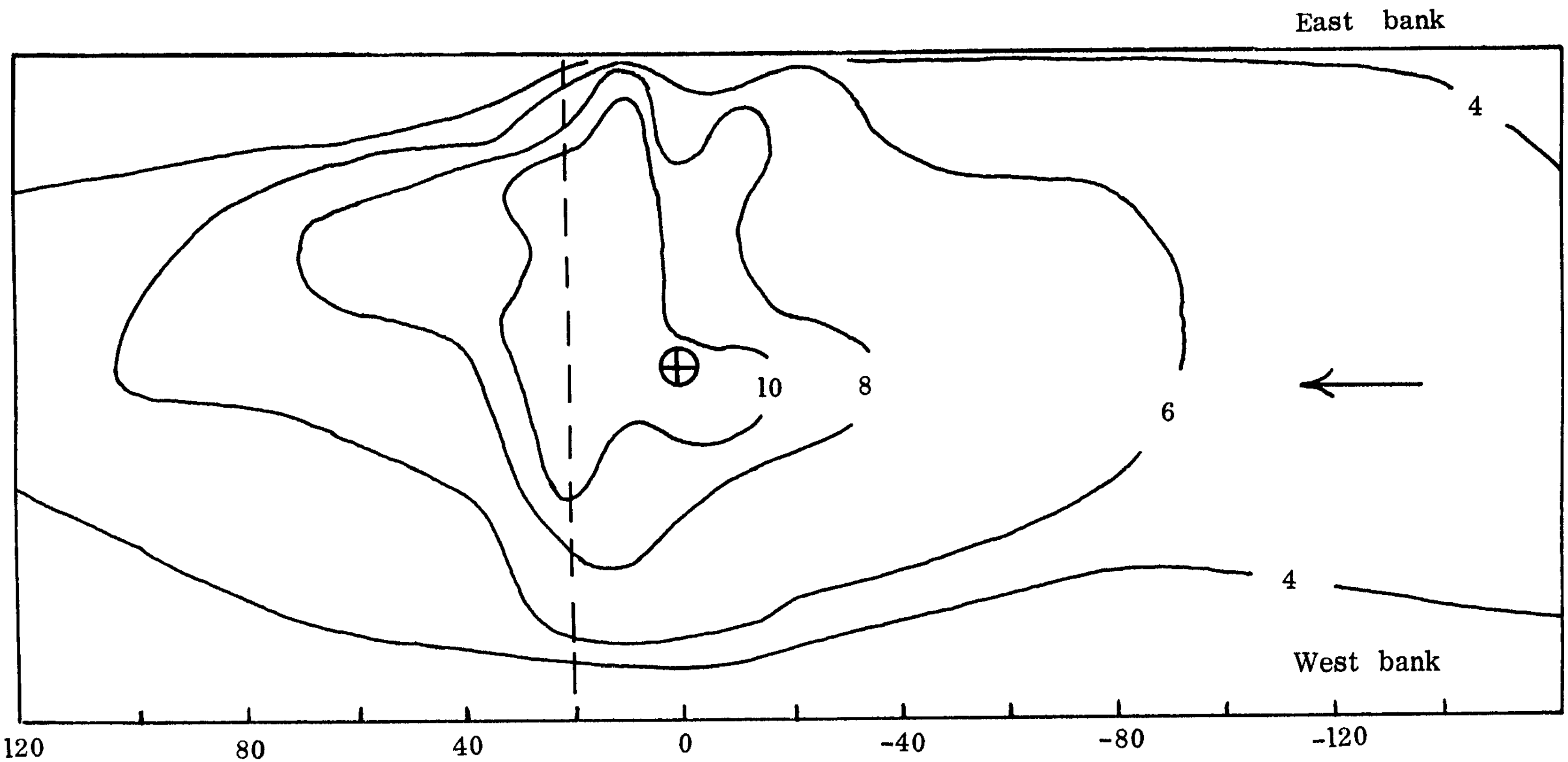

FIG. 1 TEST SITE DEPTHS

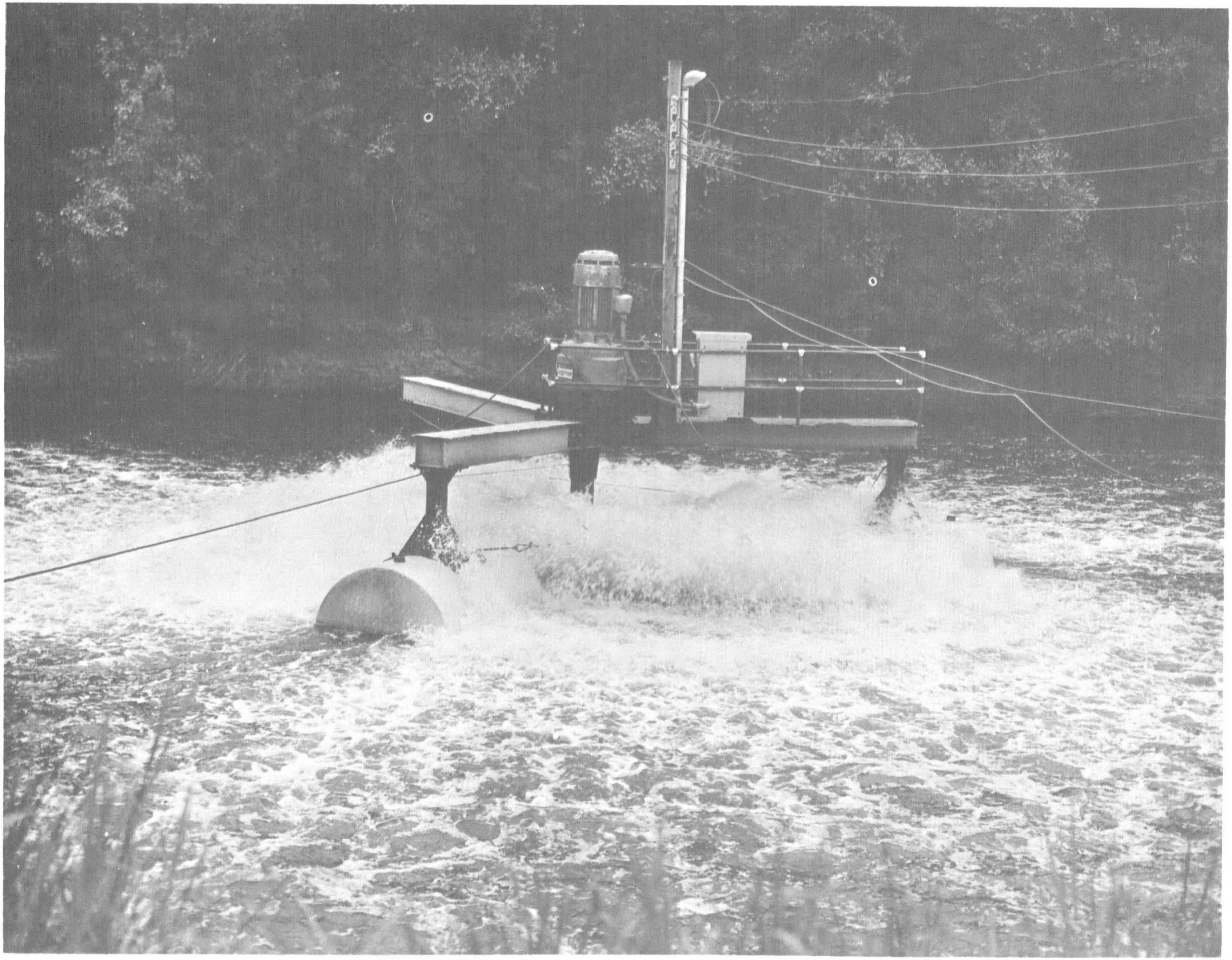

FIG. 2 MECHANICAL AERATOR IN OPERATION

The aerator machinery is supported by 3 floating pontoons. This keeps the blades at a fairly constant level with respect to the water, regardless of the constantly fluctuating level of the river.

Constant blade submergence is extremely important. Too little submergence, even 1" less than the correct value, would result in less oxygen input than the design capability of the machine. Too much submergence, even 1" excess, would overload the motor and speed reducer continuously, thus reducing the number of years' service obtainable from the investment.

The submergence of the blades can be adjusted in either of two ways, (a) by adjusting a set of 8 large bolts connecting the impeller to the drive shaft, or (b) by water addition to or removal from the floating support pontoons, which have a top inlet for that purpose.

The floating aerator was energized by a 3-phase, 240-volt power cable running from the public utility power supply on shore near the job site. A disconnect switch and starting equipment were installed in a small wooden shelter on shore; a disconnect was also installed on the aerator for personnel safety during necessary maintenance work.

The Martin Marietta oxygen diffusers were placed horizontally on the bottom of the stream and were supplied with gaseous oxygen through plastic tubes from shore. The following is a technical description of one unit, furnished by the Martin Marietta Corporation supervising engineer: "The passive diffuser assembly consists of six (6) separate trays each containing eleven (11) full blocks of aluminum oxide ceramic plus a partial block to complete the tray (see Fig. 3). These trays are rigidly fixed to a sheet of 3/4" marine grade plywood and an aluminum frame constructed of 3-inch channel section. Beneath each tray at each end is a rigid poly-vinyl-chloride tube fitting. These fittings are interconnected with flexible poly-vinyl-chloride tubing. The entire assembly (six trays) is supplied with oxygen through a single check valve and a flexible poly-vinyl-chloride tube which connects to the oxygen header on the shore. Oxygen permeates the cavity beneath the aluminum oxide blocks and passes through the pores to form the desired bubble size at the block-water interface." Because of their fineness, the individual pores were invisible. The porous ceramic plates caused the oxygen to emerge into the water in extremely fine bubbles, resulting in a slow rate of bubble rise, high specific surface, and a high percentage of absorption of the oxygen by the water.

The Martin Marietta dynamic oxygen diffusers consisted of fine-orifice metal diffuser plates; the orifices were larger, however, than those in the ceramic plates. The diffuser surface was vertical with respect to the water surface. A large centrifugal pump and piping were installed and connected to all diffusers to obtain high-velocity jets of water sweeping horizontally past the openings on the vertical diffuser plates. The purpose of the water jets was to reduce the average diameter of the oxygen bubbles by shearing action. Thus a slow rate of bubble rise, high specific surface, and high percentage of oxygen transfer should be

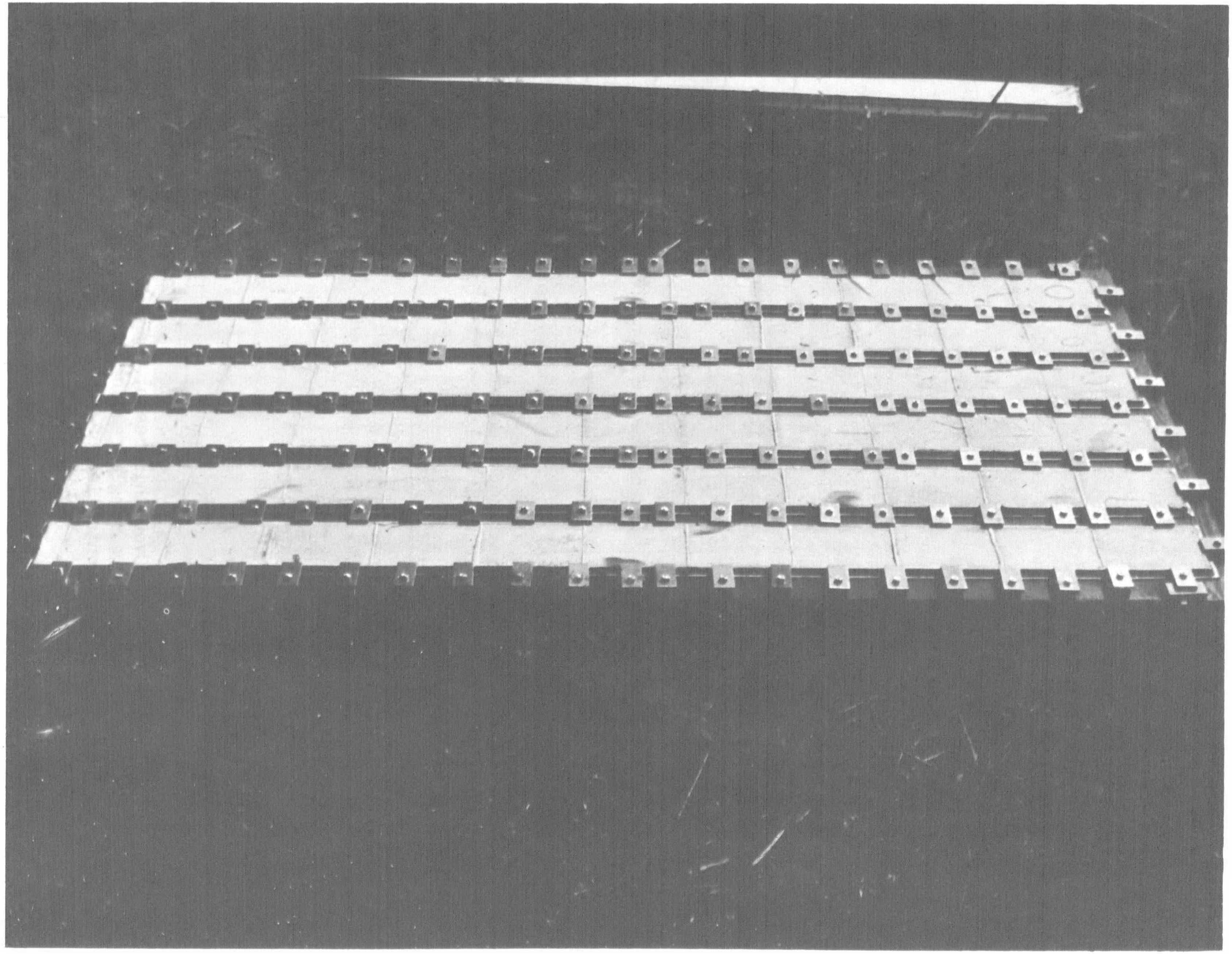

FIG. 3 MARTIN MARIETTA STATIC OXYGEN DIFFUSER

obtained, just as with the porous ceramic plates. A description of this equipment by the Martin Marietta representative is as follows: "The active diffuser assembly is a private invention and consists of a water inlet pipe which feeds five (5) rectangular cavities rigidly connected to the pipe. These cavities are each covered with eight (8) vertical gas distribution bars which expel oxygen in a lateral direction through capillary size tubes. Water is expelled through slots between adjacent gas distribution bars in a manner which shears gas bubbles at the capillary end before the gas bubble can reach maturity. Oxygen is supplied to each diffuser assembly through a check valve and a flexible polyvinyl-chloride tube which is connected to the oxygen header on the shore." The dynamic diffuser is shown in Figure 4.

Oxygen Supply and Control

A liquid oxygen tank and an atmosphere-heated vaporizer with orifice type flow recovery, flow control valves, temperature recorder, pressure indicators, and safety devices, were provided by the Martin Marietta Corporation to furnish substantially pure gaseous oxygen for the operation of their two diffuser aerators. The oxygen and tank were supplied by the Burdett Oxygen Company.

The oxygen supply stream, after being vaporized and metered, was piped to a header with multiple valves, one for each diffuser unit. From the valve header, an individual flexible tube of 5/8" x 3/8" clear vinyl plastic ran to each of the underwater diffuser units. Thus the oxygen supply to each unit in the stream could be controlled or shut off from the shore. Only the total flow of oxygen was metered, however.

Chemical for Algae Control

The growth of algae was anticipated as a source of plugging of the small oxygen outlets in the diffuser aerators. Therefore supplies of chlorine and hydrogen peroxide, and a rotameter for measuring their flow rates were incorporated into the experimental equipment.

Yeoman's Aerator Operation and Data Collection

The Yeoman aerator was operated continuously for periods of time from three to five days, and toward the end of each period one or more dissolved oxygen traverses of the stream were made. For comparison, the aerator was also shut off for periods of three to five days, and identical traverses were made. During July and August, 1970, the Passaic River was very close to steady-state conditions, as required for the mathematical simulation of the oxygen sag curve.

The dissolved oxygen traverses during the 1970 tests were primarily longitudinal, taken by motorboat at various points from 500' upstream of the aerator to 50,000' downstream. Over this reach, the river has no tributaries. During these traverses, a single reading of dissolved oxygen was taken one foot deep at the centerline of the stream; previous experience

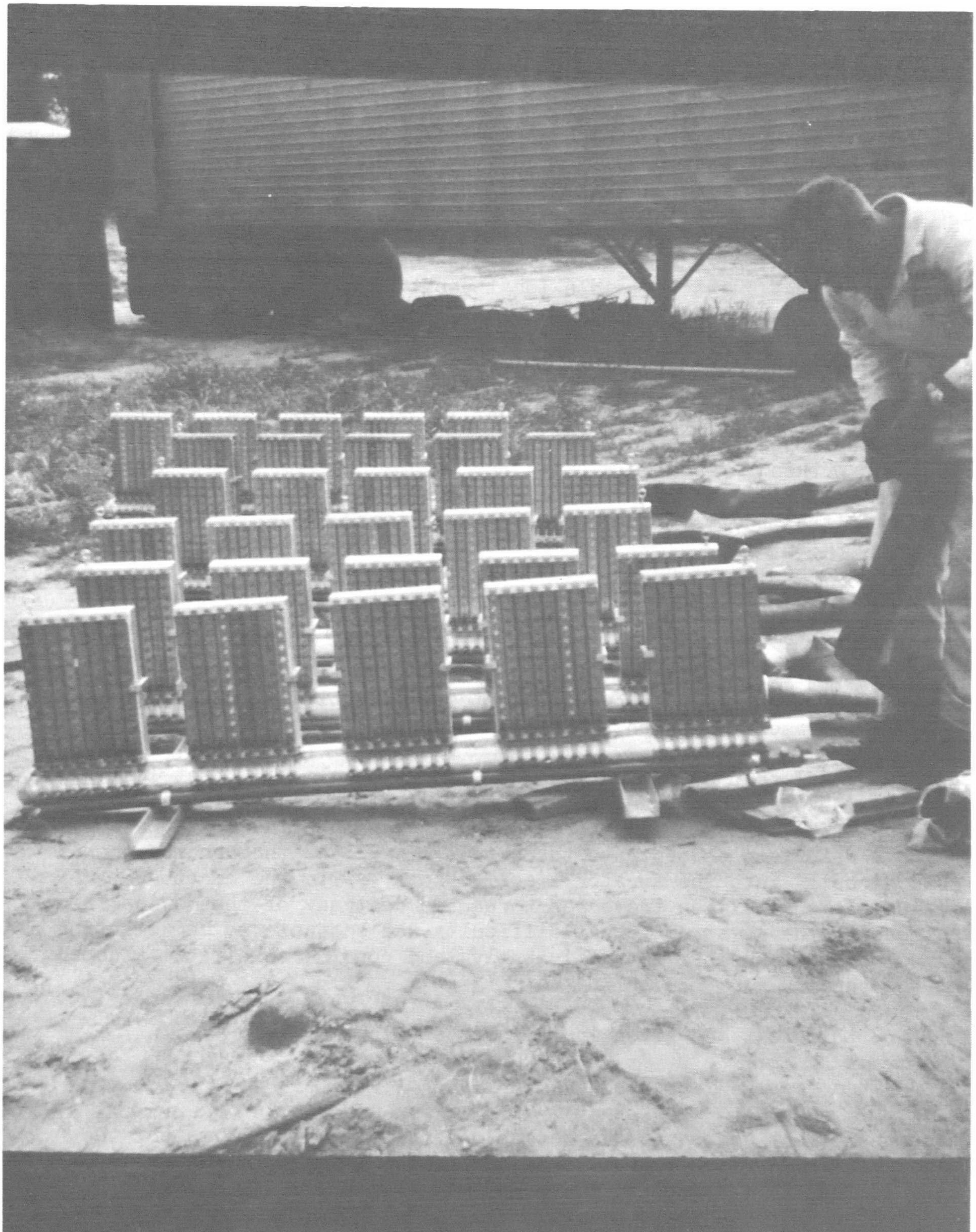

FIG. 4 MARTIN MARIETTA DYNAMIC OXYGEN DIFFUSER

has indicated that this reading is very close to the weighted mean value. The river is three to five feet deep at centerline, and 100 to 110 feet wide. The dissolved oxygen readings were taken with a Delta Model 85 meter, calibrated just before the traverse by Winkler titration of a sample of river water. Also, Winkler samples were taken as a check on 1/3 to 1/2 the meter readings. When Winkler samples were taken in the boat, they were fixed immediately using chemicals carried in the boat and transported to the office-laboratory trailer for titration.

All readings and samples were taken from the boat while heading upstream, to minimize errors due to possible local aeration of the water by the outboard motor.

The surface aerator had operated for three previous test seasons without serious difficulty with drift, since the strong surface current repells any floating objects. However, on August 11, the impeller was seriously damaged by an object believed to have been a submerged log. Eleven blades were broken or seriously bent; and it was necessary to suspend operations until August 21 for repairs. In addition to the delay, it was apparent that the alignment of the straightened blades was no longer as regular as the original. This irregularity affected efficiency of the aerator somewhat, as described in the following section.

Flow Concentration Device Tests - Surface Aerator

An important question with surface aerators is the following. Would concentration of the total flow of the stream directly through the aeration zone increase the oxygen input in lbs O_2 per horsepower hour?

To get an actual test result, a heavy canvas rectangle, 110 feet long by 8 feet wide was fabricated, with a 20-foot-long oval opening at the centerline. This was stretched across the stream about 40 feet upstream from the aerator, to concentrate the total stream flow through the opening and directly into the aerator's active zone. With the aerator operating, lateral oxygen traverses were made upstream of the device, and downstream of the aerator. Great difficulty was encountered in weighting the lower edge of the baffle sufficiently, and considerable flows escaped below the canvas.

Results of this test are given in the next section.

Shallow Water Tests - Yeoman's Aerator

To test the effectiveness of the Yeoman's aerator in shallow water, the machine was towed upstream about forty feet. This was possible because the aerator was on floating pontoons, and because the anchor cables and power supply cable were easy to rearrange in new positions.

The aerator was then operated and lateral oxygen traverses were taken, upstream and downstream of the aerator. In view of time which had been lost in the accident, as described above, little time remained for tests in this location.

Results of these tests are also given in the next section.

Martin Marietta Aerator - Operation and Data Collection

The passive oxygen diffuser plates were subject to some degree of leakage under oxygen pressure. Those plates which would operate without leaks were placed on the bottom of the stream and each was connected to its own oxygen supply tube. With a constant rate of flow of oxygen, steady state was reached, two lateral oxygen traverses were then taken, one upstream and one downstream of the diffuser plates. Oxygen contents of the water at various depths were measured by Delta meter and Winkler titration, and the total oxygen input was calculated by graphical integration. The oxygen flow was measured by means of the chlorine rotameter rather than the orifice meter, because the reduced number of passive diffuser plates required only a small oxygen flow rate.

The percent of the pure oxygen absorbed by the stream was obtained by collecting samples of the residual gas bubbling up in the surface from the passive diffuser plates. The samples were analyzed for oxygen and nitrogen on a Beckman gas chromatograph. Since the initial impurity constant of the oxygen was known, the percent of O_2 absorbed could be calculated by mass balance from the analysis of the spent gas.

No data were obtained from the dynamic oxygen diffuser during the summer of 1970 due to mechanical difficulties.

Details of the tests and of results obtained are given in the next section.

SECTION V

OXYGEN TRANSFER OF AERATORS AND OXYGEN DIFFUSERS

In this section, the oxygen transfer results of the surface aerator are outlined. The oxygen transfer rates before August 11, when the impeller was damaged, should be comparable to those previously obtained by the same aerator on both the Passaic and the Delaware Rivers. The transfer rates after this date are not strictly comparable with earlier periods, since the repaired aerator was obviously operating with less than its original smoothness; but comparisons are valid between normal operation in a deep pool, operation with and without a flow concentration device (on the same day), and operation in shallower water.

Oxygen Transfer Efficiency

The performance of an artificial aeration unit is characterized by the oxygen transfer rate, or the oxygenation efficiency, which can be generally expressed as the amount of oxygen in pounds added by the aerator per shaft horsepower-hour. In a flowing stream with relatively low oxygen demand the oxygen transfer rate for an aerator operating under steady conditions may be described by the following equation (1):

$$R_t = \frac{BQ(C_d - C_u)}{P} \qquad \text{.....5-1}$$

where

R_t = oxygen transfer rate at test conditions in lbs O_2/hp-hr
B = units conversion factor
Q = river discharge in cubic feet per second
C_d = DO concentration at downstream (of the aerator) sampling point in mg/l
C_u = DO concentration at upstream (of the aerator) sampling point in mg/l
P = power developed by the aerator in shaft horsepower

The oxygen transfer rate determined by Equation 5-1 is specific for the conditions that obtained during a particular test. For the purpose of comparison this rate must be converted to standard conditions, which are generally taken as 20°C, 760 mm Hg atmospheric pressure, 0 mg/l DO concentration, and "clean" water quality. The conversion is obtained by (3)

$$R_s = R_t\left[\frac{(C_s)_{20}}{[(C_s)_T\beta - C_m]\,(TF)(\alpha)}\right] \qquad \text{.....5-2}$$

in which

R_s = oxygen transfer rate at standard conditions
$(C_s)_{20}$ = saturation DO concentration at 20°C

$(C_s)_T$ = saturation DO concentration at test water temperature T
TF = temperature correction factor - $(1.025)^{T-20}$ (10)
β = specific DO solubility
α = specific transfer rate
C_m = DO concentration at the aerator
R_t is as defined earlier

According to laboratory test results by Hunter (8) both the specific DO solubility, β, and the specific transfer rate, α, were found to be 1.0, and the saturation oxygen concentration values, C_s, were computed with the following SED-ASCE equation.

$$C_s = 14.652 - 0.41022T + 0.007991T^2 - 0.0000777 4T^3 \quad .....5\text{-}3$$

For a temperature of 20°C, C_s = 9.02 mg/l.

During field operations, it is rather difficult to measure the exact value of the oxygen concentration, C_m, at the aerator due to the intensive turbulence created by the aerator. Consequently, the driving force $C_s - C_m$ could not be accurately determined, though several methods have been proposed in the literature to estimate it (9). According to previous experiences on the Passaic River (1), the arithmetic average of the DO readings at the upstream and the downstream sampling points provided satisfactory oxygen transfer results. Therefore, in this study the C_m values were estimated by

$$C_m = 1/2\ (C_u + C_d) \quad .....5\text{-}4$$

where C_u and C_d are as defined earlier.

Oxygen Supplied by the Aerator

The rate of oxygen added by the aerator to the stream for steady-state conditions can be computed by the relationship

$$U = 0.2246Q(C_d - C_u) \quad .....5\text{-}5$$

where U = oxygen added or uptake rate due to the aerator in lbs O_2/hr, and Q, C_d and C_u are as defined earlier.

In the present study the oxygen uptake rates were determined by both longitudinal and lateral DO traverses. For the longitudinal traverses DO readings were taken at 200 ft upstream, and 100 ft downstream of the aerator, at the depth of 1 foot along the centerline of the river. It has been shown (1) that the one-foot, centerline reading could be used satisfactorily to represent the average DO concentration over the whole river cross-section. For the lateral traverses DO and velocity readings were taken at various depths across the river at 200 ft upstream, and 100 ft downstream of the aerator. The mean DO for a cross-section was computed by using averages weighted according to stream velocity readings. It should be noted that all the DO measurements made with the Delta DO meter were corrected against corresponding Winkler readings, before the mean DO values were computed.

A summary of the field tests data, together with the computed oxygen uptake rates is given in Table 5-1.

Oxygen Transfer Rates

The oxygen transfer rates, R_t, under steady-state conditions for the mechanical aerator were computed by dividing the oxygen uptake rate, U, by the shaft power consumed, as indicated by Equation 5-1. Equation 5-2 was then used to convert these transfer rates to standard conditions.

In order to facilitate the computation, the following relationship is defined:

$$R_s = R_t \times F \qquad .....5\text{-}6$$

where

F = conversion factor from test to standard conditions.

Since F can be expressed as a function of the following:

$$F = f(C_m, C_s, T, \alpha, \beta) \qquad .....5\text{-}7$$

for given values of C_s, α, and β, F is a function of C_m and T. In this study, F is written as

$$F = \frac{9.02}{(C_s - C_m)(1.025)^{T-20}} \qquad .....5\text{-}8$$

Thus values of F for different C_m and T can be computed and shown graphically. As illustrated in Figure 5 for observed temperature and estimated C_m values, F can be found easily and the computation is simplified.

The results on oxygen transfer rates at both field and standard conditions for all the tests are listed in Table 5-2. Also given in Table 5-2 are the dates of tests, the flow rate, and the DO concentrations upstream of the aerator.

Comparison of Oxygen Transfer Rates

The field test results for all the experiments, excluding test with the flow concentration baffle and with aerator in shallow water, indicate that, over the observed flow range (107 to 268 cfs), the aerator transferred on the average 1.50 lbs O_2/hp-hr under standard conditions. However, as described in Section IV, the aerator was damaged on August 11, 1970. Although repairs were made, several of the blades of the impeller were somewhat bent. If only the data before August 11 were averaged, the transfer rate became 1.69 lbs O_2/hp-hr, which is 94% of the figure

TABLE 5-1

SUMMARY OF STEADY-STATE FIELD TEST DATA FOR

MECHANICAL AERATOR

Date (1)	Flow Q. in cubic feet per second (2)	Water temp. in degrees centigrade (3)	Shaft power in horse-power (4)	Dissolved Oxygen[a] in milligrams per liter		Oxygen added in lbs of oxygen per hour (7)
				Upstream (5)	Downstream (6)	
7/13/70	135	23.0	81.8	2.80	5.70	88.1
7/15	124	21.0	65.6	2.30	4.20	52.9
7/15	126	22.0	65.3	2.10	3.90	50.9
7/20	113	23.0	70.5	2.20	4.90	68.5
7/20	113	24.0	69.0	3.40	5.70	58.3
7/20	115	23.5	67.0	3.40	5.50	54.3
7/27	113	24.3	74.6	0.20	3.70	89.0
7/27	113	24.5	77.0	0.80	5.10	109.2
7/28	111	25.0	65.0	2.20	5.10	71.6
7/28	111	25.3	54.6	2.30	4.50	61.7
8/11	111	21.0	46.2	2.40	4.00	39.9
8/12	109	24.0	54.7	2.60	4.50	46.4
8/12	109	24.0	55.1	3.30	4.30	24.5
8/19	107	22.0	65.0	2.60	4.70	50.7
8/19	107	22.0	62.5	2.90	4.80	44.8
8/20	111	23.0	63.5	3.00	4.90	47.9
8/25	268	20.0	66.0	2.84	3.84	60.3
8/25[b]	236	22.0	66.5	3.05	4.16	58.8
8/25[b]	236	22.0	66.3	3.05	4.15	58.3
8/25	223	22.0	66.1	3.30	4.17	43.6
8/26	163	20.0	68.1	2.61	3.96	49.4
8/26	153	21.0	68.8	2.81	4.50	58.1
8/26	151	21.0	68.8	2.83	4.51	57.0
8/26[b]	145	22.0	69.4	2.98	4.62	53.4
8/27[c]	126	23.0	72.5	2.70	4.70	56.6
8/27[c]	126	23.0	71.0	2.70	4.70	56.6
8/27[c]	125	23.0	72.4	2.70	4.60	53.3

[a] DO samples taken at 200 feet upstream and 100 feet downstream of the aerator.
[b] With flow concentration device installed at 100 feet upstream of the aerator.
[c] Aerator in shallow water, at 40 feet upstream of the original site.

TABLE 5-2

SUMMARY OF OXYGEN TRANSFER RATES FOR MECHANICAL AERATOR

UNDER STEADY-STATE OPERATION

Date (1)	Flow, Q, in cubic feet per second (2)	Upstream DO concentration, milligrams per liter (3)	R_t in lbs of oxygen per horsepower-hour[a] (4)	R_s in lbs of oxygen per horsepower-hour[a] (5)
7/13/70	135	2.80	1.08	2.12
7/15	124	2.30	0.81	1.27
7/15	126	2.10	0.78	1.18
7/20	113	2.20	0.97	1.62
7/20	113	3.40	0.85	1.81
7/20	115	3.40	0.81	1.71
7/27	113	0.20	1.19	1.51
7/27	113	0.80	1.42	2.17
7/28	111	2.20	1.10	1.98
7/28	111	2.30	1.13	1.90
8/11	111	2.40	0.86	1.34
8/12	109	2.60	0.85	1.43
8/12	109	3.30	0.44	0.82
8/19	107	2.60	0.78	1.30
8/19	107	2.93	0.72	1.30
8/20	111	3.00	0.76	1.40
8/25	268	2.84	0.92	1.45
8/25[b]	236	3.05	0.89	1.51
8/25[b]	236	3.05	0.88	1.50
8/25	223	3.30	0.66	1.14
8/26	163	2.61	0.73	1.15
8/26	153	2.81	0.84	1.44
8/26	151	2.83	0.83	1.42
8/26[b]	145	2.98	0.77	1.36
8/27[c]	126	2.70	0.78	1.37
8/27[c]	126	2.70	0.80	1.39
8/27[c]	125	2.70	0.74	1.27
		average[d]	0.88	1.50

a

R_t = oxygen transfer rate under test conditions;
R_s = oxygen transfer rate under standard conditions.

b

With flow concentration baffle in place.

c

Aerator in shallow water.

d

Excluding cases when flow concentration baffle was in place or aerator in shallow water.

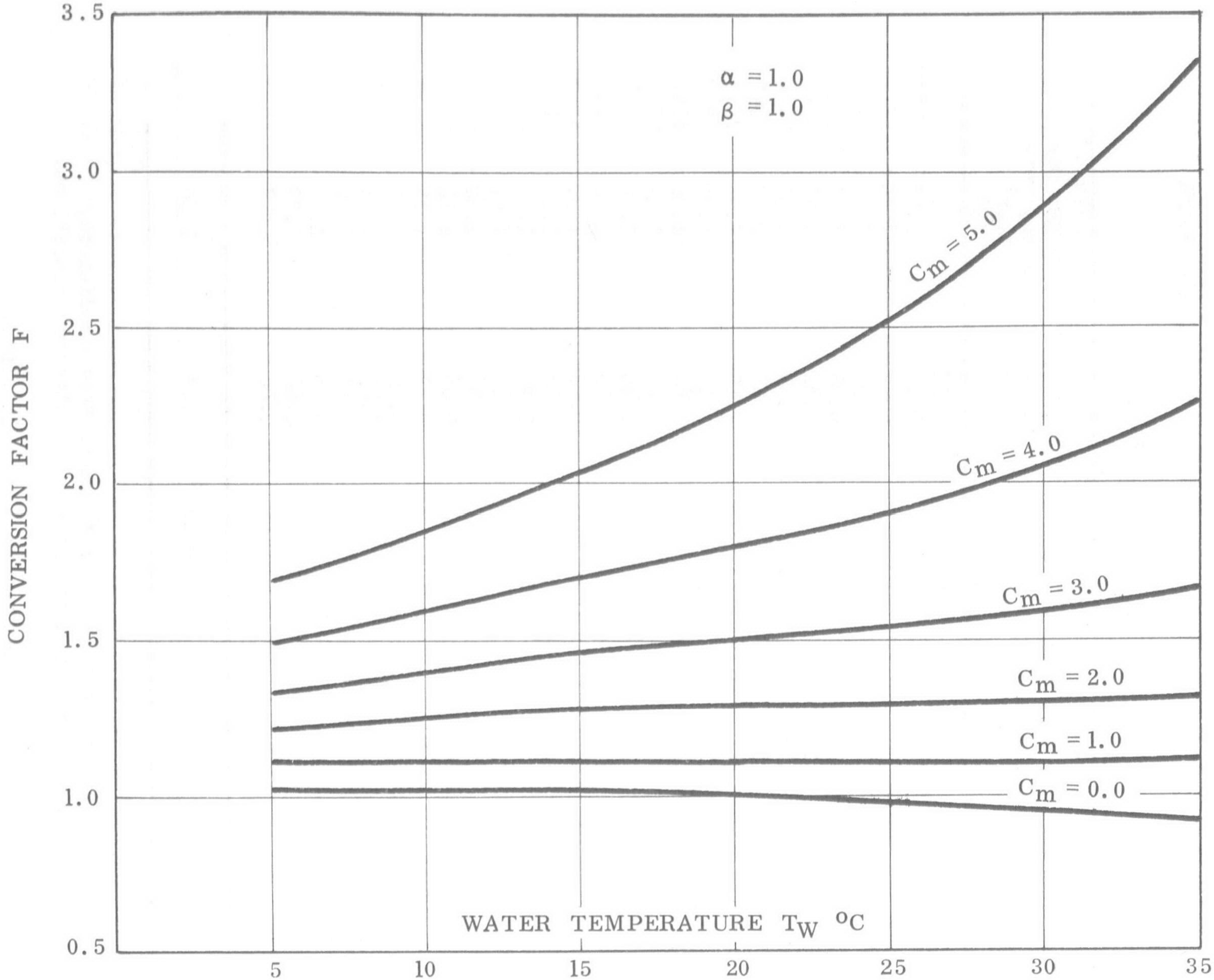

FIG. 5 CONVERSION FACTOR, F, VS WATER TEMPERATURE, T_W, AND D.O. LEVEL AT THE AERATOR, C_m

obtained during the 1968-69 experiments. (1.80 lbs O_2/hp-hr on the average). The average after August 11 was 1.29 lbs O_2/hp-hr, indicating clearly the effect of the impeller damage on the transfer efficiency (see Figure 6). Correlation between oxygen transfer rate and river discharge over the observed flow range as shown in Figure 6 indicates slightly higher transfer rates at the higher rates of flow. Also the figure shows that between the flow range of 100 to 130 cfs, there is a wide range of variation in oxygen transfer rate but the indicated variation is less if the figures before and after August 11 are considered separately. In addition to the effects of the damaged impeller, several possible factors might be responsible for variation, namely, changes in the α and β factors, effects of dispersion, short time or uncorrected irregularities in power consumption fluctuations (1), and sampling errors.

Flow Concentration Device Tests

As described in Section IV, the flow concentration tests were conducted on August 25 and August 26, 1970. The device was placed at 100 ft upstream of the aerator. DO and velocity readings, as in the other tests, were measured at 200 ft upstream and 100 ft downstream of the aerator. Readings were taken on the same day with and without the device. The field data are listed in Table 5-1, and the results of oxygen transfer are given in Table 5-2.

The results indicate that, for the August 25 field test, the average oxygen transfer rate with flow concentration was 1.50 lbs O_2/hp-hr, which was about 15 percent higher than the corresponding average transfer rate of 1.30 lbs O_2/hp-hr without the device on the same day. However, for the August 26 test, the figure of 1.36 lbs O_2/hp-hr with flow concentration was only slightly higher than the average of 1.34 lbs O_2/hp-hr without flow concentration. When the flow concentration device was in place, it was observed that the stream velocity downstream of the central opening showed a moderate increase. The increase in the velocity and hence the level of turbulence should bring about an increase in the oxygen transfer of the aerator. The fact that the device was not as tight as was expected (water was passing through both ends and also underneath) might be responsible for the relatively small increase noted in the transfer rates. The device was installed 100 feet upstream of the aerator, and bringing it closer would probably have increased its effectiveness.

Shallow Water Tests

The shallow water tests were conducted on August 27, 1970. As described earlier in Section IV, the aerator was moved upstream about 40 feet from the original site. Hydrographic surveys had shown that the mean water depth near the aerator was approximately 7 feet during low flows at the new site, whereas the corresponding depth at the original site was about 12 feet (see Figure 1). Three sets of lateral DO and velocity traverses were obtained. The basic data and the oxygen transfer results are given, respectively, in Tables 5-1 and 5-2. The average oxygen transfer rate for the shallow water tests was 1.34 lbs O_2/hp-hr under standard condi-

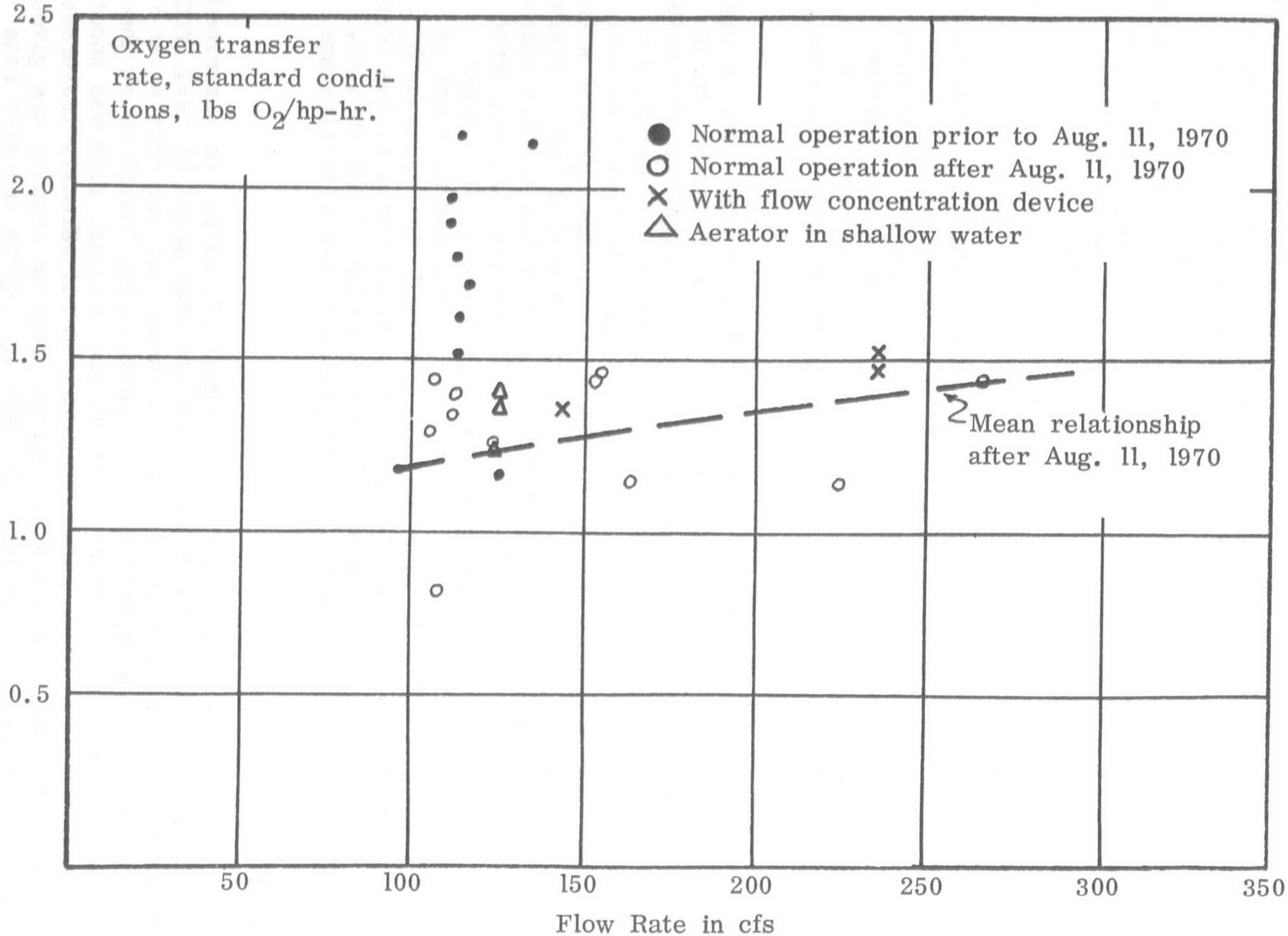

FIG. 6 OXYGEN TRANSFER RATE AND DISCHARGE

tions for discharges of 125 to 126 cfs. The efficiency was only slightly different from the deeper water average of 1.29 lbs O_2/hp-hr observed after August 11 for a flow range of 107 to 163 cfs.

Summary of Mechanical Aerator Results

Field tests conducted on the upper Passaic River during the summer of 1970 prior to the damage to the impeller resulted in an oxygen transfer rate of 1.69 lbs O_2/hp-hr under standard conditions for the mechanical aerator. This is about 94% of the performance observed in previous years.

Correlation appeared to exist between the oxygen transfer rate and river discharge for the observed flow range as had been noted in previous tests, but the number of observations and range of flows experienced were so limited as not to give conclusive verification.

The flow concentration device seemed to cause an increase in the stream velocity downstream and thus the oxygen transfer efficiency of the aerator. In order to be most effective, the device should be placed closer to the aerator and should be constructed so as to avoid major leakage.

The oxygen transfer rate observed when the aerator was operating in shallow (7 ft deep) water, was slightly greater than that with the deeper (12 ft) water but the differences are within the probable error of such observations.

Oxygen Diffuser Tests - Martin Marietta Corporation Equipment

Due to mechanical difficulties in the installation of the equipment, no conclusive tests on the dynamic type diffuser were conducted, and the static type equipment was tested in partially operative form, releasing only a fraction of the oxygen originally contemplated. This report includes results observed on all of the tests which produced significant results. Equipment is described in Section IV.

For most of the tests, lateral DO traverses were taken at river sections 10 feet above and 20 feet and 30 feet below the diffuser plates. For each section, DO and velocity readings were obtained for 10 to 15 points at various positions and depths within 30 feet of the East bank. It was observed that the effect of the operative portion of the diffuser during the sampling times was confined to this area. On two occasions, when approximate results were required quickly, longitudinal DO and velocity traverses were taken at points 10 feet upstream and 80 feet downstream of the diffuser plates, instead of the lateral traverses.

In addition, air and water temperatures were also taken during each traverse. The discharge of the river was obtained from gage readings of a U.S. Geological Survey for Pine Brook N.J. by means of a rating table. The gage was about 100 yards upstream of the test site.

The oxygen transfer rates of the diffuser plates, in terms of pounds of oxygen per hour, can be obtained by a mass balance computation. Under steady state conditions, the transfer rate of diffuser plates operating in a stream can be evaluated by the following equation:

$$R = 0.2246Q(C_d - C_u) \qquad .....5\text{-}9$$

in which

R = oxygen transfer rate in pounds of oxygen per hour
Q = river discharge in cubic feet per second
C_d = DO concentration at downstream sampling section in mg/l, and
C_u = DO concentration at upstream sampling section in mg/l.

Equation 5-9 implies that the amount of oxygen per hour supplied by the diffuser is proportional to the difference between the concentrations of oxygen downstream and upstream of the diffuser. In this equation the contributions from other oxygen sources or sinks, such as atmospheric reaeration, are considered negligible.

For the above equation to be strictly valid, it is necessary that (a) the dissolved oxygen concentrations be uniform throughout the upstream and downstream sampling cross-sections, and (b) the capacity of the diffuser must be such that the entire downstream cross-section is affected by the aerator at the time samples are taken. However, during the experiments in question, these conditions did not hold. Not only was the distribution of oxygen uneven, the velocities of the two sections involved somewhat different quantities of flow and degrees of turbulence. Therefore, the oxygen transfer was computed by means of the following equations:

$$R = \Sigma C'V'\Delta A' - \Sigma CV\Delta A \qquad .....5\text{-}10$$

where primes note conditions downstream of the diffuser. The basic assumption was made that $\Sigma V'\Delta A' = \Sigma V\Delta A$, or that the discharge recorded as passing through the downstream section was the same as that entering through the upstream section. Weighted mean values of $\overline{C}$ and $\overline{C}'$ were computed, weighting each DO reading proportionately to velocity observed at that point. The equation then reduced to a close approximation:

$$R = (\overline{C}' - \overline{C})\Sigma V'\Delta A' \qquad .....5\text{-}11$$

The amount of oxygen transfer was computed by Equation 5-9 for the longitudinal traverse results, and by Equation 5-11 for the lateral traverse results. The results together with dates, flow rate, and water temperatures are given in Table 5-3. It should be noted that in using Equations 5-10 and 5-11, the DO concentration at the upstream cross-section was assumed to be the same as DO concentration at the downstream cross-section before the aerator was turned on. The assumption seems reasonable since the two cross-sections are fairly close to each other (40 ft), and the sag curve in the vicinity was flat.

In general, the results are inconclusive. The July 9 and July 30 results are understood to be of questionable value due to imperfectly functioning

TABLE 5-3

SUMMARY OF OXYGEN TRANSFER DATA

DIFFUSER PLATES

Date	Time	Flow cfs	Water temp. °C	Upstream DO C_u mg/l	Downstream DO C_d mg/l	Oxygen transfer lbs/hr
7/9/70	9:15 a.m.	120	23.0	2.00	2.70	18.9
7/9	1:00 p.m.	120	23.5	3.80	4.10	8.1
7/30	1:00 p.m.	190	24.0	1.03	1.09	2.6
8/3	3:00 p.m.	256	25.0	1.75	1.75	0.0
8/4	9:00 a.m.	221	22.9	1.16	1.47	15.4
8/6	10:00 a.m.	152	22.0	1.95	2.04	2.0
8/6	2:45 p.m.	151	22.0	2.14	2.44	8.9
8/7	9:15 a.m.	136	23.0	2.07	2.15	2.7
8/7	1:00 p.m.	136	23.0	2.38	2.62	4.2
8/7	3:00 p.m.	136	23.0	2.56	2.79	3.6

NOTE: All DO data were obtained by lateral traverses, except for August 3 and August 4, on which longitudinal traverses were used.

diffusers. Also the longitudinal DO traverse provides only one DO reading for each cross-section. Hence the results are less reliable than those obtained with the lateral traverses.

If only the results from lateral traverses on August 6 and 7 are considered, an average oxygen transfer rate of 4.28 pounds per hour was obtained. This number seems to fall within the limits of the amount of oxygen supplied. However, a reading of 8.9 pounds per hour was computed for August 6, which actually exceeds the amount supplied. The accuracy of the DO meters and current meters was such that measurement errors of up to 4 lbs/hr might easily occur. The measurement system was planned to measure inputs of oxygen of the order of 75 pounds per hour, and accuracy cannot be assured under conditions such as those reported on here.

Proportions of Oxygen in Diffuser Bubbles and Oxygen Diffuser Efficiency

Samples were taken of the oxygen being used for the diffuser, and of the bubbles rising to the surface from the diffuser, in order to determine the proportion of oxygen in each. The original gas being bubbled was 99.4% pure oxygen. Table 5-4 shows percentages of nitrogen in the spent gases arising to the surface from the oxygen diffusers. The water may be assumed to have had approximately a saturation concentration of nitrogen relative to the atmosphere. As the fine bubbles of pure oxygen entered the water, they obviously absorbed additional nitrogen from the water, at the same time that most of the oxygen itself was entering the water. It is apparent that these ultra-fine bubble oxygen diffusers were operating at a very high degree of absorption.

TABLE 5-4

SPENT GAS FROM OXYGEN DIFFUSERS

Sample No.	% N_2*	% Oxygen plus Argon *
Air Atmosphere	78.3	21.7
#3	23.5	76.5
#4	20.8	79.2
#5	22.0	78.0
#6	22.3	77.7
#9	3.0	97.0
#16	25.9	74.1
#17	26.4	73.6
#20	43.2	56.8
#21	51.0	49.0
#24	25.9	74.1
#25	25.3	74.7

* By volume

SECTION VI

DISPERSION ANALYSIS

This section describes a dispersion test to determine qualitatively and quantitatively the downstream movement of an aerated slug of river water. Essentially bank-to-bank aeration was effected in the Passaic River owing to the narrowness of the river and the large mechanical aerator (see Figure 2). Furthermore, owing to the shallowness in this particular portion of the river, it can be assumed that vertical dispersion of the dissolved oxygen occurred completely within a very short distance downstream of the aerator. As a result, the dispersion phenomena take place primarily in the downstream direction. References (12) through (27) cover the theory of dispersive phenomena.

Background Theory

Immediately after injecting a quantity of dye into a stream, the spreading process that ensues is dominated by what are referred to as convective transport phenomena. The concentration distributions take on a conspicuous skewness in this convective region. Initially quite severe, this skewness diminishes until, at the end of the convective region, the symmetrical concentration distributions pertaining to one-dimensional, unsteady diffusion prevail. Once the concentration distributions attain this symmetrical character, their behavior is predicted by the one-dimension dispersion model. The different dispersion regions 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 in Figure 7. In (a) the view is that of a vertical plane parallel to the stream direction; in (b) are 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. However, until this occurs, the dye-cloud spreading phenomenon is convective; following this interval, it becomes dispersive. It is therefore important to arrange data-taking procedures so as to record the symmetrical gaussian concentration distributions.

Several schemes have been devised through which the longitudinal dispersion coefficient may be determined (see Ref. 17). The one employed in the present study is the change of moment method.

The three-dimensional, unsteady conservation of mass equation for the dispersion of a conserved quantity will be developed by decomposing the velocity field and the concentration of the quantity into a time averaged and fluctuating quantity. Assuming conservation of mass for the mean velocity field, we obtain, in Cartesian form

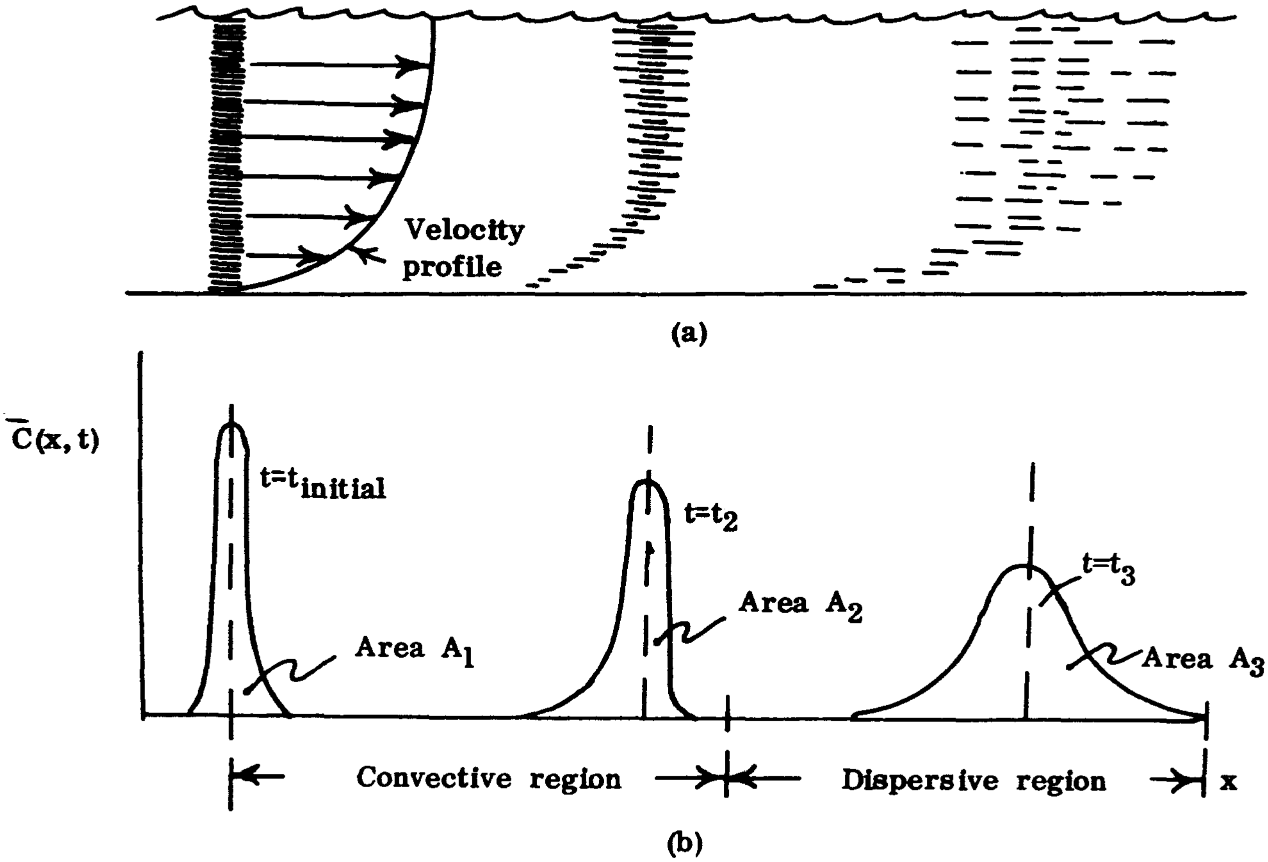

FIG. 7 DYE PATTERNS IN A STREAM

$$\frac{\partial \bar{c}}{\partial t} + \bar{u}\frac{\partial \bar{c}}{\partial x} + \bar{v}\frac{\partial \bar{c}}{\partial y} + \bar{w}\frac{\partial \bar{c}}{\partial z} = -\frac{\partial}{\partial x}(\overline{u'c'}) - \frac{\partial}{\partial y}(\overline{v'c'}) - \frac{\partial}{\partial z}(\overline{w'c'}) + D_{AB}\left[\frac{\partial^2 \bar{c}}{\partial x^2} + \frac{\partial^2 \bar{c}}{\partial y^2} + \frac{\partial^2 \bar{c}}{\partial z^2}\right] \qquad \text{..... 6-1}$$

where $\bar{u}$, $\bar{v}$, $\bar{w}$ are the usual time averaged velocities (13). The quantity $\bar{c}$ is the time average concentration and D_{AB} is a molecular dispersion coefficient that is assumed uniform and isotropic. Invoking the Fickian dispersion relations:

$$\overline{u'c'} = -E_x \frac{\partial \bar{c}}{\partial x}$$

$$\overline{v'c'} = -E_y \frac{\partial \bar{c}}{\partial y} \qquad \text{..... 6-2}$$

$$\overline{w'c'} = -E_z \frac{\partial \bar{c}}{\partial z}$$

and by dropping the molecular dispersion terms, which are dominated by their turbulent dispersion counterparts, the original conservation equation becomes:

$$\frac{\partial\bar{c}}{\partial t} + \bar{u}\frac{\partial\bar{c}}{\partial x} = \bar{v}\frac{\partial\bar{c}}{\partial y} + \bar{w}\frac{\partial\bar{c}}{\partial z} = \frac{\partial}{\partial x}(E_x \frac{\partial\bar{c}}{\partial x}) + \frac{\partial}{\partial y}(E_y \frac{\partial\bar{c}}{\partial y}) + \frac{\partial}{\partial z}(E_z \frac{\partial\bar{c}}{\partial z}) \qquad \ldots.. \; 6\text{-}3$$

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

$$\frac{\partial\bar{c}}{\partial t} + u\frac{\partial\bar{c}}{\partial x} = E_x \frac{\partial^2\bar{c}}{\partial x^2} \qquad \ldots\ldots \; 6\text{-}4$$

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

$$\bar{c}(\pm\infty, t) = 0$$

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

$$M = \rho A\int_{-\infty}^{\infty} \bar{c}(x,0)dx = \rho A\int_{-\infty}^{\infty} \bar{c}(x,t)dx \qquad \ldots.. \; 6\text{-}5$$

Solutions to the one-dimensional dispersion model, satisfying these conditions are given by

$$\bar{c} = \frac{Q_{inject}}{A\rho(4\pi E_x)^{\frac{1}{2}}}\int_0^t \frac{1}{t-\tau} e^{\frac{-[x-\bar{u}(t-\tau)]^2}{4E_x(t-\tau)}} d\tau \qquad \ldots.. \; 6\text{-}6$$

Experimental determination of the coefficient, E_x, via the method of moments (15) utilizes the transformation:

$$\xi = x - \bar{u}t \qquad \ldots.. \; 6\text{-}7$$

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

$$\frac{\partial^2\bar{c}}{\partial t^2} = E_x \frac{\partial^3\bar{c}}{\partial\xi^2\partial t} \qquad \ldots.. \; 6\text{-}8$$

Multiplying by ξ^2 and integrating overall values of ξ produces

$$\int_{-\infty}^{\infty} \frac{\partial^2\bar{c}}{\partial t^2}\xi^2 d\xi = E_x \int_{-\infty}^{\infty} \frac{\partial^3\bar{c}}{\partial\xi^2\partial t} \xi^2 d\xi \qquad \ldots.. \; 6\text{-}9$$

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

$$\frac{d}{dt}\int_{-\infty}^{\infty} \frac{\partial \bar{c}}{\partial t}\,\xi^2 d\xi = 2E_x\int_{-\infty}^{\infty} \frac{\partial \bar{c}}{\partial t}\,d\xi \qquad \text{..... 6-10}$$

Defining the variance by

$$\sigma_\xi^{\,2} = \frac{\int_{-\infty}^{\infty} \frac{\partial \bar{c}}{\partial t}\,\xi^2 d\xi}{\int_{-\infty}^{\infty} \frac{\partial \bar{c}}{\partial t} d\xi} \qquad \text{..... 6-11}$$

we obtain the following relationship for E_x:

$$E_x = \frac{1}{2}\,\frac{\Delta\sigma^2}{\Delta t} \qquad \text{..... 6-12}$$

Equation 6-11 may be transformed

$$\sigma_t^{\,2} = \frac{\int_0^{\infty} t^2 \frac{d\bar{c}}{dt} dt}{\int_0^{\infty} \frac{d\bar{c}}{dt}\,dt} - \bar{t}^2 \qquad \text{..... 6-13}$$

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

$$t = \frac{\int_0^{\infty} t \frac{d\bar{c}}{dt} dt}{\int_0^{\infty} \frac{d\bar{c}}{dt} dt} \qquad \text{..... 6-14}$$

The longitudinal dispersion coefficient, E_x, will be determined using the relations of references (23) through (25).

Experimental Results

The experimental determination of the dispersion coefficient, E_x, was performed using the constant dye-injection rate method. With this method, dye is injected into the turbulent crown of water in the aerator at an instant of time and at a constant and proper rate. As this injection continues, the sampling procedure begins at the upstream station. Here, at given intervals of time, river samples were dipped and labelled. Spot-checking of the dye concentration was also performed with a portable Turner fluorimeter. After observation of the "plateau value" of the dye concentration, which is determined by dye-injection rate and river discharge, the procedure is repeated at the downstream station. With the dye front so monitored through two such stream stations, the finite differencing calculation determines the longitudinal dispersion coefficient.

The concentration distributions moving through two stream stations are represented in Figure 8. The corresponding differentiated distributions are presented in Figure 9. Using a computerized moment method, the value of the longitudinal dispersion coefficient, E_x, is $5.5 \times 10^6 ft^2/min$. This

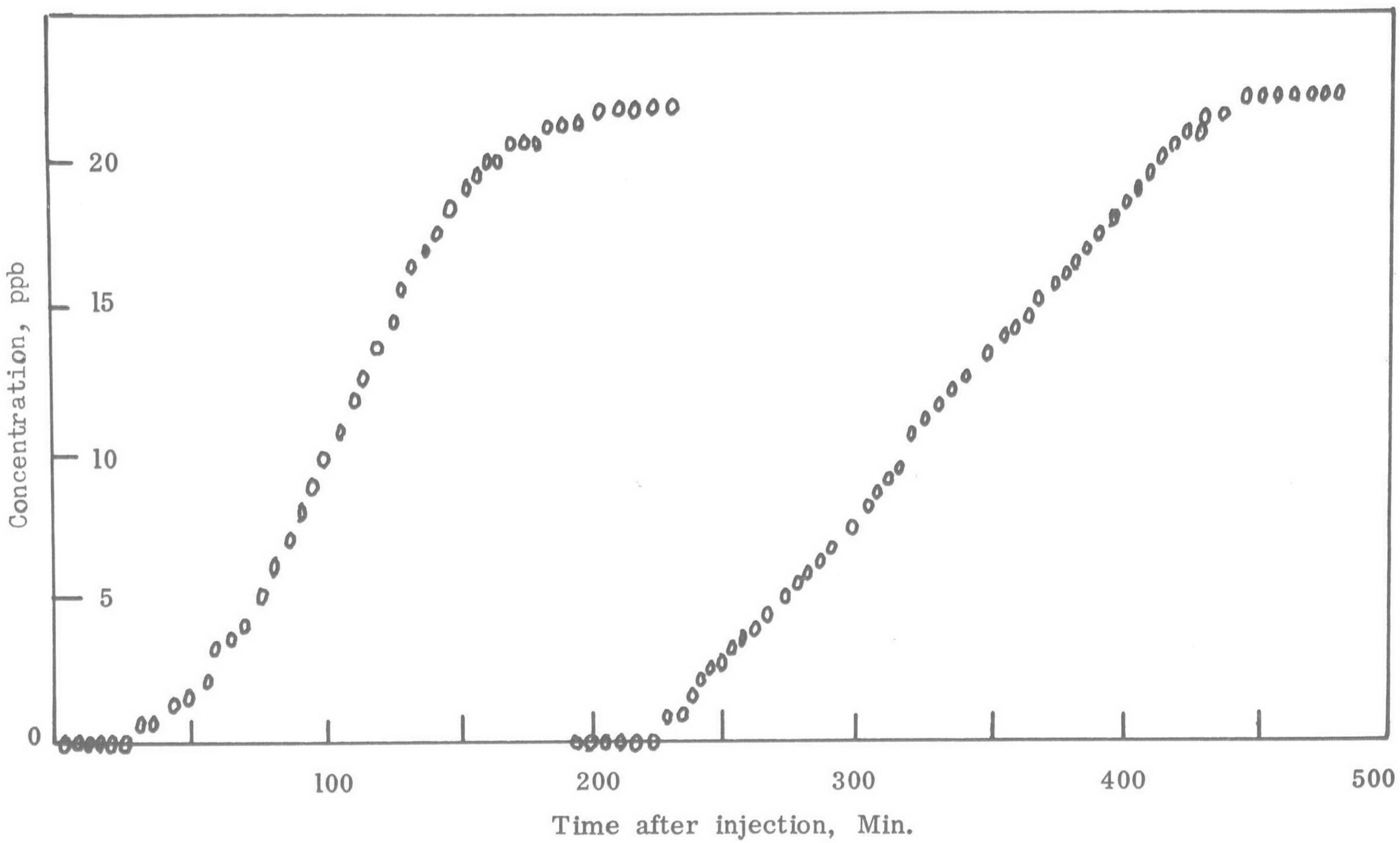

FIG. 8 DYE CLOUD FRONTAL STRUCTURE VS TIME

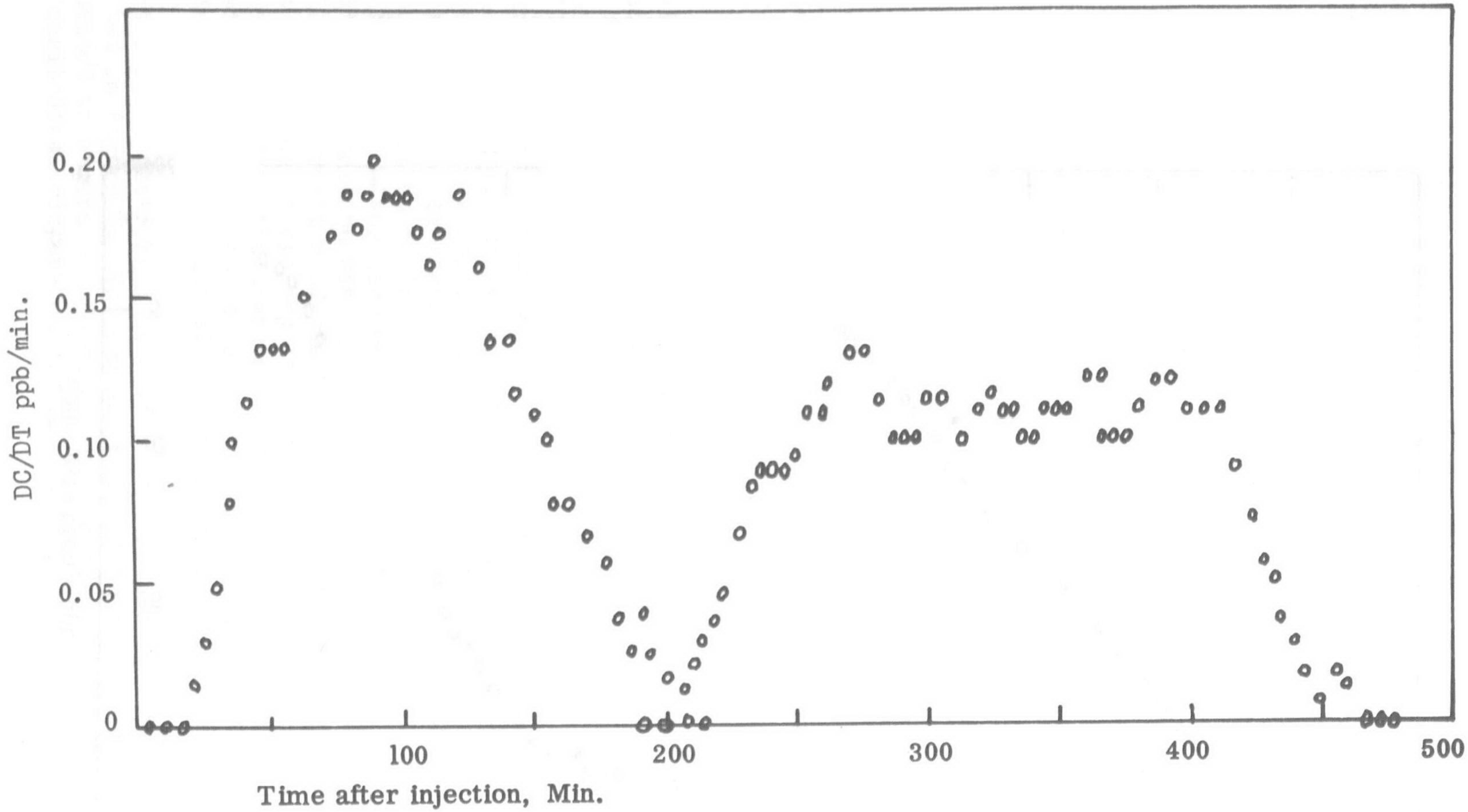

FIG. 9 DIFFERENTIATED DYE CLOUD FRONTAL STRUCTURE VS TIME

value pertains to this mechanical aerator in this reach of the Passaic River, as determined by the data taken from two stream stations 6,000 ft apart. The first station was 1,000 ft (or 20 river widths) downstream of the aerator.

This experimentally determined dispersion coefficient is slightly inflated owing to the effects of a motor boat that passed through the dye front three times. The circumstance was unavoidable since the downstream station was inaccessible by land. To minimize the effect on the coefficient, the boat was run at essentially idle speed--a speed that seldom was exceeded on this reach of the Passaic because of the danger of striking submerged logs and other debris.

This high value for the longitudinal dispersion coefficient compares very well with the coefficient determined downstream from a similarly turbulent aerator in the Delaware River ($E_x = 8.5 \times 10^6 ft^2/min$)(6). Previous coefficient values available in the literature (27) indicate that a "natural" value of $9.6 \times 10^5 ft^2/min$, 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 $1.6 \times 10^5 ft^2/min$ has been determined by Paulson (22).

Photographs of the Passaic aerator in operation reveal the turbulence imparted by it to the river water (see Fig. 2). It is this turbulence in this relatively slow (average velocity: 22.3 ft/min), shallow (4-5 ft) section of the Passaic that is primarily responsible for a dispersion coefficient that is almost an order of magnitude greater than any "natural" value.

It is significant to note from Figures 8 and 9 that the concentration levels at the dye front protrude downstream ahead of the mean stream velocity of the cloud. Assuming that the dissolved oxygen levels in the river behave similarly, it is concluded that an amount of river water greater than the mean slug quantity has experienced an increased DO. Considering travel times specifically, Figure 8 shows that the leading edge precedes the frontal mean by approximately 50% at the upstream station. At the downstream station, the leading edge protrudes by about 30% of the mean travel time.

Summary

The experimental results verify the highly dispersive nature of the mechanical aerator tested in the relatively slow, shallow Passaic River. Despite the low discharge and shallow depth, the turbulence generated by this aerator causes the longitudinal dispersion of $E_x = 5.4 \times 10^6 ft^2/min$ to exceed by a factor of five the largest "natural" coefficient yet observed. This natural value of $9.5 \times 10^5 ft^2/min$ was observed in the Missouri River flowing at 33,000 cfs.

Through this excessive longitudinal dispersion, the leading edge travel-distances are found to exceed the mean travel-distance values by 50% and 30% at the upstream and downstream stations, respectively.

SECTION VII

MATHEMATICAL MODEL AND PARAMETERS OF BOD

It is important to determine not only how much oxygen is added to a river by induced aeration, but what the subsequent reaction of the river will be to the addition. Those familiar with the dynamics of biochemical oxygen demand are acutely aware of the many irregularities and anomalies which are imperfectly encompassed by the Streeter-Phelps relationships; and of the inadequacies of the usual five-day BOD tests as indicators of future oxygen demand. Mathematical modelling of the first two years of aeration tests upon the Passaic River left inferences that parameters of deoxygenation had been increased markedly coincident with the aeration process (1). This led to a new research project (8) starting in 1970; the first phase of which was combined with the demonstration project herein reported on. For the field tests of 1970, a very careful check was made, combining nitrogen balances and various techniques of laboratory and field BOD analysis in order to provide a sound biochemical dimension of modelling. These studies, which will be reported on when completed, indicate that no substantial nitrification was occurring during the 1970 tests, despite the presence of very heavy ammonia concentrations and numbers of nitrifying bacteria. However, mathematical modelling was conducted to give the best statistical indications as to the reactions of the river. This modelling was conducted by two separate approaches, using analog and digital curve-fitting techniques.

Basic Theory

The modified Streeter-Phelps models applicable to the Passaic River are given by

$$\frac{dl}{d\tau} = -K_r L; \qquad L\ (0) = L_o \qquad .....7\text{-}1$$

$$\frac{dn}{d\tau} = -K_n L; \qquad N\ (0) = N_o \qquad .....7\text{-}2$$

$$\frac{dc}{d\tau} = K_a(C_s - C) - K_r L - K_n N + \overline{P\text{-}R} - B; \qquad .....7\text{-}3$$

where

τ = distance downstream divided by stream velocity, or time of travel.
L = ultimate BOD (carbonaceous) in mg/l.
K_r = carbonaceous BOD removal constant in $days^{-1}$ (Assumed equal to K_d, the deoxygenation constant.)
N = ultimate BOD (nitrogenous) in mg/l.
K_n = nitrogenous BOD removal constant in $days^{-1}$
C = dissolved oxygen concentration mg/l.
K_a = coefficient of atmospheric reaeration in $days^{-1}$
C_s = the saturation value of atmospheric oxygen in water mg/l.
$\overline{P\text{-}R}$ = net production of photosynthetic oxygen, in mg/l/day.
B = benthal oxygen demand in mg/l/day.

In the analysis, most of the values were determined by individual observations (such as temperature, stream discharge, L, N, and C), or approximated by determinations based upon actual data and considered reasonably characteristic of the Passaic River (C_s, $\overline{P-R}$, and B). The reaeration coefficient was determined according to the method of Owens-Edwards-Gibbs (10). Thus the parameter search could be limited mainly to determining the most likely values of K_r and K_n.

Curve Fitting Strategy by Digital Computer Method and Results

In the digital computer approach, the simulation technique was adopted in place of the usual non-linear regression analysis because of the complexity of the normal equations involved in the latter method. The procedure employed was essentially a computer search routine which would select a particular set of parameters K_r and K_n that would give the minimum standard error in fitting the observed DO data. In searching for the appropriate set of parameters, a systematic sampling uniform-grid method was used. All the computations were performed on the Rutgers IBM 360/67 computer.

For each set of data, the curve-fitting began with setting up initial values for both K_r and K_n. The following form of the Streeter-Phelps relationships indicates the deficit at each point of observation along the river reach below the aerator (1).

$$D_\tau = \frac{K_r L_o}{K_a - K_r}\left(e^{-K_r\tau} - e^{-K_a\tau}\right) + \frac{K_n N_o}{K_a - K_n}\left(e^{-K_n\tau} - e^{-K_a\tau}\right)$$

$$+ D_o\left(e^{-K_a\tau}\right) + \frac{B}{K_a}\left(1 - e^{-K_a\tau}\right) - \frac{\overline{P-R}}{K_a}\left(1 - e^{-K_a\tau}\right) \qquad \text{.....7-4}$$

where

D_τ = the oxygen deficit at holding time τ, and other symbols are as previously defined.

In the above equation all the parameters except K_r and K_n were either actually measured (11) or computed by known relationships (1). For the cases in which both L_o and N_o values were not known, the averages of the observed values were used. The computed DO deficits were then compared with the observed values in the following manner.

$$E = \Sigma_{i=1}^{n}(D_i - D_i')^2 \qquad \text{.....7-5}$$

in which

D_i = the actually observed DO deficit at point i, and

D_i' = the DO deficit computed by Equation 7-4 using assigned values of K_r and K_n.

After the E value was computed for the initial values of K_r and K_n, a new set of K_r and K_n values was assigned and a new value of E was obtained.

TABLE 7-1

SUMMARY OF RESULTS BY DIGITAL COMPUTER SIMULATION

Date	Aerator	Flow cfs	Temp. C°	C_s mg/l	D_o mg/l	B mg/l	P-R mg/l	L_o mg/l	N_o mg/l	K_a day^{-1}	K_r day^{-1}	K_n day^{-1}	S_e mg/l
7/15/70	ON	125	22.0	8.65	4.67	0.32	0.76	19.7	13.6	0.44	0.20	0.15	0.19
7/20	ON	115	23.5	8.20	2.73	0.34	0.78	13.8*	10.7*	0.49	0.10	0.05	0.51
7/22	OFF	109	21.5	8.70	5.20	0.34	0.79	13.8*	10.7*	0.46	0.25	0.15	0.14
7/23	OFF	109	20.7	8.88	6.38	0.35	0.76	13.8*	10.7*	0.44	0.30	0.15	0.32
7/24	OFF	109	22.5	8.60	5.97	0.35	0.79	13.8*	10.7*	0.46	0.60	0.05	0.38
7/27	ON	113	24.3	8.30	6.08	0.34	0.75	13.8*	10.7*	0.48	0.70	0.05	0.70
7/27	ON	113	24.5	8.25	3.20	0.34	0.75	13.8*	10.7*	0.48	1.00	0.00	0.92
7/28	ON	111	25.0	8.20	3.37	0.34	0.48	13.8*	10.7*	0.49	0.35	0.20	1.11
7/28	ON	111	25.0	8.20	3.26	0.34	0.79	13.8*	10.7*	0.49	0.40	0.10	1.40
8/12	ON	109	24.0	8.30	3.92	0.34	0.95	17.6	7.0	0.48	0.20	0.25	0.34
8/20	ON	111	23.0	8.75	4.60	0.34	0.48	6.2	10.5	0.47	0.40	0.45	0.40

* Averages of the observed data

This procedure was repeated for K_r and K_n values both ranging from 0.0 to 1.0, with an increment of 0.05. Thus there was a total of 441 combinations of the parameter values. The computer would examine all the 441 E values and select the minimum value and the associated K_r and K_n values. The range of 0.0 to 1.0 was chosen because it was thought that this range would cover the values most commonly found in the literature for such a river.

There were eight sets of DO data with the aerator "on" and three sets with the aerator "off." The results of the analysis are listed in Table 7-1. The standard error of estimate S_e, given in Table 7-1, was computed by

$$S_e = [\frac{1}{n-2} \Sigma (D_i - D_i')^2]^{0.5} \quad .....7\text{-}6$$

In order to investigate the effect of the aerator operation on the parameters K_r and K_n, the "best" values of these parameters found by the computer simulation were reduced to the standard temperature by the following relationships: (1)

$$K_r(T) = K_r(20) \times (1.045)^{T-20} \quad .....7\text{-}7$$

$$K_n(T) = K_n(20) \times (1.09)^{T-20} \quad .....7\text{-}8$$

The reduced K_r ana K_n values are listed in Table 7-2, according to the aerator operating mode:

Table 7-2

SUMMARY OF K_r AND K_n VALUES AT 20°C

Aerator ON Date	K_r	K_n
7/15/70	0.18	0.13
7/20	0.09	0.04
7/27	0.58	0.03
7/27	0.82	0.00
7/28	0.28	0.13
7/28	0.32	0.06
8/12	0.17	0.18
8/20	0.35	0.35
Average	0.35	0.12

Aerator OFF Date	K_r	K_n
7/22/70	0.23	0.13
7/23	0.29	0.14
7/24	0.52	0.04
Average	0.34	0.10

Upon examining the average values of the K_r and K_n parameters, it appears that the operation of the aerator does not have any significant effect on these parameters. The values of the parameters are a little higher when the aerator was on than when the aerator was off, but by only very small margins. For individual tests, the following points were observed:

1) There seem to be no consistent patterns that the variation in the parameters would follow either when aerator was on or off. For example, a high K_n value was obtained for August 12 when aerator was on. Yet on

several other dates, such as July 20 and July 27, when the aerator was also on, very low K_n values were obtained. As for K_r, both high and low values were found when aerator was on while medium values were obtained when aerator was off (see Table 7-2).

2) In general, parameter values were obtained which gave very good fit, i.e., small standard error of estimates of the observed data. As an exception, the July 27 and 28 data could not be fitted very well because of unusual fluctuations in the observed DO concentrations. To illustrate this, one of the July 27 sets of data is plotted in Figure 10.

3) Mathematically speaking, the "best" solutions for the parameters do not seem to be unique. One could easily change the values of the parameters and still obtain a "near-best" fit. For example, for the August 12 data, the best values for K_r and K_n were, respectively, 0.20 and 0.25 with a standard error of estimate of 0.34 mg/l. However, if K_r was increased to 0.50 and K_n reduced to 0.15, the error only increased to 0.45 mg/l; and even when K_r = 0.01 with a K_n of 0.35 the error was only 0.44 mg/l. Strictly speaking, there is only one set of parameters that represents actual conditions. Nevertheless, it seems that more than one set of parameters would produce results that are practically just as good. Also, when K_n was (forced) to be zero, then the best K_r value was 1.0, which gave a poor standard error of estimate of 1.9 mg/l. The August 12 data are plotted in Figure 11.

The Analog Computer Parameter Estimation Strategy and Results

The present state-of-the-art in curve-fitting or parameter estimation procedures does not allow for perfect delineation between the various parameters in the modified Streeter-Phelps models of the Passaic River. For example, in the context of a nonlinear regression curve-fitting procedure, all of the parameters are coupled together in a nonlinear fashion when the system equations are presented in integrated form. This situation all too frequently leads to polymodality and multiple candidate parameter sets which are difficult to arbitrate. It is preferable to have available, in addition to the results from a nonlinear regression analysis based on a digital computer solution, a parameter estimation strategy which is linked to the differential equations of the model. In the modified Streeter-Phelps equations, the parameters are linear when the model is in its characteristic differential equation form. An analog computer is ideally suited for dynamic simulation and curve-fitting strategies, which, when used systematically on the differential equations produces on-the-spot parameter estimations. These estimations can be used as a check against estimations based on the digital computer strategy.

In Figure 12, there is shown a fully scaled analog computer diagram which represents the dynamic simulation of Equation 7-1, 7-2, and 7-3. Basically, a rotational reparameterization procedure was used for parameters K_r and K_n. A visual goodness of fit criteria was established and the poor data points were weighted to varying degrees. All simulations were carried out using a TR-48 analog computer. The simulations were all recorded on a 1130 X-Y plotter.

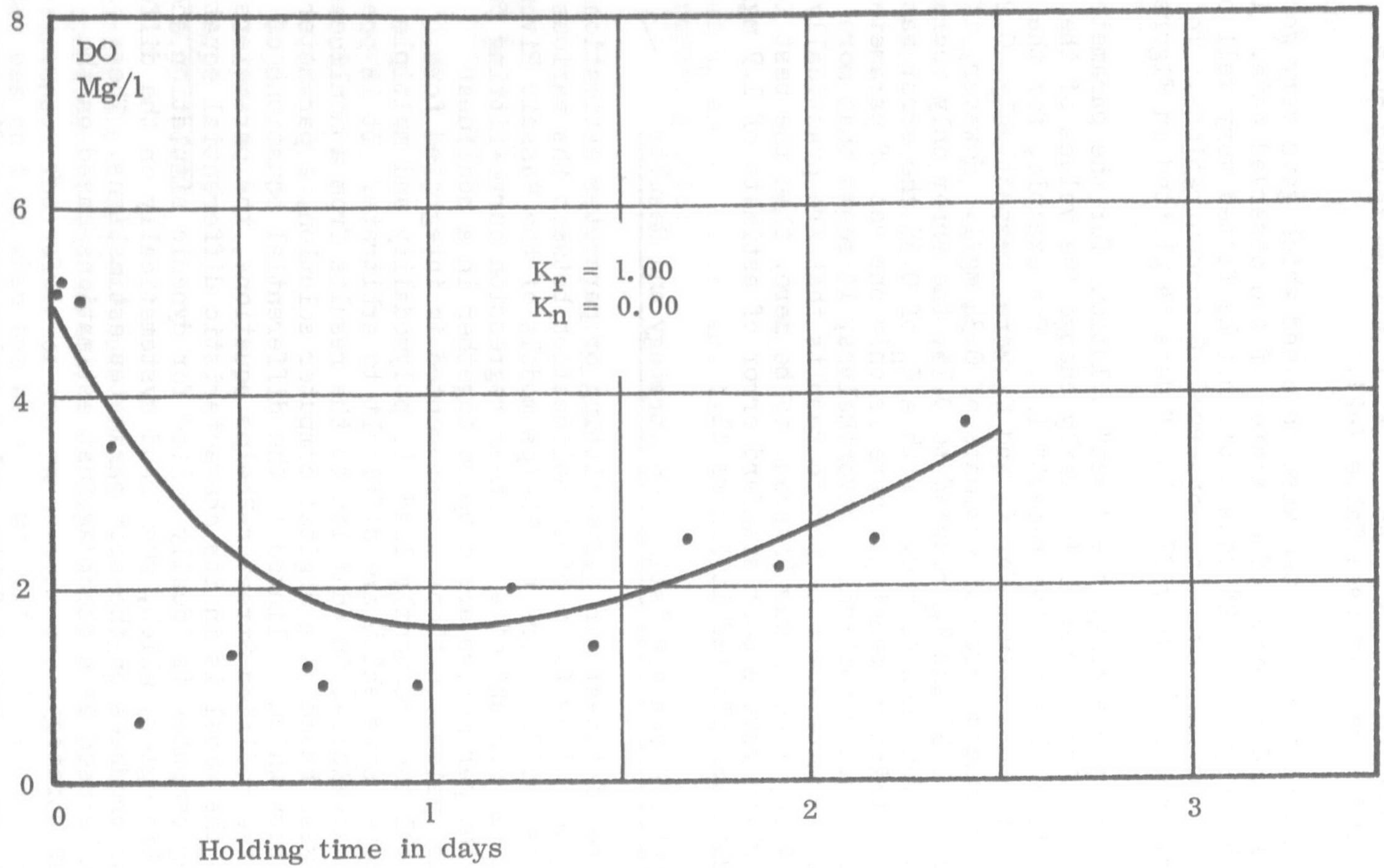

FIG. 10 DISSOLVED OXYGEN SAG CURVE FITTED BY DIGITAL COMPUTER
July 27, 1970, aerator on

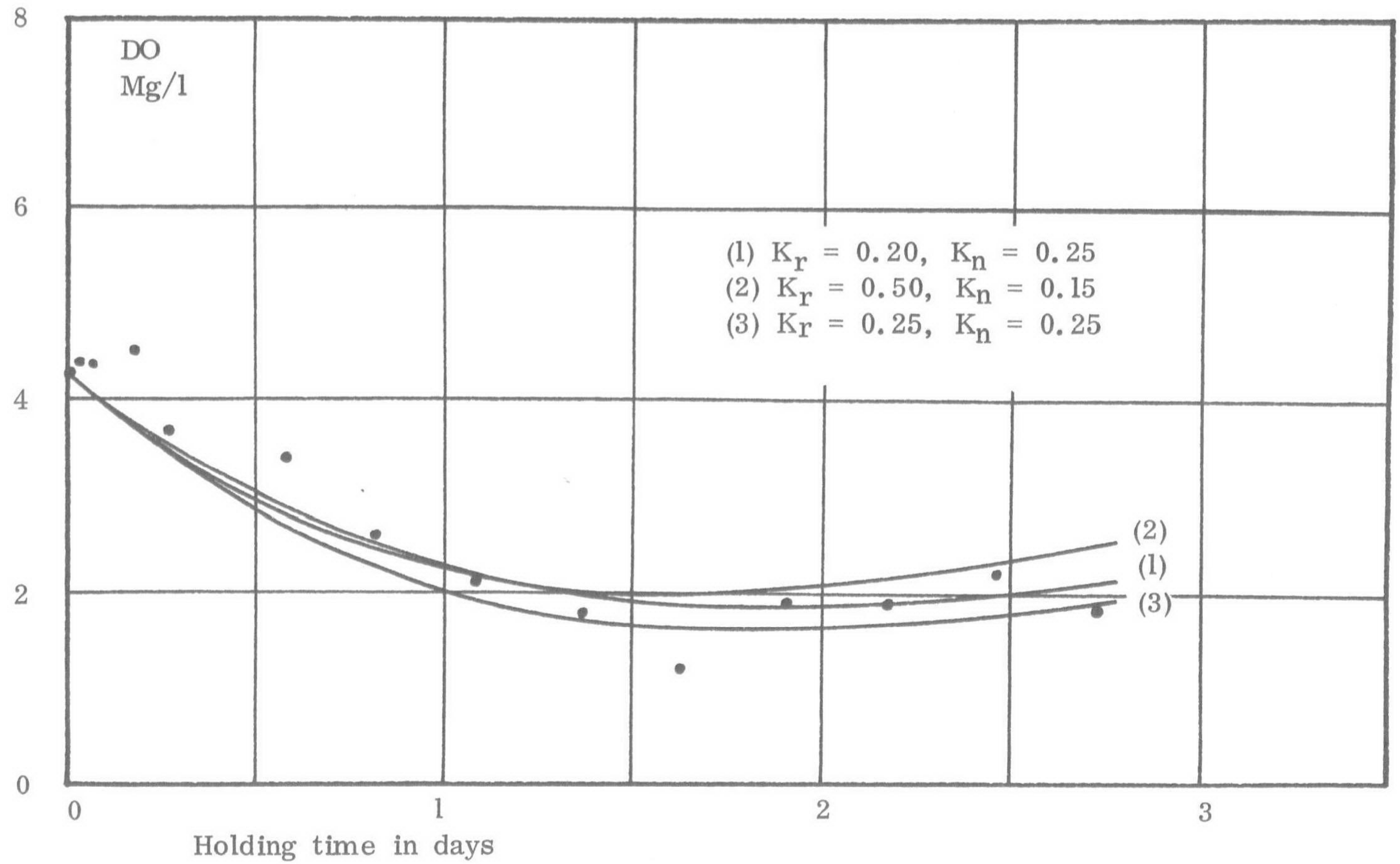

FIG. 11 DISSOLVED OXYGEN SAG CURVES FOR VARIOUS VALUES OF K_r and K_n
Aug. 12, 1970, aerator on

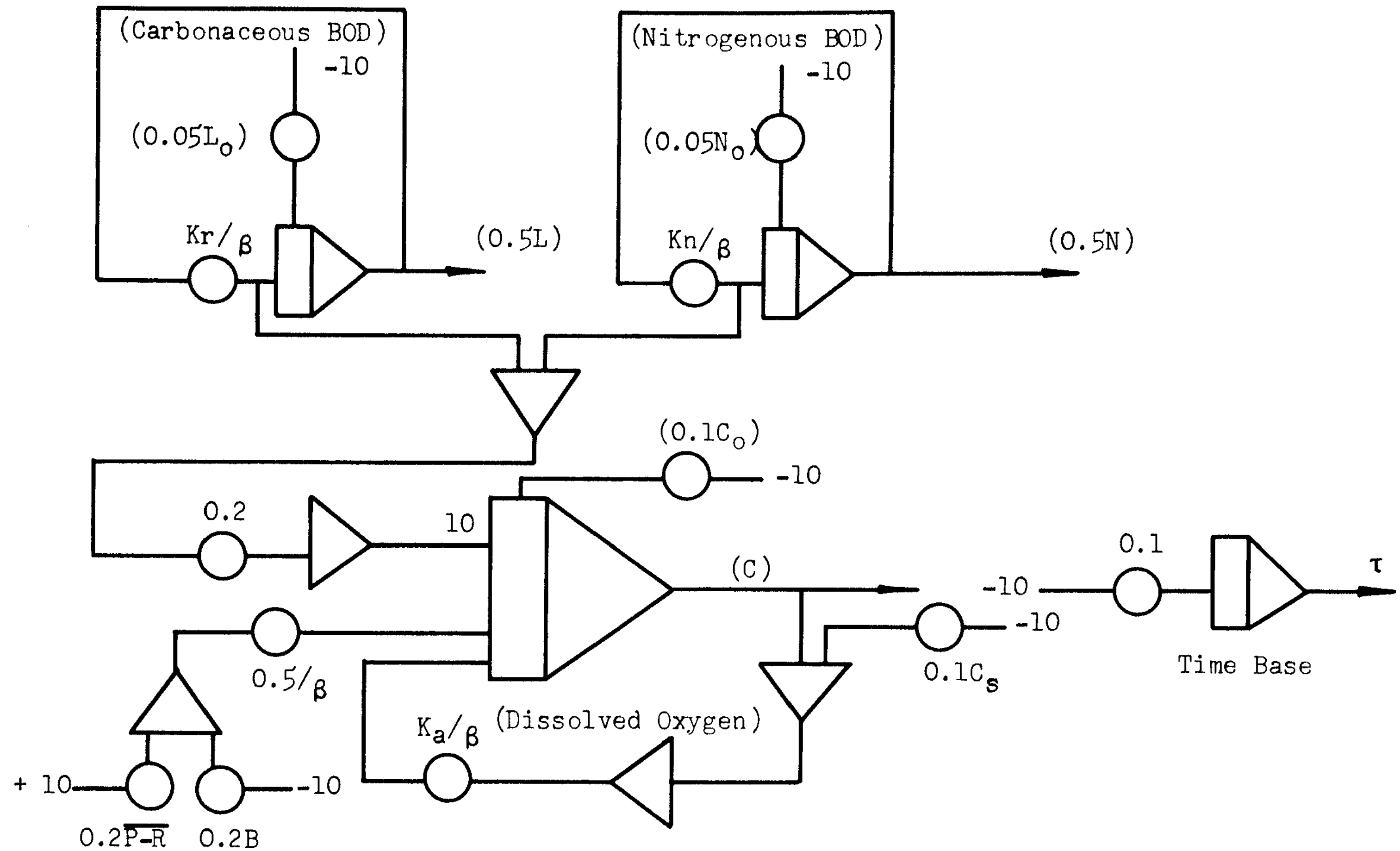

FIG. 12 SCALED ANALOG COMPUTER DIAGRAM USED IN THE SIMULTATION OF BOD, NOD, AND DO

Figure 13 shows some representative analog computer drawn curves for various K_r and K_n parameter sets. Curve number (A) represents the set of values of K_r and K_n which had been determined by purely digital computer techniques and regression analysis. This curve was used as a base line and reference grid for the rotational reparameterization strategy. Curves (B) and (C) represent extreme cases where K_r and K_n are zero. It can be surmised from the indicated trend in Figure 18 that when the aerator is on, there seems to be a rather pronounced tendency for K_n to have a value closer to 0.3 $days^{-1}$ than to a value of zero, and this trend seems to be little affected by K_r on the range of 0 to 0.2 $days^{-1}$. Figure 14 represents another set of data when the aerator was on, but the trend in K_r and K_n is not as clear. This is due primarily to the erratic behavior of the data in the 0.25 to 0.75 range of holding times. If these points are weighted lightly, then curve (B) fits the remainder of the data fairly well. Curve (A) represents the parameters derived from the digital computer. The analog computer drawn curve (A) consequently agrees nicely with what the digital computer would predict for this parameter set. If the data points in the 0.25 or 0.75 range of holding times are weighted more heavily than the points in the 1.5 or 2.0 range of holding times, we again witness an enhanced nitrogenous coefficient, even when $K_r = 0$. This is shown by curve (D). Curve (C) shows the value of K_n when the weighing of the data points are reversed. In Figure 15, results are shown for the case where the aerator is off. The parameter sets for curve (A) - (D), while all different, represent the data about equally well. For example, curve (A), which is also the digital computer result, is drawn through the middle of the cluster of points in an averaging fashion. Curves (B) - (D) on the other hand are drawn so as to weigh different parts of the data at different times. For example, curve (B) weighs the points less than 1 day and greater than 2 days more heavily than the points between 1 and 2 days. Curve (D) does likewise except that the lower range of points in the region greater than 2 days are weighed more heavily than the points with higher values of DO in the range 2-3 days. Curve (C) weighs the higher values of DO at the various values of τ. An enhanced value of K_r and a low value of K_n, however, seem to compromise the curve-fitting anomaly and would agree with the data in Figure 14.

There are several other possible interpretations of the data, but these would all involve increasing the number of undetermined parameters. For example, the reaeration coefficient, K_a, is determined from the Ownes-Edwards-Gibbs correlation, but there are several other authorities which would predict widely varying values for K_a. Each new value of K_a different from the one used here would alter significantly the range of values of K_r and K_n. Any major error or rapid changes in the BOD data would lead to much different interpretations. For example, in Figure 18, curve (C) could be interpreted as representing a situation where $K_n = 0$ and $L_o = 17.6$ mg O_2/l. This would correspond to a value of K_r = 0.39 $days^{-1}$. In Figure 14, curve (D) could be interpreted as representing a case where $K_n = 0$ with $L_o = 13.8$ mg O_2/l. This would mean that $K_r = 0.75$ $days^{-1}$. In Figure 15 curve (D) would likewise represent a situation where $L_o = 13.8$ and $K_r = 0.6$ $days^{-1}$ with $K_n = 0$. In view of the rapid fluctuations in BOD which have previously been shown to exist

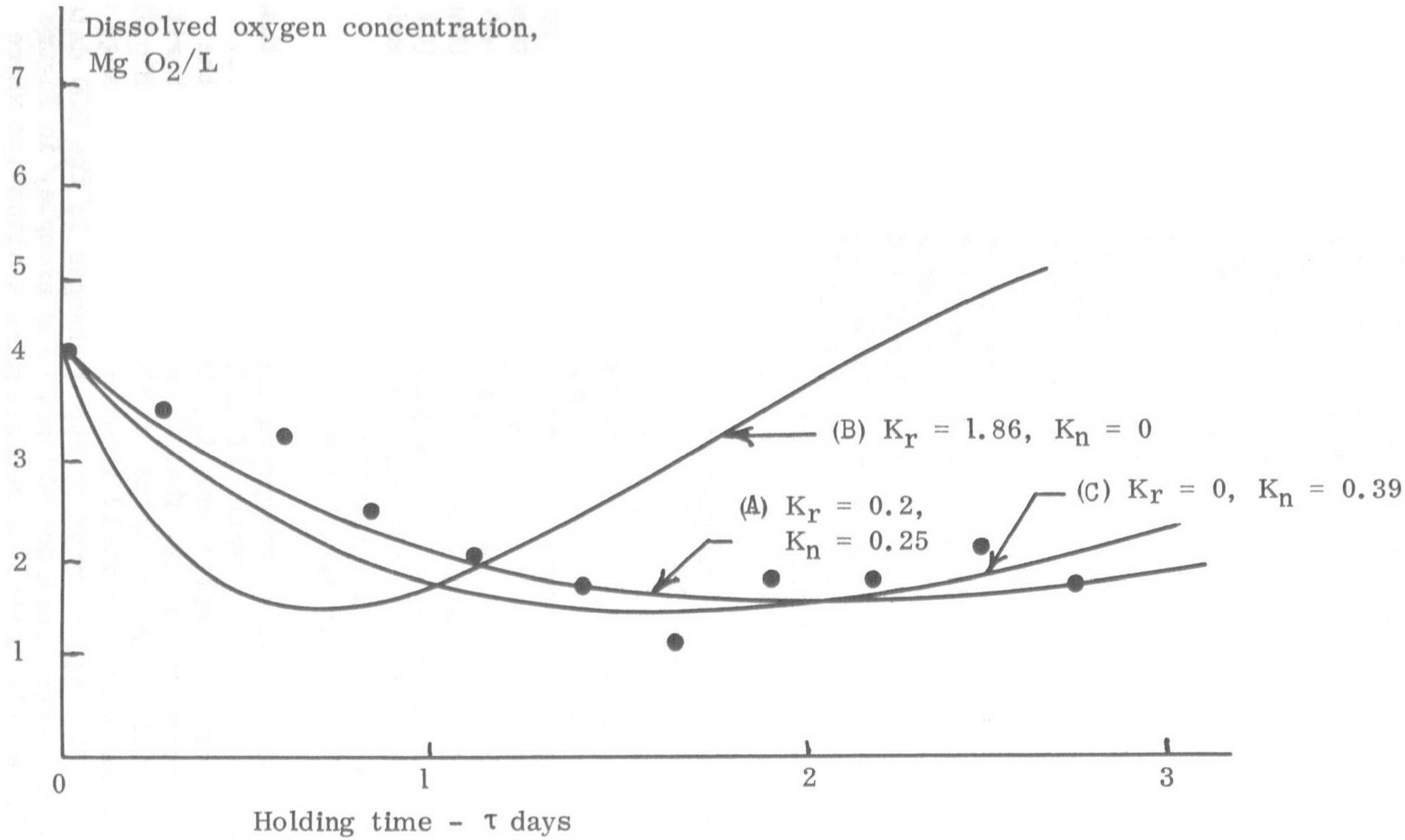

FIG. 13 ANALOG COMPUTER DRAWN CURVES OF DISSOLVED OXYGEN CONCENTRATION VERSUS HOLDING TIME, Aug. 12 data

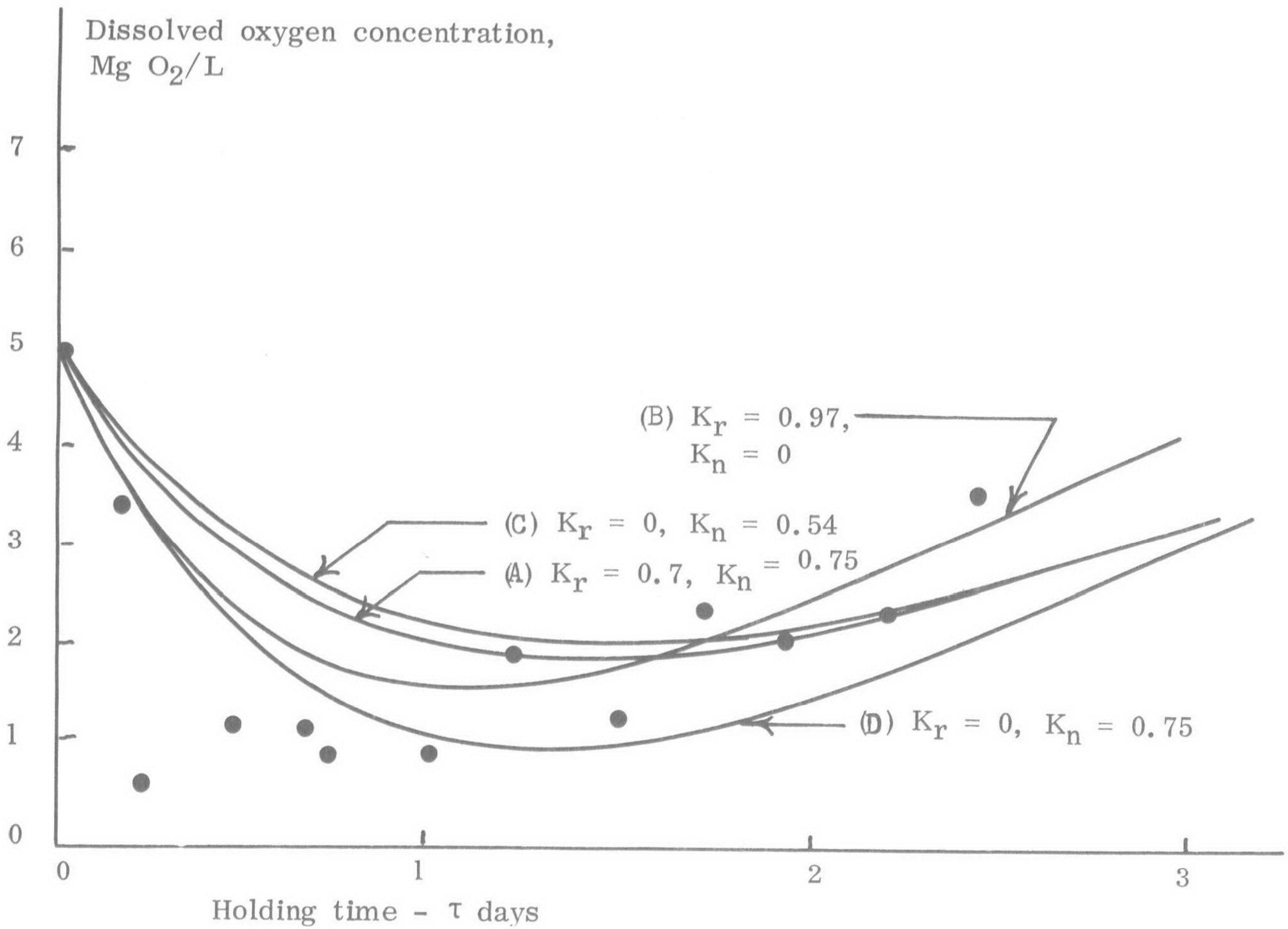

FIG. 14 ANALOG COMPUTER DRAWN CURVES OF DISSOLVED OXYGEN CONCENTRATION VERSUS HOLDING TIME, July 27 data (p.m.)

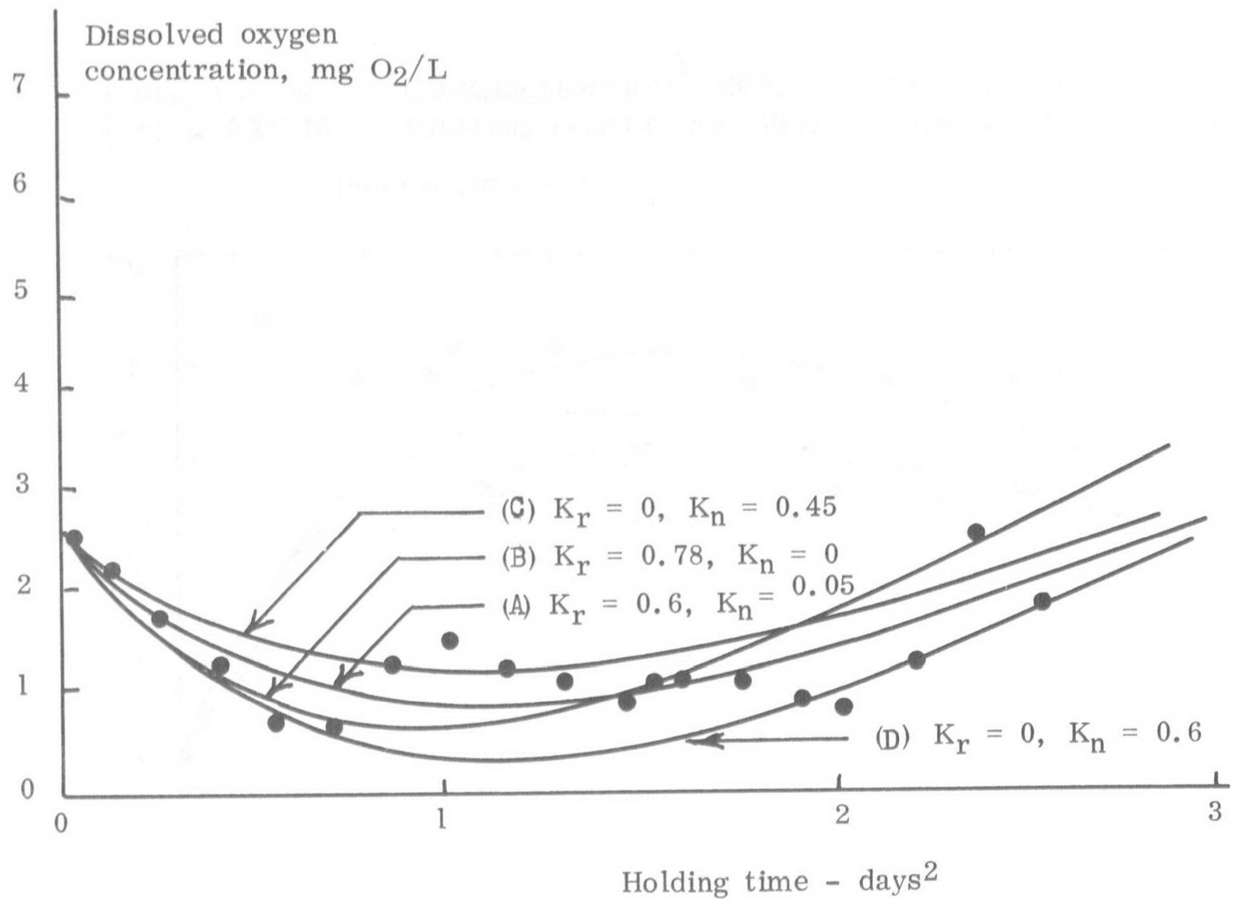

FIG. 15 ANALOG COMPUTER DRAWN CURVES OF DISSOLVED OXYGEN CONCENTRATION VERSUS HOLDING TIME, July 24 data

(1), the possibility of such changes affecting the analysis of individual sets of data must be taken into account.

Summary

There are various methods available for the computation of the parameters that would best fit the data. Yet the reliability of these computed parameters depends wholly on the accuracy of the estimation of the other parameters in the DO equation. Hence, accurate field measurements of certain parameters, such as K_a, B, $\overline{P-R}$, are essential to successful modelling.

Since fully reliable estimates of some parameters other than K_r and K_n cannot be obtained, it is of interest to model the oxygen dynamics regime for other likely values, using the analog and digital computer techniques of curve-fitting.

Based on the results of the analog and digital computer analysis, it did not appear that the operation of the mechanical aerator during the summer of 1970 had any significant or consistent effect on the parameters K_r and K_n.

Based upon statistical indications only, it would appear that appreciable nitrification was taking place during the test conditions. However, since there was strong biochemical evidence to the contrary, this aspect remains problematical.

SECTION VIII

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SECTION IX

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OXYGEN REGENERATION OF POLLUTED RIVERS: THE PASSAIC RIVER

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* Water pollution control, Water quality control, Stream improvement, Abatement, Aeration, Mathematical models.

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* Instream aeration, * Induced oxygenation

27 *Abstract*

Field tests were made of a mechanical surface aerator and of pure oxygen diffusers in a small polluted river, the upper Passaic. Results generally corroborated results of previous test, as to performance of surface aerators on such rivers, in excavated pools. A somewhat higher oxygen transfer rate was obtained with a flow concentration device, which, in a permanent installation, would take the form of low rock spur dikes, one extending from each bank, or flow concentration groins. Tests in shallower water, about 7 feet deep, were inconclusive. Tests of oxygen diffusers were fragmentary, due to mechanical difficulties with the equipment; but it was demonstrated that the very fine bubbles used were very largely absorbed in the water. A dye dispersion test gave a very high longitudinal dispersion coefficient downstream of the aerator. Mathematical modelling indicated that during the period of test, parameters of biochemical deoxygenation were not changed by the artificial aeration process. (Whipple-Rutgers)

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