THE INFLUENCE OF AIR FLOW RATE ON LINE DIFFUSER EFFICIENCY AND IMPOUNDMENT IMPACT

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by
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Introduction

Compressed air diffusers, or devices which release air bubbles at a submerged depth within an impoundment, are widely used to destratify and/or aerate impoundments. Historically these devices have been sized for particular sites by basically a trial and error method. Diffusers and compressors have been selected either in a fairly arbitrary way or as a result of experience at other sites. If the unit did not achieve the required results, it was modified or replaced by a larger unit. Little information has existed to allow systematic diffuser sizing, selection, and design to fit the needs of a particular impoundment.

The objective of this study was to collect field data and reduce them into useful diffuser design criteria. With these criteria, it is hoped that with known impoundment volume, impoundment depth, existing dissolved oxygen profiles, existing temperature profiles, desired dissolved oxygen profiles, desired temperature profiles, material costs, power costs, and physical constraints an optimum diffuser design for a specific site can be achieved.

Lake Casitas, near Ventura, California, was selected as the site at which the field data would be collected. The Lake was created by Casitas Dam which was built by the Water and Power Resources Service, formerly the U.S. Bureau of Reclamation. The dam was completed in 1959. The dam, reservoir, and distribution system are now owned and operated by the Casitas Municipal Water District. The reservoir primarily functions as a supply of domestic and industrial water. The lake has a maximum volume of 254,000 acre-ft (3.1×10^8 m^3), a maximum depth of 250 ft (76 m), and a maximum surface area of 2700 acres (1100 ha). The dam has a selective withdrawal outlet structure which contains nine gates located at 24-ft (7.3 m) vertical intervals.

The reservoir is monomictic (mixes once each year). Prior to any destratification efforts, the lake would begin to stratify in late February or March and would turn over in December. In the early years from July to November, the lake would experience anaerobic conditions

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below the thermocline. These conditions yielded water of marginal quality and caused operation difficulties. These conditions also limited the lake fishery and recreational use.

To treat this problem, in 1968 the District installed a destratification diffuser system. After a year or two of refinement, the diffuser system took the form of four bubble point sources, figure 1, on 70-ft (21 m) centers at a depth of 140 to 160 ft (43 to 49 m). The diffuser system was supplied an air flow rate of approximately 640 stdft^3/min (18.0 std. m^3/min) by two 75-hp (56 kW) electric compressors. The system was operated continuously from early May to mid-October.

Operation of this system partially destratified the entire lake from its surface to the depth of the diffusers. The partial destratification was such that cold water was maintained in the lower destratification region and yet aerobic conditions were also maintained throughout the region. Consequently; cold, high quality water could be withdrawn from the lake throughout the summer months. A trophy cold water fishery was also established and the number of yearly algae blooms on the lake was reduced. This diffuser system was operated from 1968 through 1976. Operation and maintenance costs increased steadily through that period. In the later years costs were over $20,000 per year, with the largest portion of this sum being the cost of electric power to drive the compressors.

Because of the existing compressed air diffuser facilities, the extensive existing lake water quality data, the desire of the Water District to reduce its operating costs, and the desire of the Water and Power Resources Service to develop diffuser design guidelines, the Service and the Water District agreed to perform research at Lake Casitas. It was decided that any new device tested would be sized and operated in such a way that resulting destratification and oxygenation levels would be similar to those achieved in the past. Thus, the District was assured adequate water quality. Biological monitoring of the lake was started nearly a year before line diffuser operation to allow comparison of the influences of the two diffusers. Contracts were established with Dr. Arlo Fast to monitor the biological properties of the lake and with the Department of Fish and Game of the State of California to assist in fisheries research studies. The Water District continued the monitoring of physical and chemical properties as practiced since the establishment of the lake.

Parameter Considerations

The temperature and dissolved oxygen states of an artifically destratified lake are a function of two sets of parameters. The first set comprise the natural terms or the parameters that would be present if the diffuser was operating or not. Such parameters include atmospheric effects, inflow effects, lake productivity and BOD, and lake geometry. If no diffuser operation was occurring, these parameters would dictate the natural lake temperature and DO (dissolved oxygen) status. It should be noted that for a specific site, the influence of these parameters can be evaluated. The natural lake temperature and DO response can then be predicted for years when this response is modified due to diffuser operation. In this way, the influence of these parameters can be separated from the diffuser influence and, thus, the diffuser influence can be evaluated.

The other set of parameters that would influence artifically destratified lake response is made up of those parameters that control diffuser influence. Included would be the configuration of the diffuser, the depth of submergence of the diffuser, the air flow rate per unit length of diffuser or the bubble distribution, and the bubble size which is a function of diffuser orifice size and gas flow rate per orifice. To have complete diffuser design guidelines, it would be desirable to have a knowledge of the influence of each of the parameters on diffuser destratification and reoxygenation efficiency. To evaluate the influence of a single parameter, lake response should be observed while all other parameters are held constant and the one parameter is varied. After considering the alternatives it was decided that the gas flow rate per unit length of diffuser would be varied while the other parameters would be, as much as possible, held constant.

It was noted that a wide variety of diffuser configurations are presently in use. Included here would be circular, point source, parallel straight lines, and single straight line diffusers; with the single straight line diffuser, figure 1, being the most common. It was also noted that the single straight line diffuser probably has the greatest potential for interaction with the lake body. The single straight line diffuser has the potential to create a widely spread bubble curtain. It is felt that in a dense or highly concentrated bubble plume a portion of the bubbles rise to the surface with reduced gas transfer and upwelling energy transfer to the lake body. Thus, a portion of the bubbles would be ineffectively used. In addition the concentrated plume would likely either start with, or through coalescence yield, large bubbles. Large bubbles would have less efficient gas transfer and energy transfer characteristics. The single straight line diffuser would also have effective interaction with the lake body on both sides of the bubble curtain. This would not be the case, for example, with the circular diffuser. The circular diffuser would create a cylindrical bubble curtain. The outer surface of this cylinder would have good interaction with the lake. The inner surface would, however, be isolated from the lake by the bubble curtain itself. Thus, a portion of the bubbles would not have optimum interaction with the impoundment. For these reasons the single straight line diffuser was selected for use in these studies.

At any site the desired depth of submergence is largely a function of the lake depth. Experience indicates that diffusers do not mix or aerate water that is deeper than the diffuser. Thus, to destratify or aerate a large portion of the lake volume, the diffuser must be located fairly deep. At the same time the diffuser must be kept at sufficient distance above the bottom to prevent mixing of bottom sediment. Historically, Lake Casitas has operated with approximately 150 ft (46 m) of diffuser submergence. To maintain continuity with past data, the 150 ft (46 m) submergence was held constant throughout this study. It should be noted that greater submergence will result in a longer bubble curtain that will consequently yield more interaction between the bubble curtain and the lake body. Deeper submergence, thus, produces increasing upwelling and, therefore, greater aeration and destratification efficiencies. Likewise, shallow submergences would show reduced efficiencies. Work done by Straub' [1] and Bulson [2] indicate a fairly direct linear relationship between submergence and quantity of flow upwelled. It is thought that future work that relates depth of submergence to destratification and oxygenation efficiency would be of value.

With respect to bubble size, it was theorized that smaller bubbles would produce more efficient destratification and oxygenation. As previously noted smaller bubbles would have greater surface area to volume ratios. Thus, they would have more potential for gas transfer per unit of bubble volume. The smaller bubble size would also experience high coefficients of drag and, thus, would yield greater destratification energy transfer per unit bubble volume. Thus, efforts were made to design a diffuser that would yield minimum feasible bubble sizes. Previous research [3, 4] indicates that bubble size is a function of orifice size, pressure differential across the orifice, gas density at the orifice, and surface tension of the fluid into which the bubbles are released. At a specific depth of submergence and in a water body, gas density at the orifice and surface tension of the fluid are near constants over the flow rate ranges tested. Therefore, orifice size and pressure differential were the two parameters considered further.

Orifice size influences diffuser operation in two ways. First, by adjusting orifice size and thus, total orifice area for the diffuser, the pressure differential across the orifice is varied for any given air flow rate. It was considered desirable to have sufficient pressure differential that small changes in diffuser elevation will not cause large variations in air flow rate along the diffuser length. Secondly, for lower air flow rates, orifice size does affect resulting bubble size. However, for the air flow rates tested of approximately 3 to 12 ft^3/hr/orifice (0.085 to 0.34 m^3/hr/orifice) bubble size is independent of orifice size if the orifice size is less than 0.5 inches (13 mm) in diameter.

Considering these factors, a 1-mm-diameter orifice size was selected. This yielded approximately a 3-lb/in^2 (21-kPa) average pressure differential across the orifices at the minimum air flow rate. With this differential, a ±1-ft (0.3-m) fluctuation in diffuser elevation will yield a ± 7 percent variation in air flow rate. Likewise, resulting bubble size is minimized for the air flow rates used. The 1 mm diameter is also a minimum orifice size that could be easily hand drilled.

As previously noted, for air releases into water at 150 ft (46 m) depth, bubble size is a function of orifice size and gas flow rate per orifice. For the selected orifice size, bubble size is solely a function of flow

* Numbers in brackets refer to references at end of report.

rate. Van Krevelen [3] and Coppock [4] note that bubble diameter increases at approximately the 0.4 power of the flow rate increase. Thus, a 4 fold increase in flow rate would yield a 1.7 fold increase in bubble diameter. The 1-mm-diameter orifice would yield approximately a 15-mm-diameter bubble at a flow rate of 3 ft^3/hr (0.085 m^3/hr) and a 25 mm diameter bubble at 12 ft^3/hr (0.34 m^3/hr). Both of these bubbles are large enough to have spherical cap shapes and both would be rising in a Reynolds number range which would give them approximately the same coefficient of drag. The resulting force of drag on the bubble, which is an indicator of upwelling energy transfer to the surrounding water, is then a function of relative rise velocity and bubble cross-sectional area. Using Haberman and Morton's [5] terminal velocity data, it appears that the larger bubble will have approximately 4.7 times the drag of the smaller bubble and will have 4.9 times the volume. Thus, for a unit volume of air ratio for the two bubble sizes yield similar total drag and therefore this bubble size difference should have little effect on the presented results.

Because of short (a few days) and moderate (a few weeks) time period lake temperature and DO fluctuations which result due to natural parameters, and because of the slow response of the lake to a change in diffuser operation it was concluded that only one air flow rate could reasonably be tested per year. Thus, diffuser configuration, diffuser orifice size and spacing, and depth of diffuser submergence have been held constant while the air flow rate per unit length of diffuser has been varied on an annual basis.

Test Procedure and Equipment

The test procedure used consisted of closely monitoring the biological, chemical, and physical state of the lake throughout the year and in particular throughout the destratification season. For each destratification season, the diffuser system was operated at a different air flow rate per unit length of diffuser.

As reported by Barnett [6, 7], the destratification system used by the Water District prior to 1977 consisted of four compressed air point source diffusers which were located at 140 to 160 ft (43 to 49 m) of depth and which were positioned at 70-ft (21-m) centers. The diffusers were supplied an air flow rate of approximately 640 stdft^3/min (18.0 std. m^3/min) from two 75 hp (56 kW) electric motor driven, rotary screw, single-stage, positive displacement compressors. The air was delivered to the diffuser by means of approximately 1700 ft (518 m) of 3-inch (76-mm) pipe which was suspended about 1 ft (0.3 m) below the water surface. The four-point source diffusers were attached to the end of the line with a 3-inch (76-mm) header system.

The line diffuser used the same compressor and 3-inch (76-mm) supply line. Seven 100-ft-(30-m)-lengths of 2-inch (51-mm) PVC pipe were hung end-to-end from the supply line. The 2 inch (51 mm) diameter is large enough that line losses did not affect air distribution. Each 100 ft (30 m) was individually valved to allow variation in the length of diffuser operated. The 100 ft (30 m) lengths also allowed easier handling. Each diffuser length was supplied air by a 1 inch (25 mm) inside-diameter hose. The diffuser was hung at a depth of 150 ft

(45 m). Both diffuser systems were located high enough above the bottom to prevent disturbance of bottom sediments. The line diffuser had 1 mm diameter orifices drilled at 1 ft (0.3 m) centers.

Tabulated below are diffuser lengths, total air flow rates, and unit air flow rates for the test years.

Year	Diffuser	Air flow rate total std ft^3/min	Air flow rate unit std ft^3/min/orifice
1976	Four-point source	640	160
1977	700-ft-line	290	0.41
1978	700-ft-line	530	0.76
1979	400-ft-line	440	1.10

Data Reduction

Two methods of evaluating diffuser influence on the lake were considered. In both cases, the objective was to compare observed stability and total DO data for diffuser-operated years to a prediction of what lake conditions would have been if no diffuser operation had occurred. The problem then is predicting what these nonmixed conditions would have been. The options considered were use of either historical data or a mathematical model to predict these conditions.

To begin with, temperature and dissolved oxygen data were compiled for 1960 to 1967 or the years prior to any destratification efforts, for 1976 or the last year of operation of the point source diffuser, and for 1977 through 1979 or the years of line diffuser operation. On approximately a monthly basis total lake dissolved oxygen and lake stability were calculated. Plots such as those shown in figures 2 and 3 were developed. These show the variation in stability and total DO over particular years.

Hypolimnion volumes were adjusted so that lake volume would be constant from year to year. This allowed direct comparison of stability and total DO for the various years. It was noted that stability and total DO patterns did shift somewhat from year to year. No trend could be detected in these variations. 1960 to 1967 temperature and DO profiles were compared to profiles from diffuser-operated years. In particular, early spring conditions prior to diffuser startup and conditions in the water below the diffuser, which are not affected by diffuser operation, were compared. It was concluded that pre 1968 temperature and DO profiles are representative of 1976 through 1979 lake conditions if no diffusers were operated. It was also concluded that if historical data were to be used as a base for diffuser evaluation, prediffuser operation years of both high and low stability and total DO should be used. Comparison of diffuser-operated years to both high and low base years would allow bracketing of probable diffuser influence.

The other option would be to use a mathematical model to predict these base conditions. Using the 1960 to 1967 prediffuser data, efforts were made to fit a temperature prediction model to Lake Casitas. It was noted that to obtain better base data than what could be obtained from the historical data, the mathematical model must consistently predict temperature profiles within $\pm$ 0.5 °C over the full stratified season. Historical data were used to tailor the model to Lake Casitas. Predicted model profiles were then obtained for other years for which historical data were available. It was found that the mathematical model could not yield improved accuracy in base year prediction. Consequently, historical data were used as base data.

Total DO and lake stability were then compared between years of diffuser operation and base year historical data. The difference between the two, shown as the crosshatched areas in figures 2 and 3, was concluded to be due to diffuser operation.

These differences were then related to energy used in the diffuser system and destratification and oxygenation efficiencies were obtained. Efficiencies were calulated based on both the metered electric power used by the compressors and on calculated total energy levels in the air as it passes from the diffuser orifices. Efficiencies based on metered power consumption represent efficiencies for the total diffuser system. Included are the electric motor efficiencies, compressor efficiencies, energy losses in the distribution lines, and the efficiency of the bubble curtain itself. For similar motor, compressor, and line characteristics to those tested, the power consumed efficiencies presented here can be used to size diffuser systems. The efficiencies calculated based on the total flow energy, on the other hand, are independent of motor, compressor, and line characteristics. The kinetic, buoyant, and compressive energy in the air as it exits from the orifice was calculated for the various flow rates tested. This energy level was then used in place of the metered power to calculate efficiencies. The resulting destratification and oxygenation efficiencies are the efficiencies of the bubble curtain alone. Use of these efficiencies in the design process would yield required air flow conditions at the diffuser for the particular site. The motor, compressor, and lines could then be designed to meet these needs. In this way specific motor, compressor, and line characteristics could be considered in the design process.

Results

Figure 4 shows the relationship found between the air flow rate per foot of diffuser and the destratification efficiency of the diffuser. The figure shows the relationship for both the total diffuser system efficiency and the bubble curtain efficiency. Again, it should be noted that the relationships are shown as a bounded region in the coordinate field. This is the result of scatter in the base year data and, thus, scatter in the determined effects of the diffuser. As can be seen, for particular air flow rates, the relationships yield bracketed diffuser system and bubble curtain efficiencies. A conservative design could be achieved by using the low end efficiencies in system sizing.

Likewise, figure 5 shows the relationships developed for oxygenation efficiency. Again presented are efficiencies based on total power consumed and on total energy in the flow at the orifice. Again the relationships yield bracketed oxygenation efficiencies for particular air flow rates and again conservative designs can be obtained by using the low-end efficiencies.

Efficiencies were also calculated for the 1976 operation which was the last year of use of the point source diffuser. Air was supplied to this diffuser by both compressors operating in combination and, thus, each point source was releasing approximately 160 stdft^3/min (4.5 stdm^3/min). It was found that destratification efficiency based on power consumed ranged between 0 and 0.43 percent. The corresponding oxygenation efficiency ranged between 0.8 kg/kWH and 1.8 kg/kWH. The much higher efficiencies produced by the line diffuser yield substantial reductions in required operating power. At Lake Casitas, this means approximately a halving of power consumed or a savings of 250,000 kWh per season. This yields an annual operating cost reduction in excess of $10,000.

One other item should be noted. Use of the line diffuser has yielded a very different mixing pattern in the lake. Typical midsummer temperature and DO profiles for prediffuser years, for point source diffuser years, and for line diffuser years are shown in figure 6. It can be seen that the point source diffuser caused breakdown of the thermocline and created a nearly linear temperature and DO profile from the diffuser to the surface. On the other hand, the line diffuser did not break down the thermocline and, thus, more traditional temperature and DO profile shapes were maintained. However, with the line diffuser, a second thermocline is developed at the diffuser elevation. Below this lower thermocline an undisturbed hypolimnion exists. It is thought that the point source diffuser develops higher upwelling velocities in the bubble curtain. Although energy transfer from this curtain is not as efficient as for the line diffuser, higher velocities and more momentum are established in the water that is upwelled. Sufficient momentum exists to overcome buoyant forces and the cold hypolimnion water is raised to the lake surface. Some mixing occurs with epilimnion and thermocline water and then the cold water drops back. It is thought that this action yields a strong mixing of hypolimnion water with epilimnion and thermocline water and results in the breakdown of the traditional profile shape. On the other hand, the line diffuser creates much lower upwelling velocities. The cold hypolimnion water is not upwelled to the lake surface. It is thought that mixing does occur between the upwelled water and the thermocline and that a strong mixing cell is established in the hypolimnion above the diffuser. The resulting temperature and DO profiles have the traditional shape. The hypolimnion above the diffuser is, however, warmer and at higher DO levels than the hypolimnion below the diffuser. This indicates that variation of air flow rate not only affects destratification and oxygenation efficiency, but it also, over large flow rate variations, affects the resulting temperature and DO profile shapes. Thus, profile shape can be balanced against diffuser efficiencies as an additional design consideration.

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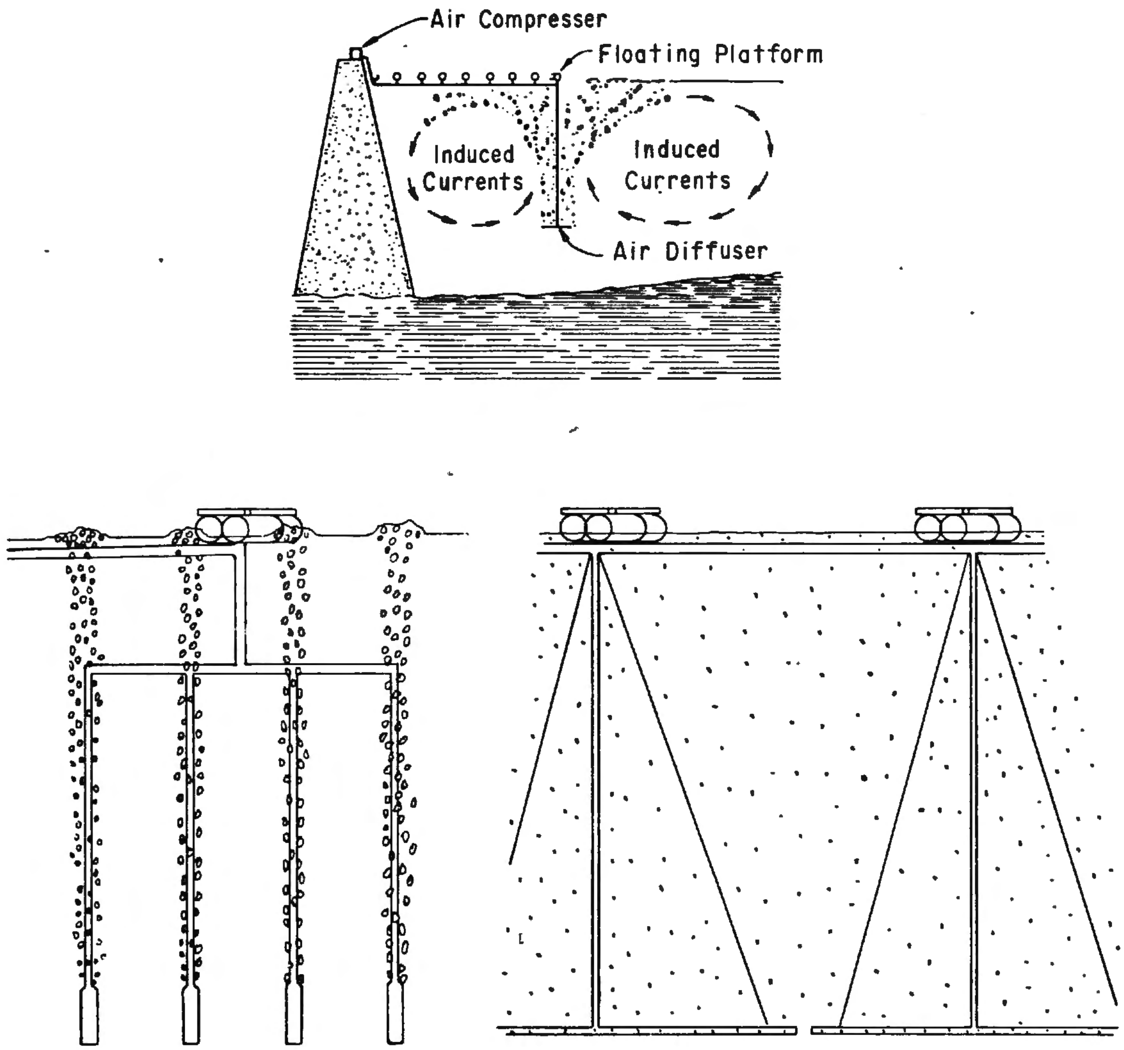

POINT DIFFUSER

LINE DIFFUSER

FIGURE I — DIFFUSED AIR SYSTEMS

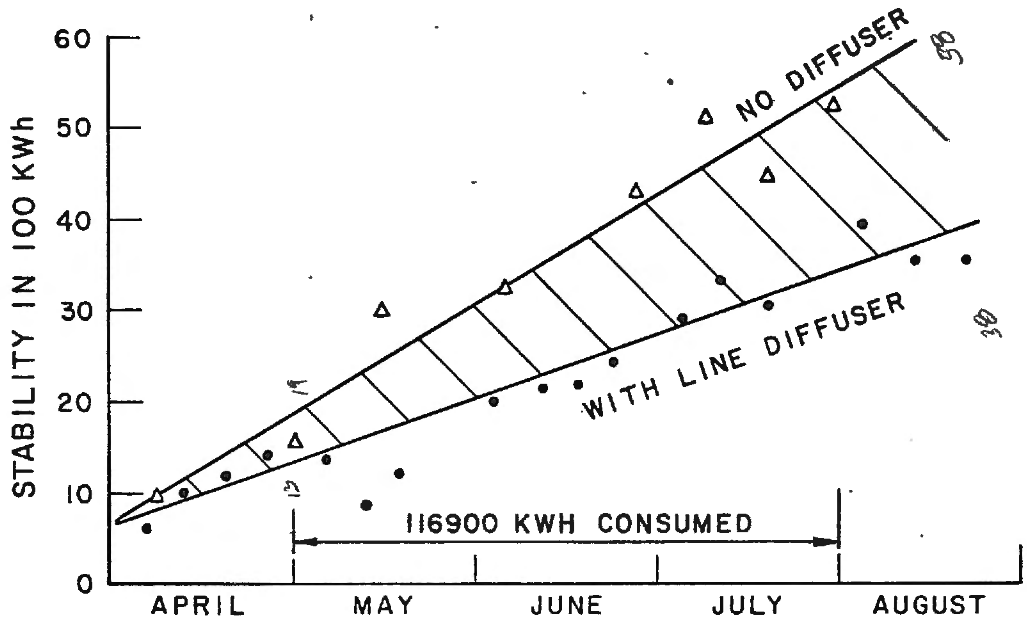

FIGURE 2 - TYPICAL LAKE TOTAL STABILITY DEVELOPMENT

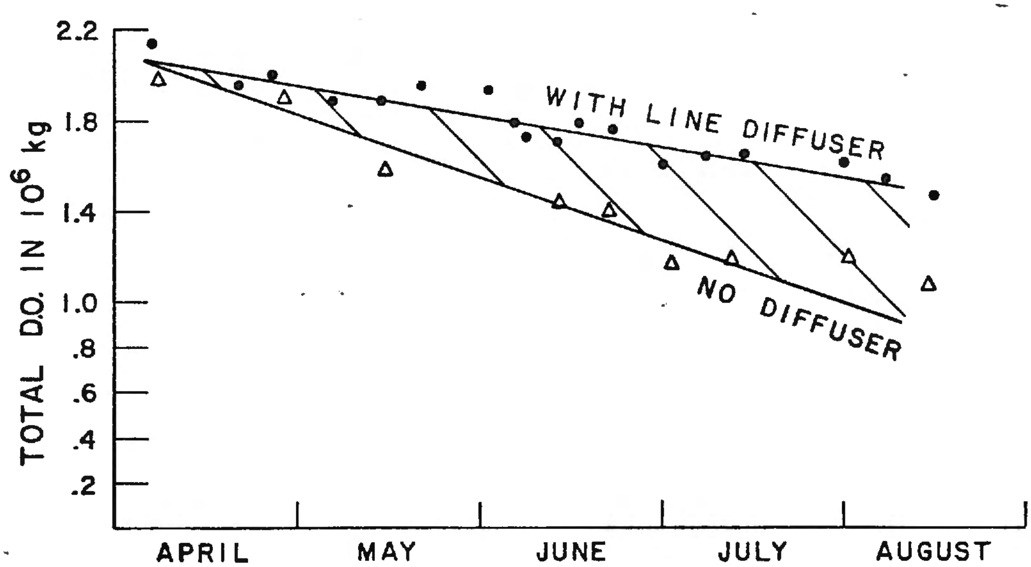

FIGURE 3 - TYPICAL LAKE TOTAL DISSOLVED OXYGEN TRENDS

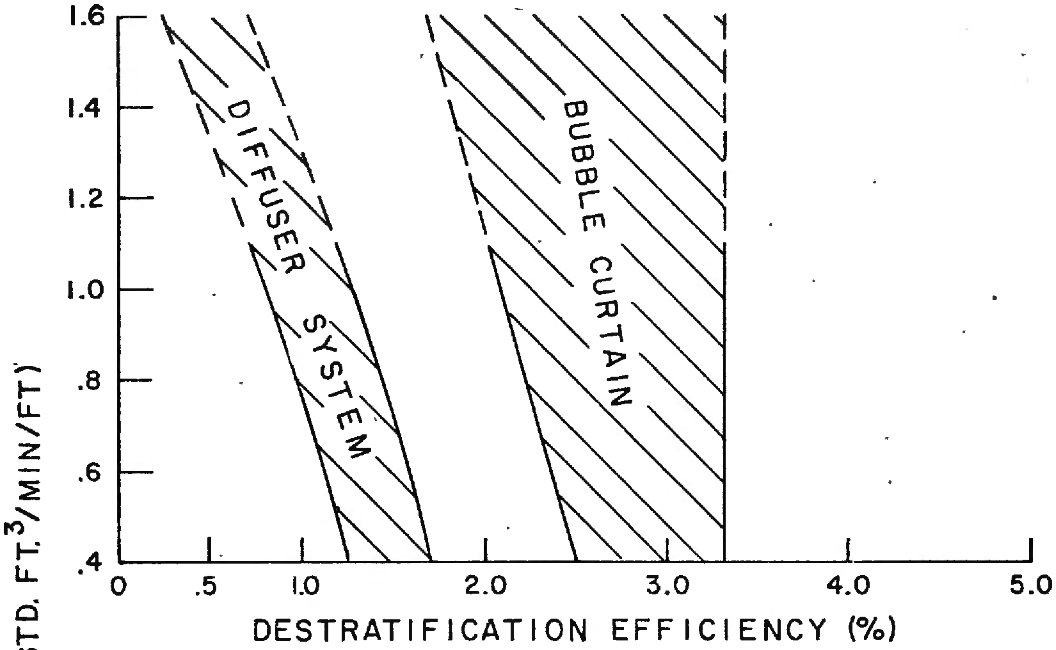

FIGURE 4 - DIFFUSER DESTRATIFICATION EFFICIENCY AS RELATED TO UNIT AIR FLOW RATE

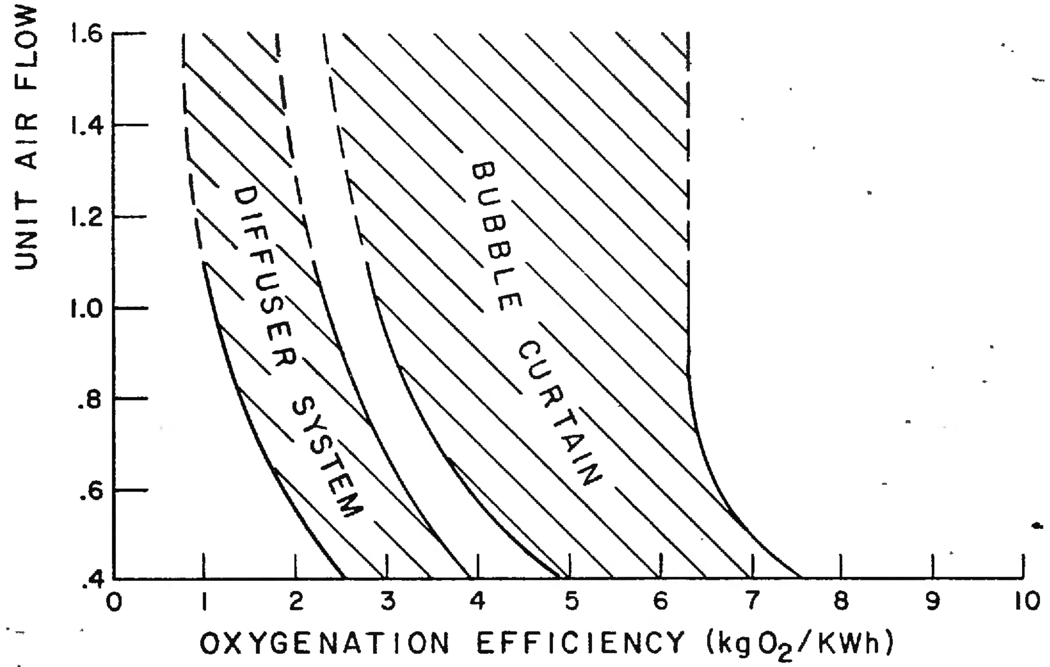

FIGURE 5 - DIFFUSER OXYGENATION EFFICIENCY AS RELATED TO UNIT AIR FLOW RATE

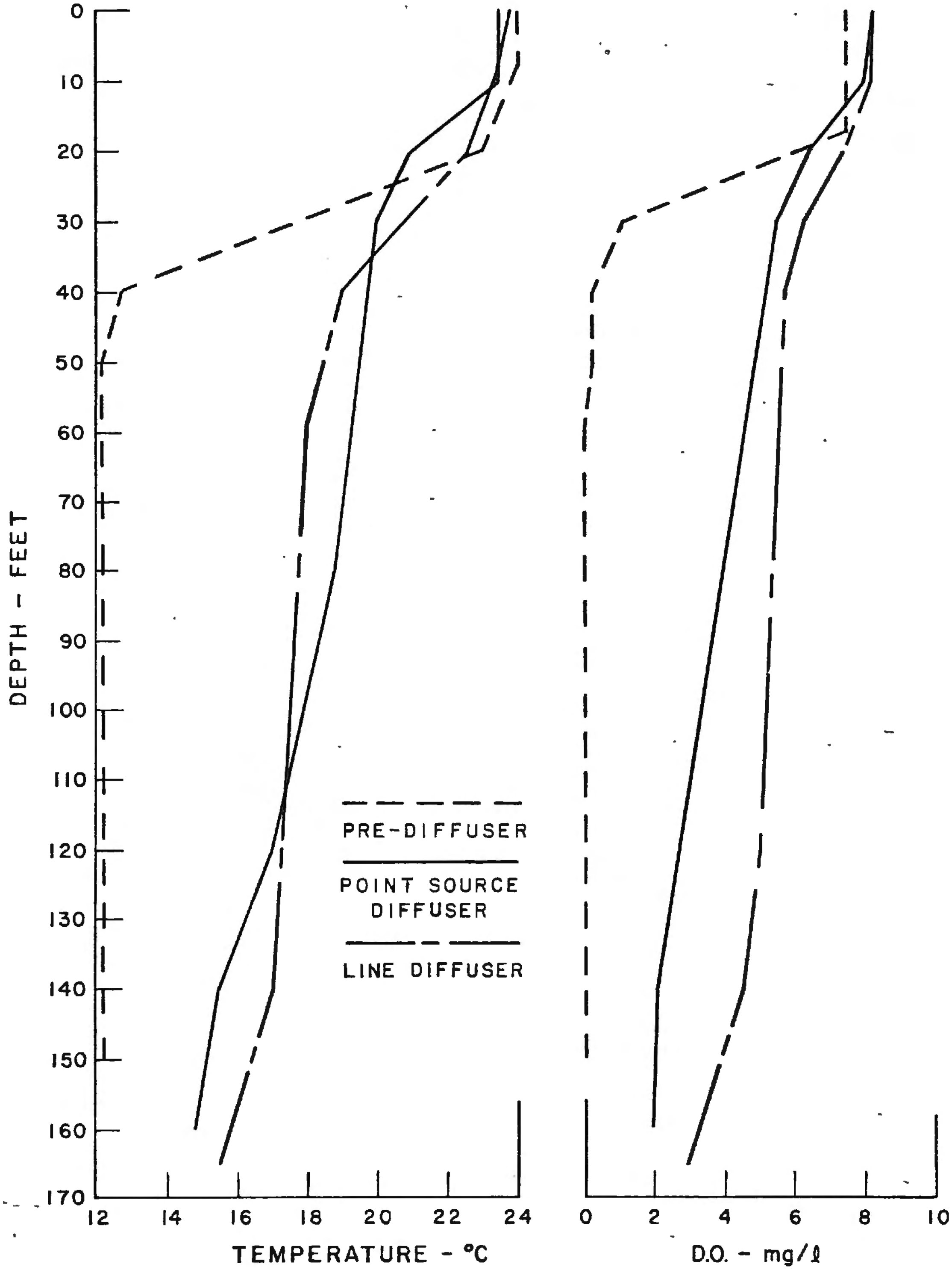

FIGURE 6 - TYPICAL TEMPERATURE AND D.O. PROFILES