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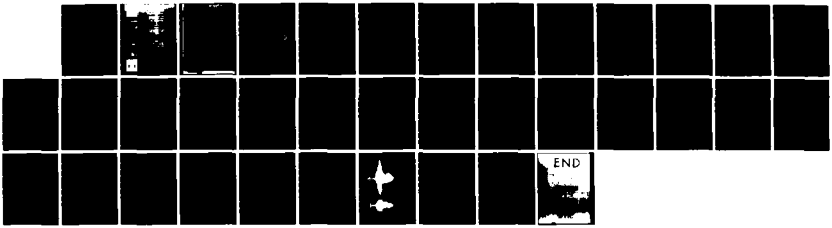

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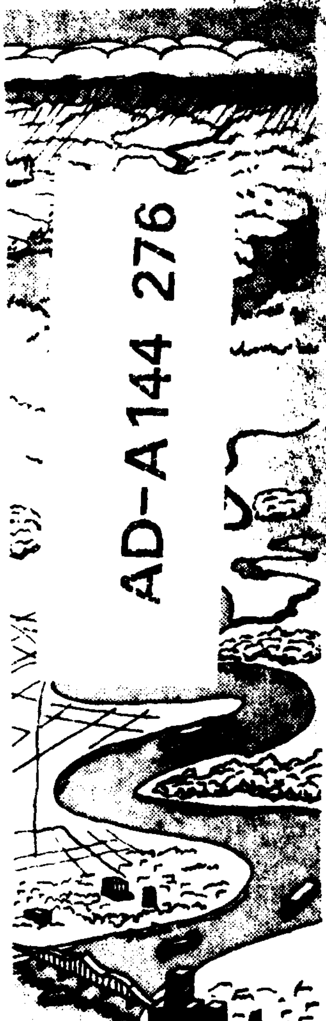

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During the late spring or early summer months, many Corps of Engineers reservoirs become thermally stratified. The subsequent density stratification limits or negates vertical mixing in these reservoirs with the result that vertical strata of decreasing water quality are formed. Releases from the lowest of these strata, the hypolimnion, may be of generally poor quality due to its relative oxygen deficiency which results from the coupling of limited

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vertical mixing and hypolimnetic oxygen demand. Localized mixing, a simple and relatively inexpensive method for the enhancement of these releases, utilizes the effects of jet mixing to transport high-quality epilimnetic water down to the hypolimnetic withdrawal zone for dilution of the release. In order to effectively enhance downstream release quality, the localized mixing system must produce a jet of sufficient quantity and initial momentum so that it will both penetrate into the hypolimnion and adequately dilute the release.

The results of laboratory investigations showed jet penetration into the hypolimnion to be a linear function of the densimetric Froude number at the thermocline. Qualitative analysis of the dilution of a given release showed a maximum dilution expected beyond which the additional pumping of epilimnetic water resulted in wasted resources. From these results, a procedure for the initial design of a localized mixing system was synthesized. An example of this design procedure is presented.

PREFACE

This analysis was sponsored by the Office, Chief of Engineers (OCE), under Work Unit 31605 (IIIB) of the Environmental and Water Quality Operational Studies (EWQOS) Program. It was conducted at the U. S. Army Engineer Waterways Experiment Station (WES) by the Hydraulics Laboratory (HL) during the period from September 1981 to August 1982. The OCE Technical Monitors were Messrs. Earl E. Eiker, John Bushman, and James L. Gottesman, respectively. The EWQOS Program Manager at WES was Dr. J. L. Mahloch. Mr. H. B. Simmons, Chief of the HL, and Mr. J. L. Grace, Jr., Chief of the Hydraulics Structures Division, directed the effort. Mr. J. P. Holland, Chief, Reservoir Water Quality Branch, conducted the study and prepared the text under the direct supervision of Dr. Dennis R. Smith, former Chief, Reservoir Water Quality Branch, who also reviewed this report. Messrs. S. C. Wilhelms and M. S. Dortch, HL, provided assistance in the concepts and testing reported herein.

Commander and Director of WES during this study was COL Tilford C. Creel, CE. Technical Director was Mr. F. R. Brown.

This report should be cited as follows:

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CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
acre-feet	0.000811	cubic metres
cubic feet per second	0.0283168	cubic metres per second
feet	0.3048	metres
feet per second	0.3048	metres per second
feet per second per second	0.3048	metres per second per second
gallons (liquid) per minute	0.00006309020	cubic metres per second
inches	2.54	centimetres

PARAMETRIC INVESTIGATION OF LOCALIZED MIXING IN RESERVOIRS

PART I: INTRODUCTION

Background

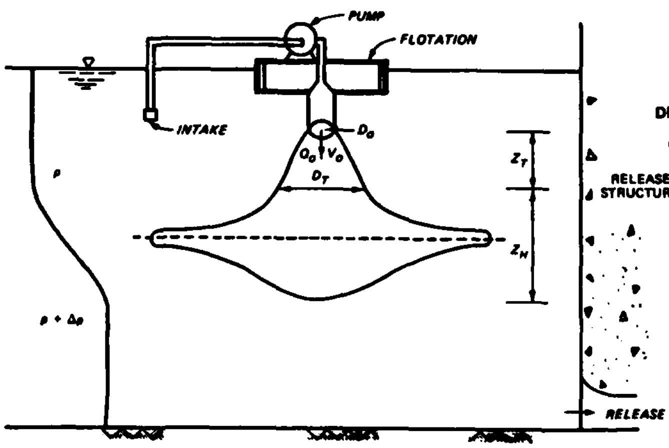
1. During the late spring or early summer months many Corps of Engineers (CE) reservoirs become thermally stratified. The subsequent density stratification limits or negates vertical mixing in these reservoirs, resulting in the formation of three vertical strata in the reservoir. The epilimnion, the upper region, contains warm, low-density water which is generally high in dissolved oxygen (DO) concentration due to surface exchange and wind mixing, and is thus considered high quality. The region of rapid temperature change just below the epilimnion is called the thermocline or metalimnion. The hypolimnion, the lowest region of the reservoir, consists of cooler, high-density water which, due to the mitigation of vertical mixing as a result of stratification, is often low or deficient in DO. This stratification may present a serious water quality problem for reservoirs with low-level (i.e. bottom) or hypolimnetic release outlets. The water released from these outlets, which will be either predominately or completely hypolimnetic, will be of generally poor quality due to its relative oxygen deficiency. Further, during certain periods of the year, these waters may become anoxic, resulting in the release of high concentrations of substances such as iron, manganese, and hydrogen sulfide.

2. Several feasible solutions have been considered for the enhancement of hypolimnetic releases, including artificial destratification, hypolimnetic oxygenation, structural modification, and localized mixing. However, artificial destratification destroys either most or all of the stratification within the reservoir, and hypolimnetic oxygenation and structural modifications are generally expensive alternatives. Conversely, localized mixing is designed to destratify the reservoir in the vicinity of the release structure, and field applications of this

concept have shown it to be a simple, cost-effective approach for the improvement of low-level releases (Garton and Peralta 1978, Dortch and Wilhelms 1978). It is, in fact, the simplicity of the localized mixing concept which promotes its cost-effectiveness.

3. The concept of localized mixing is shown in Figure 1. A downward vertical jet composed of epilimnetic water transports high-quality water downward into the hypolimnion. This jet is formed near the release structure in a number of ways, ranging from the use of an axial flow propeller located in the epilimnion (Garton and Peralta 1978) to the use of a surface pump with an epilimnetic intake and outflow as shown in Figure 1. Regardless of the mechanism, the jet is designed with adequate initial momentum to penetrate to the level of the release outlet in the hypolimnion. A portion of the transported epilimnetic water will then be withdrawn from the reservoir along with a quantity of hypolimnetic water, thus diluting the hypolimnetic outflow and improving the total release quality. The quantity of epilimnetic water required for transport will depend in part on the quality desired for the given release and the qualities of both the hypolimnion and the epilimnion. Obviously, the poorer the hypolimnetic quality, the larger the quantity of epilimnetic water required to enhance, or dilute, the hypolimnetic release in order to obtain a given release quality.

4. While a number of parameters have been identified which are



DEFINITION OF TERMS USED IN FIGURE 1:

Q_o, V_o, D_o = VOLUME FLUX, VELOCITY, DIAMETER OF JET AT THE OUTLET
D_T = DIAMETER OF JET AT THERMOCLINE
Z_T = DISTANCE FROM JET OUTLET TO TOP OF THERMOCLINE
Z_H = PENETRATION DEPTH BELOW TOP OF THERMOCLINE
ρ = EPILIMNETIC DENSITY
$\rho + \Delta\rho$ = HYPOLIMNETIC DENSITY
$\Delta\rho$ = ABSOLUTE DIFFERENCE BETWEEN EPILIMNETIC AND HYPOLIMNETIC DENSITIES

Figure 1. Schematic of localized mixing application

important in the localized mixing concept (Busnaina et al. 1981), it is imperative for the successful application of localized mixing that two general conditions be met. First, the epilimnetic jet must penetrate to the level of the release outlet. If the jet fails to penetrate to this level, the improvement of release quality will be lessened. Further, penetration of the jet beyond the outlet represents a waste of energy which reduces the cost-effectiveness of the method. In certain cases, such as for bottom outlets, overpenetration may disturb bottom sediments and degrade rather than improve release quality.*

5. The second general condition which must be met for a successful localized mixing application is that a sufficient volume of epilimnetic water must be jetted into the hypolimnetic withdrawal zone such that the flow-weighted average of epilimnetic and hypolimnetic qualities is equal to the desired quality of the total release. This epilmnetic flow may be idealized by

$$C_{rel} = \frac{Q_e(C_e) + Q_H(C_H)}{Q_{rel}} \tag{1}$$

and

$$Q_{rel} = Q_e + Q_H \tag{2}$$

where

C = concentration of given quality parameter

Q = volume flux

e, H, and rel = epilimnetic, hypolimnetic, and total release of Q and C, respectively

This process of augmenting the quality of the release with an epilimnetic component is referred to as "dilution of the release."

6. Limits exist, however, on the amount of epilimnetic water which may be practically withdrawn for release enhancement or effectively pumped into the hypolimnion. Thus, care must be taken to pump enough epilimnetic water into the hypolimnion for dilution while minimizing waste of the epilimnetic resource due to overpumping.

* Personal Communication, J. E. Garton, 1979, Oklahoma State University, Stillwater, Okla.

Purpose and Scope

7. For the design of an effective localized mixing device, both the required rate of epilimnetic pumping (hereafter called "dilution factor") and the penetration of the subsequent jet must be quantified. The purpose, then, of this report is to present initial investigations of these two parameters. To quantify penetration depth, laboratory model studies were coupled with field data as a part of research sponsored under the Environmental and Water Quality Operation Studies (EWQOS) Program Task IIIB.1 "Improvement of Reservoir Destratification/Mixing Techniques." Analysis of the parameters governing penetration depth and the results of the subsequent laboratory testing are presented as the primary topic of this research. An overview of the work of Moon, McLaughlin, and Moretti (1979) will also be presented in order to provide qualitative guidance on the pumping rates required for dilution of a given downstream release.

PART II: PARAMETRIC ANALYSIS OF PENETRATION DEPTH

8. The quantification of jet penetration depth was idealized by considering the reservoir to be a system of two separate stagnant, homogeneous layers. The upper layer was considered to be low-density ρ epilimnetic water which resided over a high-density $\rho + \Delta\rho$ hypolimnion. Water of the same density as the epilimnion was assumed to initially comprise the downward vertical jet used for mixing. Thus, within the epilimnion, the jet was characterized as a nonbuoyant jet and the classical analysis of nonbuoyant jets was used to quantify jet characteristics in this region. However, beyond the thermocline (which is idealized herein as a sharp interface between the epilimnion and hypolimnion) the effects of buoyancy are opposed to the predominate direction of flow of the jet. Using dimensional arguments, the penetration of the jet into the hypolimnion (as measured from the thermocline) was related to the kinetic and potential energy fluxes at the thermocline K_{ET} and P_{ET}, respectively) by the expression

$$Z_H = C_1 \left(\frac{K_{ET}}{P_{ET}} \right)^{C_2} + C_3 \tag{3}$$

where C_1, C_2, and C_3 are coefficients to be determined, and

$$K_{ET} = \frac{1}{2} \rho Q_T V_T^2 \tag{4}$$

$$P_{ET} = \Delta\rho Q_T g Z_H \tag{5}$$

where

Z_H = depth of jet penetration into the hypolimnion as measured from the top of the thermocline, ft

ρ = jet density at thermocline (equal to density of epilimnion), g/cc

Q_T = jet volume flux at thermocline, cfs

V_T = jet velocity at thermocline, fps

$\Delta\rho$ = absolute difference between jet (epilimnion) and hypolimnion densities, g/cc

g = acceleration of gravity, 32.18 ft/sec^2*

Turner (1966) and Abraham (1967), using dimensional analysis, found $C_2 = 0.5$. Equation 3 may then be expressed as the following simplified, nondimensional function of the densimetric Froude number, F_r :

$$\frac{Z_H}{D_T} = C_1 F_r + C_3 \tag{6}$$

where

$$F_r = \frac{V_T}{\sqrt{\frac{\Delta\rho}{\rho} g D_T}} \tag{7}$$

and D_T = diameter of the jet at the thermocline, ft

9. The coefficients C_1 and C_3 must be determined to solve Equation 6. Further, the hydraulic characteristics of the jet at the thermocline (volume flux, velocity, diameter) must be described in dimensionless forms which, for the most effective utilization in a design mode, are functions of the initial values of each parameter (Q_o , V_o , D_o , respectively) at the origin of the jet. Thus, the problem of quantifying jet penetration from an epilimnetic source into the hypolimnion may be analyzed as a two-part problem: (a) computation of jet characteristics from the source to the thermocline; and (b) computation of penetration from the thermocline into the hypolimnion based upon the values computed in step (a). Since the jet is assumed to be nonbuoyant over the range from the jet origin to the thermocline (the epilimnion), the work of Albertson et al. (1950) presents formulations that are used to describe the jet volume flux, velocity, and diameter at the thermocline as functions of their initial value counterparts. These formulations are overviewed below. However, the given reference should be consulted for a complete description of these formulations.

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 3.

Overview of Albertson et al. Formulations

10. Albertson, Dai, Jensen, and Rouse (Albertson et al. 1950) performed an extensive theoretical/experimental analysis to describe the mean flow characteristics of submerged two-dimensional (slot) and three-dimensional (round) jets issuing into a stagnant, homogeneous ambient. Their analysis was concerned with the flow characteristics of ordinary momentum jets in homogeneous fluids and is assumed to describe the flow characteristics of the localized mixing jet in the epilimnion.

11. These investigators found two basic regions of flow having differing mixing regimes: (a) the zone of flow establishment, the initial jet region wherein mixing has not yet penetrated to the centerline of the jet; and (b) the zone of established flow, the region of fully turbulent flow beyond the zone of flow establishment. Albertson et al. found the zone of established flow to begin approximately 6.2 initial jet diameters beyond the jet outlet. In order to maximize entrainment of the jet in the epilimnion (which increases the volume of high-quality water jetted downward for withdrawal), the localized mixing jet should exhibit fully established flow before passing the thermocline. Thus, the jet pumping outlet should be a minimum of 6.2 initial jet diameters above the thermocline. Only those Albertson et al. formulations characterizing jet flow in the zone of established flow will be presented herein. Albertson et al. (1950) should be consulted for further descriptions.

12. Albertson et al. found that entrainment at a given point in the zone of established flow was a function of the number of jet diameters (6.2 minimum) the point was downstream from the outlet. Expressing this in analogous localized mixing terms for epilimnetic entrainment yields

$$\frac{Q_T}{Q_o} = 0.32 \frac{Z_T}{D_o} \tag{8}$$

where

Q_o = initial jet volume flux at pump, cfs

Z_T = distance from jet pumping outlet to thermocline, ft

D_o = initial jet diameter, ft

Albertson et al. also found the change in kinetic energy flux from the jet outlet to the thermocline to be (again in localized mixing terms)

$$\frac{K_{ET}}{K_{eo}} = 4.1 \frac{D_o}{Z_T} \tag{9}$$

where K_{eo} = initial kinetic energy flux at the jet outlet as defined by

$$K_{eo} = \frac{1}{2} \rho_j Q_o V_o^2 \tag{10}$$

where

ρ_j = epilimnetic jet density, g/cc

V_o = initial jet velocity at pump, fps

Combining Equations 4, 8, 9, 10, and the continuity equation

$$Q = VA \tag{11}$$

where $A = \pi D^2/4$. The velocity at the thermocline and mean jet diameter at the thermocline are expressed as

$$V_T = 3.58 \frac{D_o}{Z_T} V_o \tag{12}$$

and

$$D_T = 0.30 Z_T \tag{13}$$

13. Thus, the work of Albertson et al. (1950) can be used to express the values of jet volume flux, velocity, and mean diameter, respectively, at the thermocline in terms of their counterpart values at the jet pumping outlet. Assuming the validity of the Albertson et al. work in characterizing the jet at the thermocline, the quantification of jet penetration from the thermocline into the hypolimnion becomes a

problem of computing the coefficients C_1 and C_3 from Equation 6. In order to compute these two coefficients, a regression analysis of the results of over 100 laboratory tests was performed. As the purpose of these tests was to quantify penetration from the thermocline into the hypolimnion (the characteristics of jet penetration through the epilimnion having been assumed) these laboratory tests were run with no epilimnion. Rather, a jet of lighter density ρ_j was issued vertically downward directly into a stagnant ambient of heavier density $\rho_j + \Delta\rho$ in order to simplify the testing procedure. Results of these tests are presented below.

Computation of Coefficients for Penetration into the Hypolimnion

14. In order to compute the two regression coefficients, over 100 laboratory tests were conducted for initial jet diameters ranging from 0.5 to 1.5 in., flow rates ranging from 0.5 to 3.50 gpm, and $\Delta\rho$ values ranging from 0.001 to 0.003 g/cc. A description of the experimental procedures is given in Appendix A. The initial jet diameter, volume flux, and velocity at the jet origin were also defined to be the respective jet values at the thermocline. This was done so that the penetration depth description found with this analysis would be properly formulated for prediction of jet penetration from the thermocline into the hypolimnion for a two-layer system.

15. Figure 2 shows a plot of the densimetric Froude number at the thermocline (which is also the initial densimetric Froude number in this case) versus dimensionless depth of jet penetration from the thermocline into the hypolimnion, Z_H/D_T. Two least-squares fits were found to be best for these data,

$$\frac{Z_H}{D_T} = 1.66F_r - 0.66 \qquad F_r > 1.65 \tag{14}$$

$$\frac{Z_H}{D_T} = 1.60F_r \qquad F_r \leq 1.65 \tag{15}$$

each with a correlation coefficient (r^2) value of 0.96 over the combined data set. However, analysis of the two-layer tests (described in the next section), coupled with reinvestigation of the data in Figure 2, showed that the predictive capability of each equation was greatly changed at a densimetric Froude number of 1.65.

16. Several investigators have found similar descriptions for "penetration" of a buoyant jet into a stagnant homogeneous ambient. Each investigation presented from the literature considered the issuance of a heavy-density jet vertically upward into a lighter ambient. As the effects of buoyancy act counter to the predominate direction of flow for each of these investigations, the results obtained are directly comparable to those given by Equations 14 and 15. As shown in Table 1, the regression coefficients of Equations 14 and 15 are similiar to values found by the cited investigators.

17. The good agreement of the experimental results characterized by Equations 14 and 15 with previous investigators of analogous flow regimes adds support to the validity of these descriptions of jet penetration in the hypolimnion. However, the thermocline boundary conditions associated with these descriptions, which were defined in the 100 laboratory tests as the jet outlet conditions, must be calculated in a

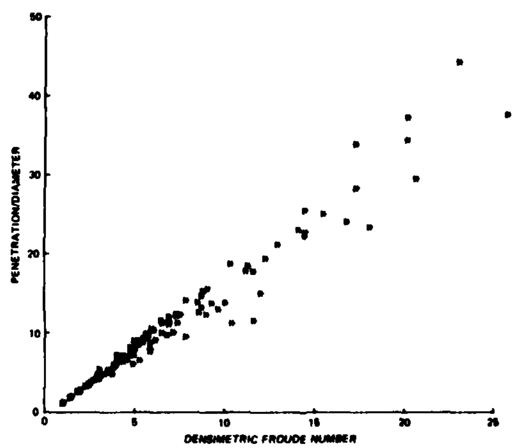


Figure 2. Plot of dimensionless penetration depth versus densimetric Froude number at thermocline

Table 1

Comparison of Coefficient Values C_1 and C_3

in Functional Form $Z_H/D_T = C_1 F_r + C_3$

Coefficient Value			
C_1	C_3	Reference	Type of Study
1.94	0	Abraham (1967)	Theoretical
1.86	0	Priestley and Ball (1955)	Theoretical
1.45	0	Morton (1959a and b)	Theoretical
1.74	0	Turner (1966)	Experimental
1.72	0	Zeitoun et al. (1970)	Experimental
1.76	0	Ignacio and James (1979)	Experimental
1.66	-0.66 ($F_r > 1.65$)	Present study	Experimental
1.60	0 ($F_r \leq 1.65$)	Present study	Experimental

two-layer stratification based upon the work of Albertson et al. (1950). In order to investigate the predictive capabilities of Equations 14 and 15 when coupled with the Albertson et al. work, a second series of laboratory tests were run for idealized, two-layer reservoir stratification. The results of these tests are now presented.

Application of Penetration Prediction to a Two-Layer System

18. Summer reservoir stratification was idealized in the laboratory in the general manner shown in Figure 3. Thirty-one tests were run for flow rates ranging from 0.75 to 3.00 gpm, $\Delta\rho$ values from 0.0009 to 0.0027 g/cc, initial jet diameters from 0.5 to 1.0 in., and distances from the outlet to the thermocline Z_T of 0.88 to 1.21 ft. A more thorough discussion of the laboratory procedure is given in Appendix A. Figure 4 shows that a strong point of differentiation exists at $F_r = 1.65$ between predicted penetration depths Z_H for the two-layer tests computed with Equations 14 and 15. Using percent error (i.e.,

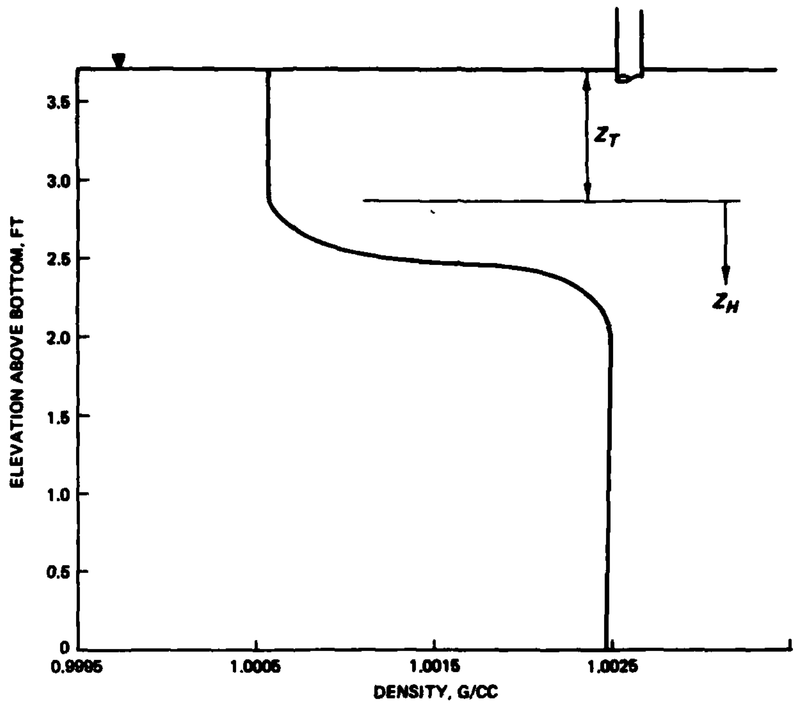


Figure 3. Typical laboratory stratification

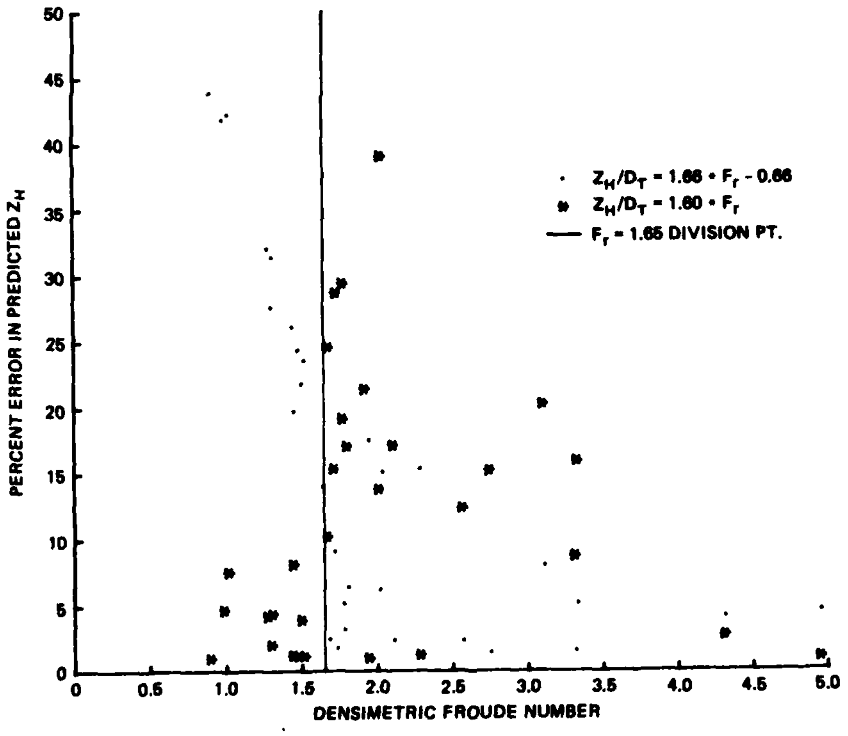
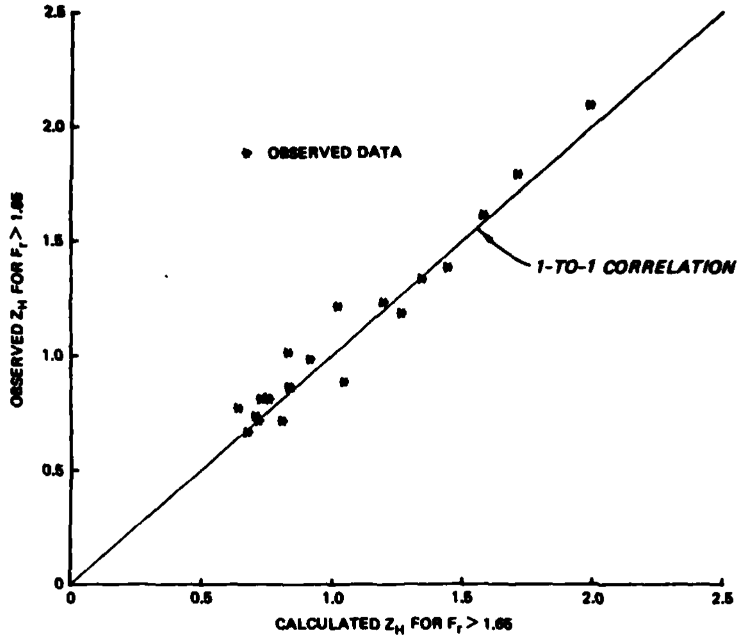


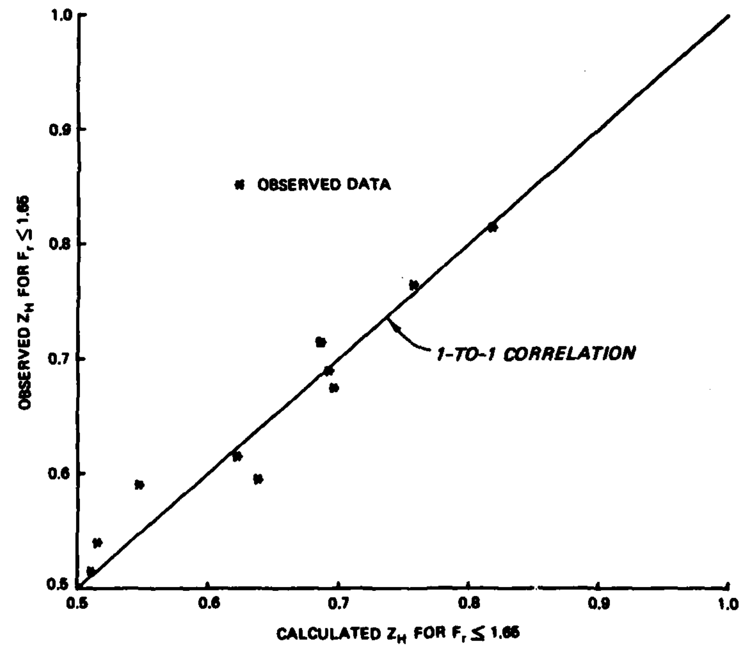
Figure 4. Error of prediction of penetration depth for the two-layer tests

observed minus predicted penetration divided by observed times 100 percent) as an indicator of prediction, Equations 14 and 15 obviously diverge in predictive utility at $F_r = 1.65$. The divergence could be a result of the increased entrainment and/or buoyancy force (due to higher pumping rates) which limit penetration at higher densimetric Froude numbers. Only three tests with $F_r > 1.65$ showed percent error of prediction for penetration in excess of 10 percent when computed by Equation 14. These tests were low in the applicable densimetric Froude number range for the equation, and subsequently the predicted and observed dimensionless penetration values were relatively small. Thus, while the percent error of prediction was near 15 percent, the absolute error of each predicted penetration was relatively small.

19. Figures 5a and 5b show additional results from these tests. The standard error of prediction of penetration into the hypolimnion (as measured from the thermocline) was 4.9 and 7.9 percent of the observed value for $F_r \leq 1.65$ and $F_r > 1.65$ predictions, respectively. Each of the figures also shows that high correlation (i.e., 1-to-1 denotes observed and calculated value equality) was obtained for all of these tests. The figures also show that Equations 14 and 15 often underpredicted the observed penetration depth (i.e., observed data above the 1-to-1 correlation line). This error was felt to be due to an erosion of the sharp thermocline during these tests contrary to the two-layer assumptions on which Equations 14 and 15 were based. The introduction of local mixing at the thermocline seems to have created a small region below the thermocline for which $\Delta\rho$ was not equal to the absolute differences in epilimnetic and hypolimnetic densities. Thus, the buoyancy flux was less for this region than assumed in Equations 14 and 15, leading to a smaller change of kinetic energy to potential energy in this region. Therefore, the available kinetic energy flux in the region just below the thermocline may have been greater for the observed tests than assumed in the theoretical basis of Equations 14 and 15. This increased kinetic energy flux would, in turn, produce greater penetration than predicted. However, given that the error of observation of penetration depth was approximately ±5 percent, and that the theoretical basis of



a. From Equation 14 for $F_r > 1.65$



b. From Equation 15 for $F_r \leq 1.65$

Figure 5. Penetration depth values

this analysis was two-layer stratification, the predicted results are quite adequate.

20. These laboratory results compare favorably with results from field data of Garton 1981* who found total penetration from the jet outlet to be a specified hypolimnetic water quality intake characterized by

$$\frac{Z_p}{D_o} = 1.695\ F_r \qquad (16)$$

where

Z_p = distance from pump outlet to water quality intake, ft

F_r = pump outlet densimetric Froude number, $V_o/\left[(\Delta\rho/\rho)gD_o\right]^{1/2}$

It should be noted that Garton's work uses a pumping device which produces little jet entrainment so that little change in jet kinetic energy is expected in the epilimnion. Thus, the initial characteristics of the jet are generally representative of those at the thermocline with the Garton pump, and the penetration of the jet (which is measured from the pumping outlet rather than the thermocline) is characterized by the same general function as that found in this study.

21. The agreement of laboratory, field, and theoretical results suggests that the penetration of a jet of known initial characteristics into a given stagnant stratification may be closely approximated. Conversely, if the depth of required penetration is known, the initial densimetric Froude number of the jet required to produce this penetration may be determined. Since the initial densimetric Froude number is a function of Q_o and D_o, one of the two is chosen and the other computed. Generally, Q_o is chosen due to its effect on the overall enhancement of the release quality. An overview of Moon, McLaughlin, and Moretti (1979) guidance on computation of this epilimnetic flow rate is presented in Part III.

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* Unpublished data.

PART III: JET DILUTION OF RELEASE

22. Moon, McLaughlin, and Moretti (1979) have given guidance on the practicable dilution of a hypolimnetic release by an epilimnetic jet. These investigators define dilution DF as

$$DF = \frac{Q_2}{Q_{rel}} = \frac{\rho_o - \rho_1}{\rho_2 - \rho_1} \qquad (17)$$

where

Q_2 = volume flux of epilimnion water released

ρ_o = release water density during pumping

ρ_1 = release water density prior to pumping

ρ_2 = density of the epilimnion water

Moon, McLaughlin, and Moretti further defined the ratio of the pumping rate of the epilimnetic water at the pump, Q_o, to total release rate, Q_{rel}, to be Q^*.

23. If the release flow includes all of the fluid pumped down by the propeller, then a reasonable approximation is that $Q_o \cong Q_2$ and therefore $Q^* = DF$ as shown in Figure 6 by the dashed straight line. In fact, the release flow generally includes a major portion of the pumped water plus epilimnion water which is entrained by the jet. This explains why experimental measurements by Moon, McLaughlin, and Moretti of the dilution shown in Figure 6 actually fall above the $DF = Q^*$ line for $Q^* < 0.40$. Once a value of $Q^* = 0.40$ is reached, the dilution data level off and approach a value of approximately 0.75. This indicates that no matter what pumping parameters are chosen, beyond $Q^* = 0.4$ approximately 25 percent of the release flow will come from the hypolimnion. Thus, if a maximum contribution of 75 percent epilimnetic flow in the release is insufficient to raise the mixed release quality to the desired level, localized mixing may prove to be only partially successful. Further, the greater the epilimnetic jet entrains hypolimnetic water, the more the epilimnetic quality is diluted prior to withdrawal. A final maximum component of epilimnetic water in the release might be well below this 75 percent level.

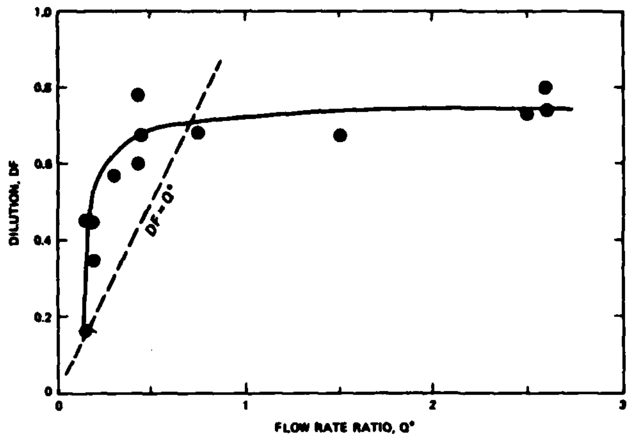

Figure 6. Dilution as a function of the flow rate ratio (Moon, McLaughlin, and Moretti 1979)

24. Moon, McLaughlin, and Moretti also show that, once the 75 percent dilution has been reached, increased pumping of epilimnetic water is a waste of resource. They suggest the minimum point at which the 75 percent dilution is reached to be $Q^* = 0.5$; as shown in Figure 6, by $Q^* = 1$, the 75 percent has definitely been reached. Therefore, beyond the point that the epilimnetic pumping rate is $0.5 \leq Q_o \leq 1$, Moon, McLaughlin, and Moretti show the maximum effect of the epilimnetic jet has been achieved.

25. The Moon, McLaughlin, and Moretti work was accomplished using laboratory results from experimentation with two model release structures and a model Garton pump. Although the range of data and type of pump are limited, these results provide qualitative guidance for the estimation of both the pumping rate required to meet a specified release quality and the order of the maximum release enhancement expected due to localized mixing. By coupling the Moon, McLaughlin, and Moretti guidance with the procedure for penetration depth calculation given by Part II, the initial design of a localized mixing system for a given set of hydrological, meteorological, and operational conditions may be obtained. An example of such a design is demonstrated in the next section.

PART IV: EXAMPLE OF LOCALIZED MIXING DESIGN

26. The initial design of a localized mixing system is demonstrated in this section for a hypothetical reservoir. This system is designed to be capable of jetting adequate epilimnetic water into the hypolimnion to result in a DO concentration of 6 mg/ℓ for a 100-cfs release. The hypothetical reservoir DO and temperature profiles are given in Figure 7. The release outlet is assumed to be on the reservoir bottom. Using the work of Smith and Dortch (1983) to define the limits of withdrawal, bottom withdrawal of 100 cfs for this stratification resulted in an upper limit of withdrawal at 24 ft above the bottom (38-ft depth) and a release DO concentration of 3 mg/ℓ. Assuming that all the epilimnetic water jetted into the withdrawal zone is released, the epilimnetic volume flux at a DO concentration of 10.0 mg/ℓ which must cross the thermocline and subsequently be withdrawn (Q_T) to result in a 6-mg/ℓ DO release concentration is approximately 46 cfs; this results in a DF of 0.46. Using the work of Moon, McLaughlin, and Moretti shown in Figure 6, this DF value corresponds to a Q^* value of approximately 0.22; subsequently, an initial epilimnetic pumping rate of 22 cfs is required to achieve the desired dilution of this release. Jet entrainment in the epilimnion produces the additional 24 cfs required for release enhancement.

27. Based upon the temperatures from Figure 7, the density difference between the epilimnion and hypolimnion was found to be 0.00109 g/cc. The thermocline was at a depth 20 ft below the water surface. The jet was designed to penetrate through 80 percent of the withdrawal zone thickness (in order to ensure no overpenetration and possible disturbance of bottom sediments) resulting in a Z_H value of 38.0 ft. An initial estimate of the minimum expected densimetric Froude number at the thermocline was made in order to determine whether Equation 14 or 15 was to be used in system design. The maximum value of Z_T, which by definition is the distance from the surface to the thermocline (20 ft in this example), was used in the solution of Equation 13 in order to provide a maximum expected value of D_T. For the given Z_T, D_T was

computed to be 6 ft. Solution of Equation 11 for D_T and Q_T (46 cfs) resulted in an average velocity at the thermocline (V_T) of 1.63 fps. Subsequent solution of Equation 7 for the given $\Delta\rho/\rho$, V_T, and D_T values resulted in a minimum estimated F_r of 3.55 which, from paragraph 15, designates the use of Equation 14 in this design.

28. Substitution of Equations 8, 11, and 12 into Equation 14 resulted in

$$\frac{Q_T}{D_o} D_o^{5/2} + 1.62\ Z_H D_o^{3/2} = 3.79 \left(\frac{Q_o^3}{\frac{\Delta\rho}{\rho}\ gQ_T} \right)^{1/2} \tag{18}$$

Substituting the values for Q_T, Q_o, $\Delta\rho/\rho$, Z_H, and g (46 cfs, 22 cfs, 0.00109, 38 ft, and 32.18 ft/sec^2, respectively) into Equation 18 produced an initial jet diameter of 2.75 ft for this hypothetical

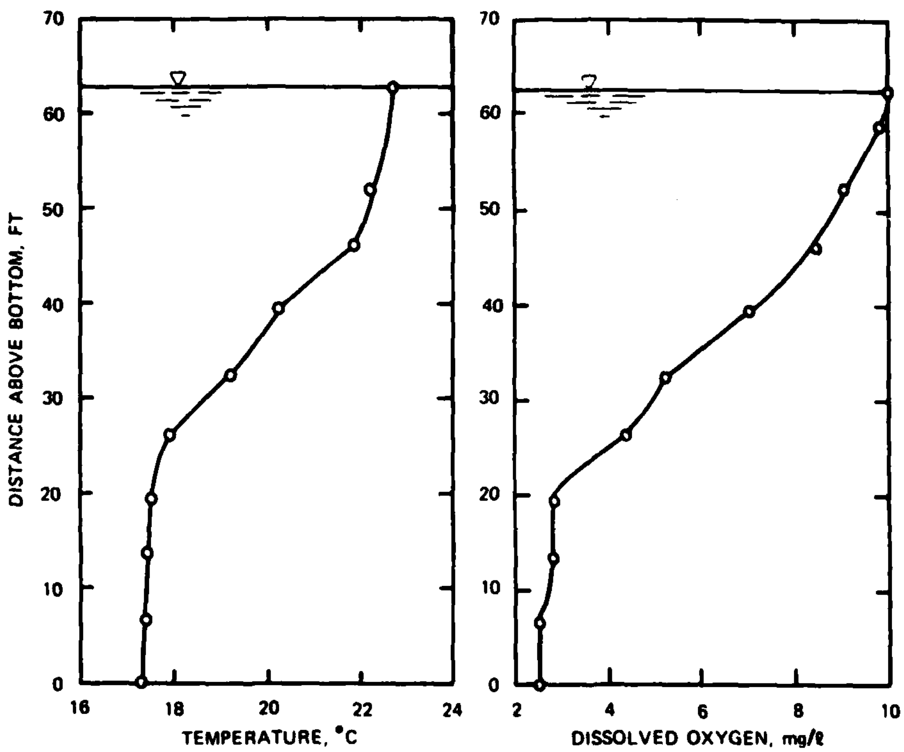

Figure 7. Temperature and DO distribution for hypothetical reservoir

example. Solving Equation 8 for this value of D_o resulted in a required distance from the outlet to the thermocline of 18.0 ft. Thus, the outlet must be 2.0 ft below the surface.

29. The initial characteristics were thus defined for a jet which must penetrate 38 ft below the thermocline and provide an epilimnetic volume flux at the thermocline of 46 cfs. The jet must have an initial diameter of 2.75 ft and transport epilimnetic water at an initial volume flux (pumping rate) of 22 cfs. The outlet for this jet should be 18 ft above the thermocline, or 2 ft below the surface. This results in an initial exit velocity of 3.7 fps. A check of the penetration of a jet with these initial characteristics, as calculated with Equation 14, showed the Z_H value was indeed 38 ft. The outlined procedure, however, is a first-order approximation for the general design of localized mixing systems for real-time reservoir stratifications. Certain hydrodynamic effects for localized mixing systems were assumed. The effects of localized mixing on the limits of selective withdrawal were assumed negligible. Although all of the epilimnetic water crossing the thermocline was assumed withdrawn, Moon, McLaughlin, and Moretti show that this assumption becomes increasingly less valid as the ratio of pumping rate to release rate Q^* approaches 1.0. While the Q^* value for this example was 0.22, higher Q^* values are certainly plausible. Further, at higher initial pumping rates, the kinetic energy of the epilimnetic jet may become so large that a very large initial jet diameter may be required to obtain the proper penetration of the jet without overpenetration. Due to the requirement that the epilimnetic jet be fully developed before reaching the thermocline (paragraph 11), the jet outlet must be at least 6.2 initial jet diameters from the thermocline. For initial jet diameters of more than 4 ft, this distance can be seen to be larger than many total epilimnetic regions. Care must be exercised so that an initial pumping rate is chosen which will allow the design of a system which conforms to the hydrodynamic constraints listed herein.

PART V: SUMMARY AND RECOMMENDATIONS

30. Localized mixing may be a viable method of enhancing the water quality of releases from hypolimnetic outlets. Localized mixing acts to jet a volume of good-quality epilimnetic water down to the point of withdrawal of a given outlet where it is released with a quantity of hypolimnetic water. The release produced is of a quality which is better than that of the hypolimnion. The degree of enhancement of the release is a function of several parameters. However, two conditions are necessary to promote successful localized mixing: (a) the epilimnetic jet must penetrate to the outlet or well into the withdrawal zone of the outlet; and (b) the jet must provide sufficient volume of epilimnetic water to effectively enhance the water quality characteristics of the release upon withdrawal from the reservoir.

31. Jet penetration into the hypolimnion was found to be a linear function of the Froude number. Observed laboratory penetration results for an idealized reservoir (approximately two-layer stratification) showed excellent agreement with predictive equations for penetration which were obtained through experimental investigation. The results of Moon, McLaughlin, and Moretti (1979) were used to provide qualitative guidance on the required pumping rate for a specified release enhancement and the maximum release enhancement generally expected. A coupling of these results could then be used, for a given required penetration, dilution, and reservoir stratification, to provide a preliminary design for a localized mixing system capable of enhancing a given downstream release. These results, however, provide initial guidance on penetration and dilution. Certain localized mixing characteristics, such as the effect of site-specific near-field release conditions and unique reservoir geomorphology, were not considered in this investigation. Many of these prototype effects may require site-specific modeling (physical and/or numerical) in order to produce an efficient localized mixing design.

32. Evaluation of the applicability of the localized mixing technique for a project is, indeed, a site-specific effort. The depth of

penetration, pattern of density stratification, reservoir geomorphology, and the quantity of epilimnetic water required to enhance a given total release must be considered for each project individually in order to assess the utility of localized mixing. However, a general requirement for the use of this technique is that a pumping system must be employed which will jet a required quantity of epilimnetic water that penetrates to a specified depth in the reservoir. If a pumping system can be employed which will simultaneously transport a specified quantity of a lighter density water down to a given location within a heavier density region, this technique is viable. If the combination of density stratification, required epilimnetic dilution quantity, total release quantity, and depth of required penetration precludes this action, then the applicability is diminished. This suggests the practicable limits of applicability for the use of localized mixing. It is not applicable for strongly stratified impoundments having deep withdrawal points and large releases (i.e., large-scale hydropower).

33. Complete quantification of the limits of applicability for localized mixing, as well as other factors such as maintenance and capital costs, the effects of wind on the pumping system, and operational constraints, has not yet been rigorously investigated due to limited use on Corps-sized impoundments. More definitive guidance on these subjects should evolve from more-extensive field application of this technique. It is recommended that the approach outlined in this report be used to obtain a working design for a localized mixing system. Field application of this design, along with appropriate physical and/or mathematical modeling, could then be used to further refine the initial design.

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APPENDIX A: LABORATORY PROCEDURES

1. Discussion of the laboratory procedures used for the localized mixing tests described herein is best presented in separate sections delineating one- and two-layer testing procedures. The one-layer testing procedures will be presented first.

One-Layer Testing Procedure

2. The term "one-layer" testing represents 100 laboratory tests which were run without an epilimnion in order to predict the penetration of a jet of density ρ_j into an ambient of density $\rho_j + \Delta\rho$.* The apparatus used in these tests are shown in Figure A1. The testing tank was 8 ft long by 4 ft wide. A constant water depth of 3.53 ft was maintained. Light-density water was pumped from the mixing tank where a blue dye had been added for flow visualization in the testing tank. This water was pumped through a flow meter, whose flow was controlled by the valve just downstream, vertically downstream into the testing tank which contained a heavy-density ambient (well-mixed saltwater). The density of the jet and the ambient (both of which were well mixed prior to each test) were measured with a hydrometer reading from a grab sample of each.

3. The penetration of the light-density jet into the heavier ambient can be characterized by Figure A2a. The jet penetrates downward initially to a maximum depth; following the onset of steady-state conditions, the jet front oscillates randomly about a mean distance Z_H from the outlet. A reverse flow field is initiated resulting from the positive buoyancy of the lighter jet fluid. This fluid rose to the water surface where it was released by an overflow weir. The penetration was computed by averaging the measured penetration depths for several observations taken during steady-state conditions. Flow rates ranging from 0.5 to 3.50 gpm, density differences between jet and ambient

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* Terms are identified in the main text.

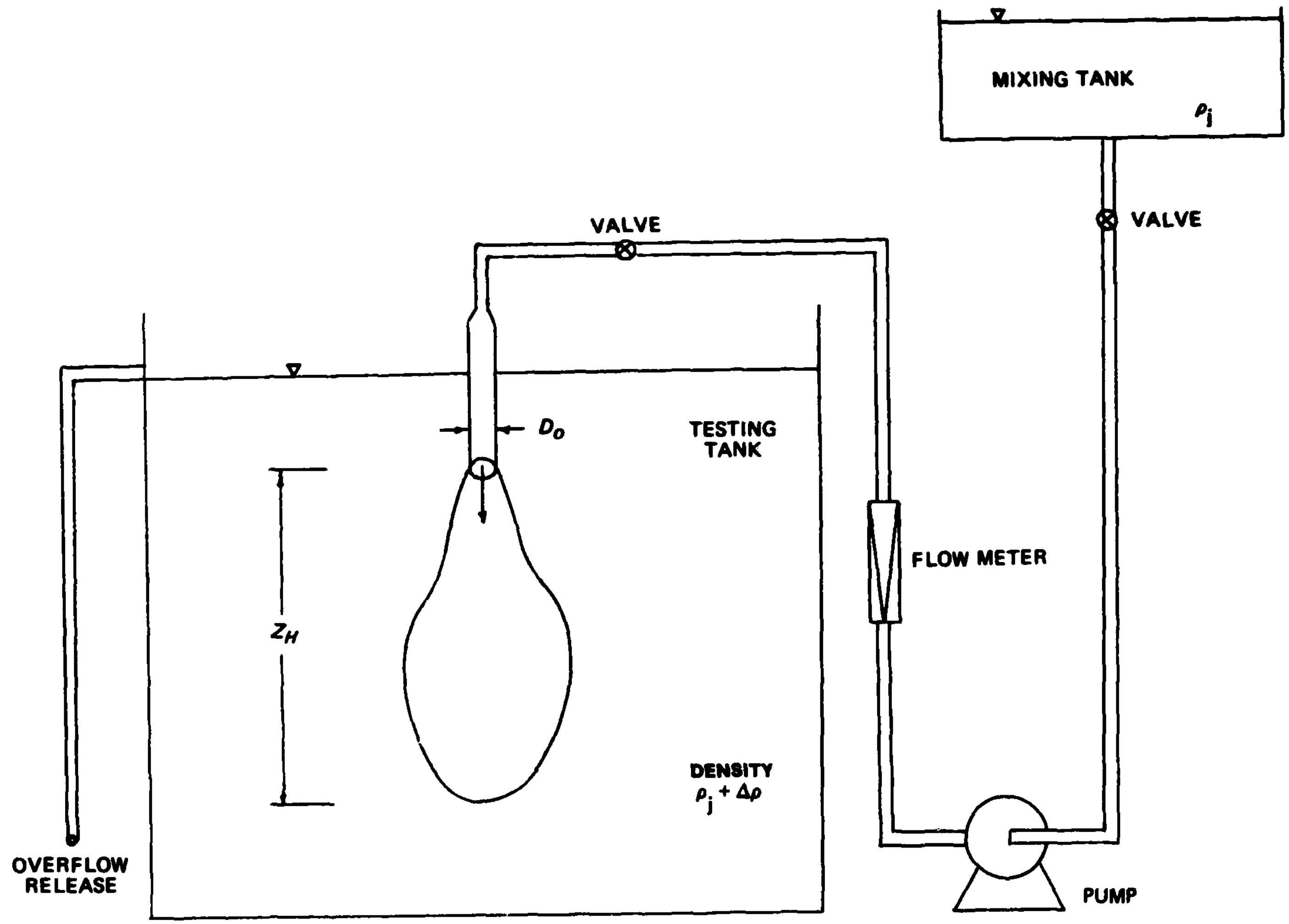
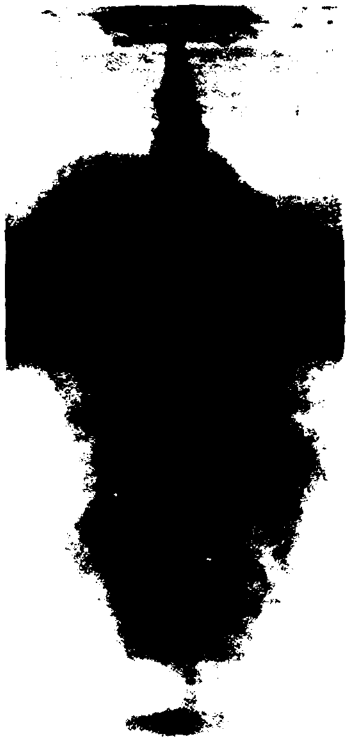


Figure A1. Schematic (not to scale) of laboratory procedure for one-layer tests



a. One layer

b. Two layer

Figure A2. Photograph of jet penetration into one- and two-layer ambient conditions, respectively. Jet is issued from orifice at top of each photo. Due to angle of photographs, the side wall of testing tank appears to be below the water surface conditions ranging from 0.001 to 0.003 g/cc, and initial jet diameters ranging from 0.5 to 1.5 in. were investigated.

Two-Layer Testing Procedure

4. The term "two-layer" testing refers to those 31 penetration tests which were run with an epilimnion (density ρ); a small, sharp thermocline; and a hypolimnion (density $\rho + \Delta\rho$) to predict penetration of a localized mixing jet into an idealized reservoir stratification. The laboratory equipment used in these tests are shown in Figure A3. The testing tank was 40 ft long by 16 ft wide. Water depths from 3.5 to 3.7 ft were tested. A pump, with an intake placed in the epilimnion, transported epilimnetic water through a flow meter which was controlled by a downstream valve. The water, to which dye was added just prior to pumping, was jetted vertically downward through the epilimnion region of the idealized reservoir where it was nonbuoyant. The jet then, for the tests analyzed, passed through the thermocline and into the hypolimnion. Figure A2b characterizes this penetration. Upon issuance through the thermocline, the jet experienced positive buoyant forces. The jet penetrated initially to a maximum depth, and, following the onset of steady-state conditions, oscillated randomly around a mean penetration depth. A reverse flow pattern was initiated due to the positive buoyancy of the epilimnetic jet. This reverse flow rose to a point of neutral buoyancy and spread laterally and longitudinally throughout the tank as shown in Figure A2b. The penetration of the jet, as measured from the thermocline, was computed in the manner used for the one-layer tests. Flow rates ranging from 0.75 to 3.00 gpm, initial jet diameters ranging from 0.5 to 1.0 in., distances from the outlet to the thermocline of 0.88 to 1.21 ft, and epilimnetic-hypolimnetic density differences of 0.0009 to 0.0027 g/cc were run. An initial vertical density profile, taken just prior to test initiation, was used to compute the density difference for the given test. The tank was initially stratified by floating fresh water over a well-mixed layer of saltwater. The depths of the freshwater and saltwater layers were changed periodically to simulate differing depths of epilimnion and distances from the outlet to the thermocline.

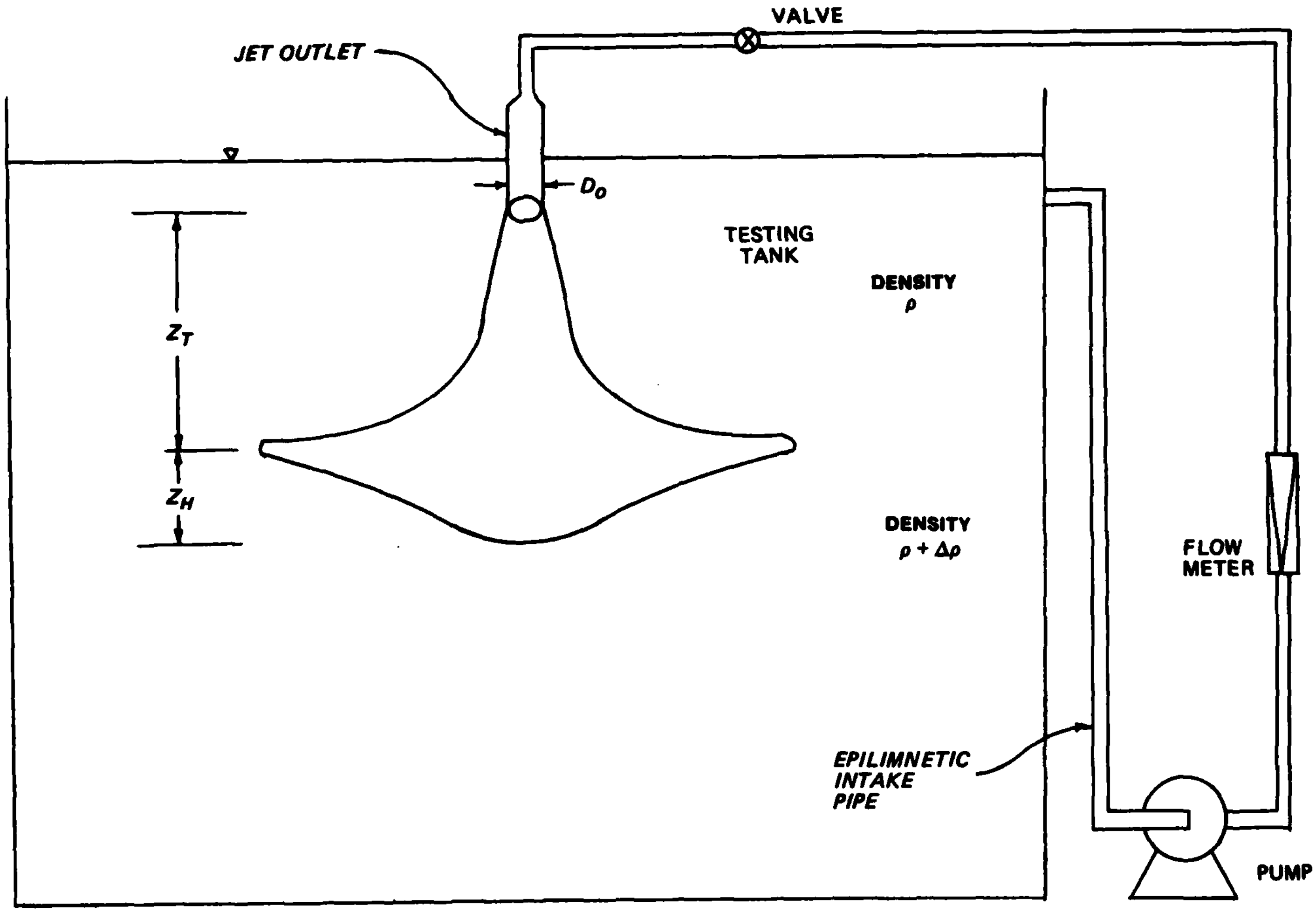


Figure A3. Schematic (not to scale) of laboratory procedure for two-layer tests

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