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"RESEARCH ON OUTLETS FOR SELECTIVE WITHDRAWAL"

by
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INTRODUCTION

As increasing national attention is being focused on the control of water quality, the Bureau of Reclamation is similarly placing increased emphasis on the quality of its reservoir water. Bureau impoundments are used primarily for irrigation supplies and generation of power; however, municipal and industrial uses have increased in recent years. Regardless of the use of stored water, the quality of the water is an important factor. Even if releases are made primarily for the generation of electric power, quality must be kept at a high level for maintenance of fishlife, assimilation of wastes, and recreation in the downstream river.

Experience shows that the parameter most easily controlled by selective withdrawal is temperature. However, many other physical or chemical properties might be considered, such as dissolved oxygen, turbidity, taste and odor caused by algae, fertilizer and pesticide residues, and others.

The design of an outlet works is made more complex by the requirement for selective withdrawal. Proper design and operation of multiple outlets depend on a thorough knowledge of reservoir mechanics. The stratification pattern in a given reservoir will determine the optimum outlet configuration for a particular case.

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Design of facilities for selective withdrawal can be divided into two categories: (1) improvement of existing structures and (2) design of new structures. Existing structures can be improved by modification of outlets or by creation of artificial barriers such as skimmer walls or submerged weirs. Such modifications are often practical for relatively small installations, but are usually not justifiable for large projects with deep reservoirs. The design of either new or modified outlets depends on reasonably accurate prediction of stratification patterns and the movement of layers within a reservoir. This prediction depends upon the reservoir size, shape, and location (latitude and altitude) and the season during which the selective withdrawal occurs. Optimum outlet operation can be achieved only when reservoir conditions are continually monitored, which is usually impracticable and often impossible for large reservoirs. Location of sampling stations and determination of realistic sampling time intervals also require a basic understanding of reservoir mechanics.

Most Bureau of Reclamation reservoirs have large volume, are often operated for the purpose of providing peaking power, have a stratification pattern similar to Figure 1, and are characterized by spring and fall overturns. Several Bureau of Reclamation projects include selective outlets with varying degrees of complexity. In most cases, the structure does not include multiple outlets but consists of a single outlet strategically placed to provide partial control of a single quality parameter.

A few dams, including Arrowrock, Shasta, Martinez, Grand Coulee, Sherburne Lake, Yellowtail, Elephant Butte, Whiskeytown, and Arbuckle include two or three outlets with vertical spacing from 10 to 100 feet. Casitas Dam

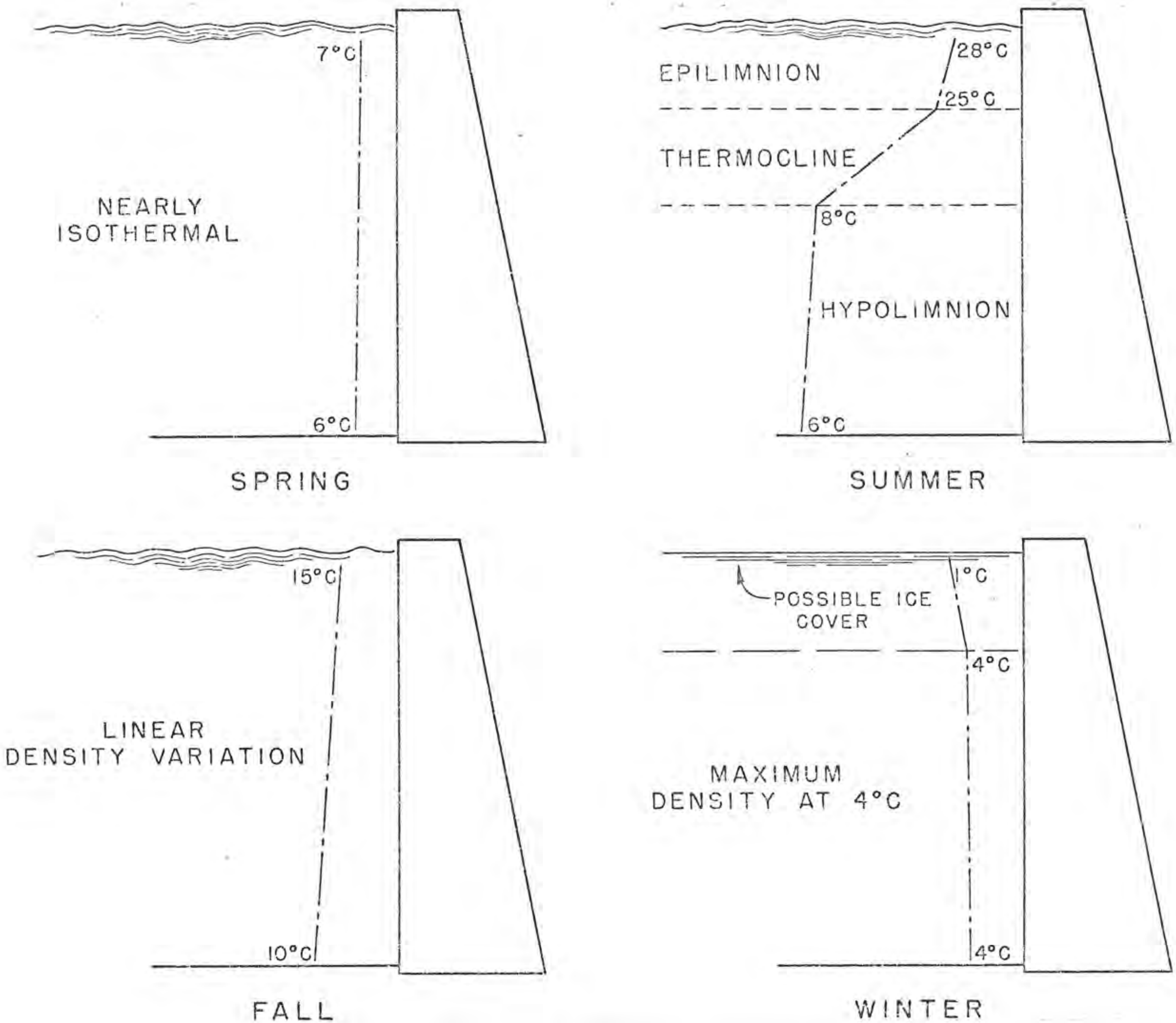

FIGURE 1. HYPOTHETICAL RESERVOIR STRATIFICATION CONDITIONS

includes multiple outlets in a sloping tower on the upstream face of the earth embankment. Cachuma Dam and Cheney Dam have multiple outlets in a vertical tower; similar facilities are included at Sanford Dam. Folsom Dam was successfully modified to allow selective withdrawal by placing shutter gates on the penstock trashracks.

Bureau of Reclamation experience with selective withdrawal at four dams has been described in a paper by Austin, Gray, and Swain.[2/] Design criteria have largely been based on the results of such prototype experience, and on a relatively minor amount of laboratory research. Complete flexibility in selective withdrawal is very attractive; however, multilevel outlets are expensive and redundancy should be avoided. On the other hand, facilities with less than the optimum number of outlets can result in costly damage to fisheries and cause other water quality problems. Such problems can also be caused by improper operation of otherwise adequate facilities.

LIBRARY RESEARCH

In 1966, the writer completed a library study to determine the state of the art and to define research needs.[3/] The library study showed that research on stratified flow is being carried out by many agencies and institutions, both public and private. Some areas which apparently

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2/ "Report on Multilevel Outlet Works at Four Existing Reservoirs," G. H. Austin, D. A. Gray, D. G. Swain, ASCE Hydraulics Division Conference, Cambridge, Massachusetts, August 21-23, 1968

3/ "Hydraulics of Stratified Flow - First Progress Report - An Analysis of the State of the Art and a Definition of Research Needs." By D. L. King, Report No. HYD-563, Hydraulics Branch, Bureau of Reclamation, June 3, 1966 have not been investigated, or which have been investigated to a small extent, are the influence of reservoir and intake geometry on selective withdrawal and the optimization of intake design, model studies of particular reservoirs and correlation with prototype data, artificial alteration of density currents in reservoirs and estuaries, and effects of hydraulic structures such as stilling basins on reoxygenation of cold-water releases.

The library study included preparation of a selective bibliography of publications describing many applications in the hydraulics of stratified flow. References on instrumentation were reviewed and a temperature measuring system was recommended. The configuration of the test facility was formulated.

PILOT STUDIES

Scope and Limitations

Research by the Bureau of Reclamation is being conducted to determine criteria for the design of selective outlets. Testing procedures and instrumentation have been developed and methods of inducing thermal stratifications in a hydraulic model are being evaluated. The study is producing basic data concerning the mechanism of selective withdrawal.

These tests are not concerned with predicting the stratification pattern. It is assumed that a given temperature stratification pattern exists, for which the mechanics of selective withdrawal are determined. The Bureau's hydraulic model is being used to study the three-dimensional flow pattern within the region near the intake.

Other investigators have been and are presently engaged in predicting stratification; however, the influence of withdrawal on the pattern of stratification is not well understood. Most research has been concerned with the idealized case of two-layer stratification with withdrawal from a slot, usually at the bottom of the dam. However, the situation existing in nature is often a three-layer stratification, with an approximately linear density gradient in each layer. The present study is concerned with this natural configuration, and the more probable method of withdrawal through an orifice located somewhere on the face of the dam.

Temperature stratification, as opposed to salinity stratification, was chosen for the study primarily because of the availability of reliable temperature instrumentation.

Model Configuration

Figure 2 shows the flume used for the laboratory tests. The flume is divided into a mixing compartment and a test compartment, with the refrigeration system located in the mixing compartment. The cold water flows through a selective-level bulkhead and sinks to the floor of the test compartment. After several hours, a well-defined thermal stratification exists in the test compartment. Outflow occurs through a small orifice with adjustable elevation and is recirculated to the mixing compartment or discharged to waste. Thermistor probes are placed in desired locations in the test compartment. The thermistors are connected through a scanning device to a digital thermometer and a printer where temperatures are displayed and recorded with an accuracy of 0.02° C.

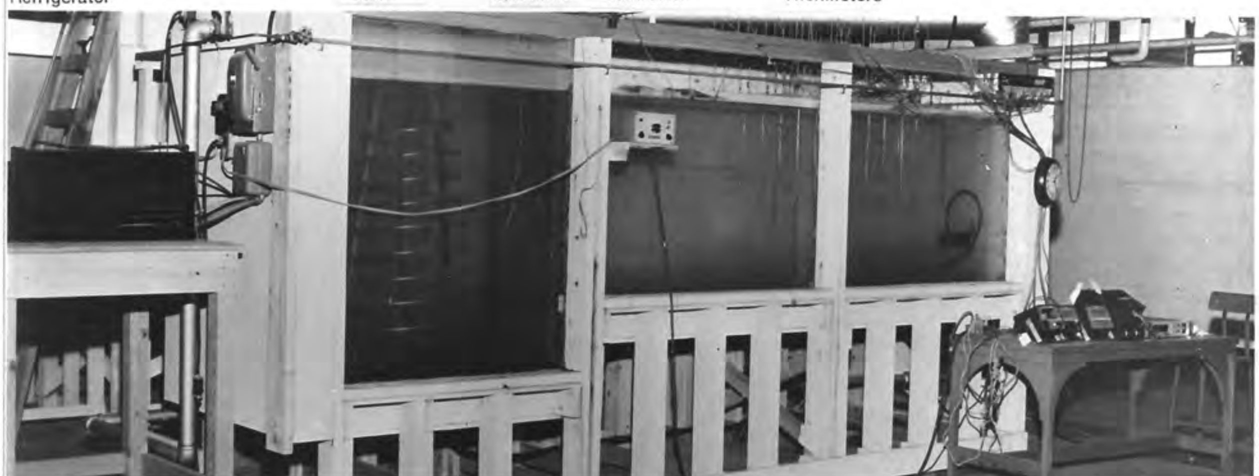

FIGURE 2. TEST FACILITY AND INSTRUMENTATION

Figure 2 also shows the instrumentation. Two very accurate quartz probes, with a digital thermometer are available for calibration and checking of the thermistor probes.

Description of Tests

Conditions near the outlet. - The first series of tests was concerned with the flow pattern and temperature distribution near the outlet. Effects of sudden starting and stopping of outflow, and vertical circulation on the dam face were of particular interest.

Outflow was through a 1-inch-diameter orifice at a rate of approximately 0.02 cfs. The outflow orifice was located 0.82 feet above the floor in a total reservoir depth of 3.5 feet. Inflow was through a 1-inch slot located 1.29 feet above the floor, at a distance of about 10 feet from the face of the dam. Inflow was across the full width (3 feet) of the flume. The orifice flow discharged into a 1.75-inch-radius semicircular tube, representing an intake tower. The curved upstream face of the tower was located approximately 8 inches from the face of the dam. Movement of dye tracers along the dam face showed no vertical circulation. However, "ride-up" occurred which is analagous to wave impingement on a barrier in homogeneous, free-surface flow. The amplitudes of the "ride-up" and accompanying reflected waves depend on the velocity of the moving layer. Also, positive and negative waves are formed during sudden rejection or demand of the outflow.

Time-lapse movies of the movement of dye in the withdrawal layer showed that the dye moved to the intake tower, then hesitated. A portion of the dye flowed through the orifice while the remainder moved around both sides of the withdrawal tower to the dam face. The dye then moved upstream toward the sides of the flume at an angle of approximately 45°.

The temperature data, Figure 3, show that the temperature distribution at the dam was representative of upstream temperature conditions in the reservoir during withdrawal. These results indicate that thermometers embedded in the upstream face of concrete dams (for the purpose of structural behavior measurements) could be used to monitor conditions of stratification in the reservoir.

The data of Figure 3 were recorded 2 hours after the start of withdrawal. During the 2 hours the overall temperature of the tank increased about 0.1° C due to heat transfer from the room. The numbers in parentheses indicate the temperature profile before withdrawal began, corrected for the temperature increase. The thermistors near the water surface reflected the increased rate of heat transfer through the open top of the flume. The two rows of thermistors above the orifice level on the dam face, show the effect of withdrawal. Other thermistors were relatively unaffected.

The temperature profiles in Figure 4 indicate mixing of the hypolimnion during the withdrawal and accompanying recirculation. The shaded area shows the region of mixing for the center vertical row of thermistors. Theoretically, the area of temperature increase should equal the area of temperature decrease. However,

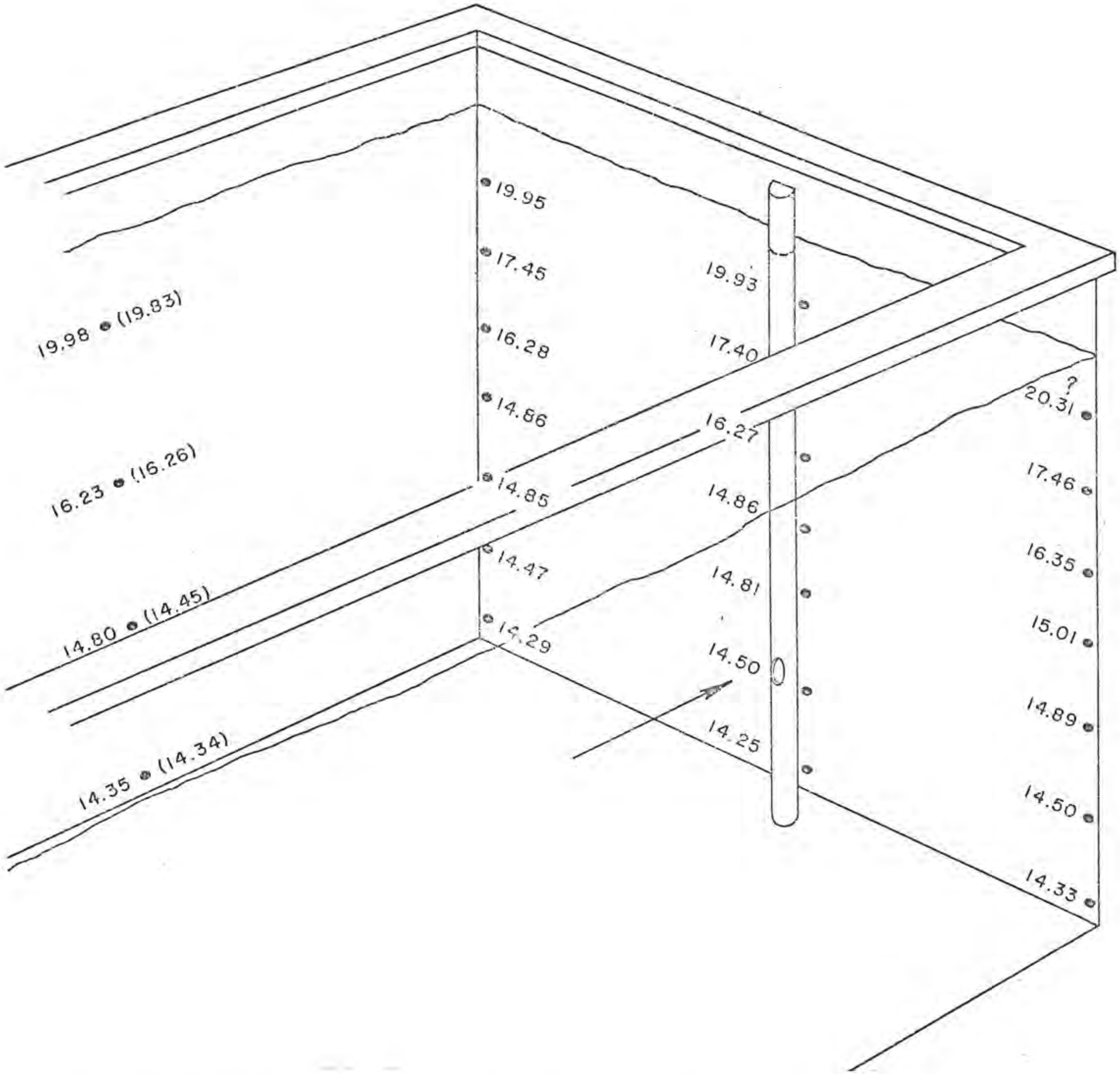

FIGURE 3. TEMPERATURE DISTRIBUTION IN FLUME

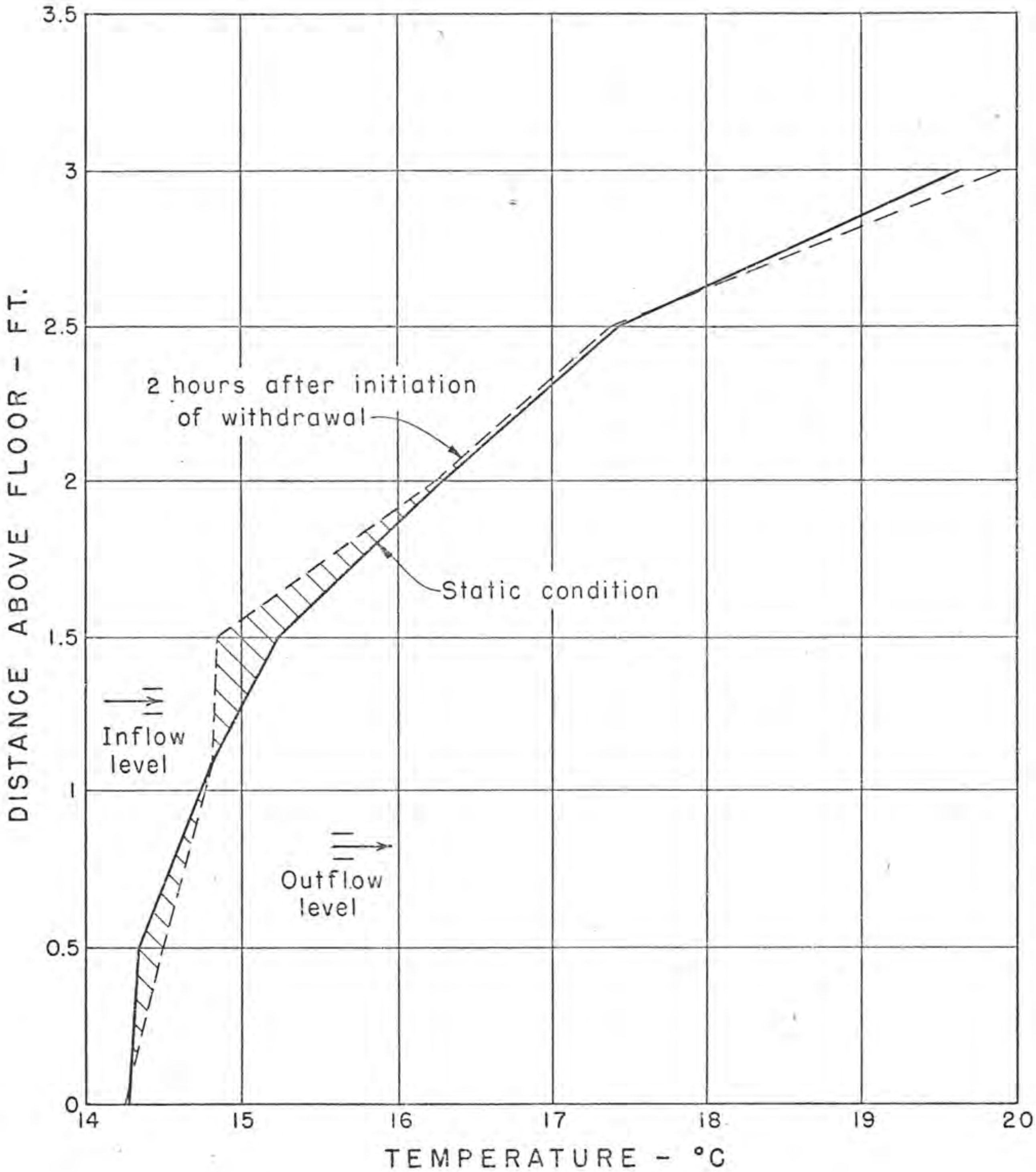

FIGURE 4. EFFECT OF WITHDRAWAL ON TEMPERATURE PROFILE

the temperature distribution on the dam face is not strictly two-dimensional. Also, closer spacing of the thermistors would be necessary to accurately define the temperature profile.

Another factor that must be considered is warming of the water during recirculation to the mixing compartment. For this particular test, the refrigerating unit was inadequate to maintain a constant temperature. The inflow to the test compartment sought progressively higher levels. Therefore, the profile in Figure 4 is a result of both mixing within the withdrawal layer and the addition of heat from the inflow.

A plan view of the dye pattern in the reservoir is shown in Figure 5. The unusual spiral motion exhibited in the model has also been observed in prototype reservoirs and in oceans. The cause has been described as the coupling of the effect of wind and the Coriolis effect. The Coriolis effect causes the direction of the wind-induced surface current to deviate slightly to the right of the direction of the wind (in the northern hemisphere). The deviation to the right occurs in each succeedingly lower layer of the reservoir, resulting in a spiral pattern. It should be noted that this theory is not universally accepted.

With no withdrawal and no detectable surface air movement, a clockwise spiral appeared in the epilimnion of the model. In the hypolimnion, water at the bottom of the flume moved slowly downstream and there was a marked upstream movement about 6 inches above the bottom. The remainder of the hypolimnion was essentially motionless.

FIGURE 5. SPIRAL VELOCITY PATTERN

A fan was then used to generate a surface wind toward the dam. In the center portion of the flume the surface water moved downstream. A layer at a depth of about 3 inches moved upstream and a layer at about 6 inches depth moved downstream. A strong surface current moved upstream along the sides of the flume. Upstream movement of a layer 6 inches above the bottom continued and the clockwise spiral was again evident.

Because the spiral effect occurred without withdrawal, and both with and without surface wind the spiral pattern in the model was believed to be something other than a Coriolis spiral. The temperature data from the thermistors on the dam face (Figure 3) showed slightly higher temperatures on the right side near the plexiglass. This would cause convection currents. However, the fact that the hypolimnion was nearly motionless indicated that the slight horizontal temperature gradient was probably not the cause. This absence of motion would also preclude the possibility of residual currents resulting from filling of the model.

The mechanics of this phenomenon seem very complex. The cause is being investigated further. Although many theories have been advanced, the knowledge that such currents might exist in reservoirs is significant.

Determination of withdrawal layer thickness. - The temperature of outflow depends on the thickness and location of the layer from which water is withdrawn in a stratified reservoir. In an isothermal reservoir the thickness will correspond to the entire reservoir depth. For a given rate of withdrawal from a reservoir with a linear density gradient, the thickness will be inversely proportional to the steepness of the gradient. In the idealized two-layer case, discharge will occur only from one layer until a critical rate is reached at which withdrawal from the other layer begins.

It is the opinion of the writer that, in the more common case, each of three main regions (hypolimnion, epilimnion, and thermocline) can be treated as a separate body with a linear density gradient. When the withdrawal layer thickness becomes equal to the thickness of the main region, the critical rate in the two-layer case must be considered.

C. S. Yih[4/] forms the basis for later studies in the flow of a fluid with a continuous density gradient toward a line sink. Yih uses potential theory to show that withdrawal from discrete layers will occur below certain critical rates of discharge. Motion of a stratified fluid is characterized by the densimetric Froude number $F' = \frac{V}{\sqrt{g'd}}$, where V is the velocity in the moving layer; g' is the adjusted acceleration of gravity ($g\frac{\Delta\rho}{\rho}$), ρ is the density at the bottom of the layer, $\Delta\rho$ is the change of density from bottom to top of the layer; d is the depth of the layer.

In any fluid system, a given particle is acted upon by the vertical forces of gravity and buoyancy. In a homogeneous fluid, these forces are

4/"On the Flow of a Stratified Fluid," C. S. Yih, Third U.S. National Congress on Applied Mechanics, 1958 and opposite

exactly equal. Within a stratified fluid, the force of weight is larger than the force of buoyancy. The particle is thus more stable against mixing.

The analogy to free-surface flow is apparent. In the limiting case of an air-water interface, $\frac{\Delta\rho}{\rho}$ is essentially equal to one and g' = g. The motion of one layer of a stratified fluid is therefore similar to ordinary open-channel flow with reduction of the gravity term according to the density difference.

Yih's theoretical solution gives the critical value for the densimetric Froude number as $\frac{1}{\pi}$ (0.318). Selective withdrawal can be accomplished only for Froude numbers below the critical value. Discharges with higher Froude numbers will draw from the entire depth of fluid.

Kao[5/] presents a theoretical solution for the interface position and streamlines for a continuous density gradient with densimetric Froude numbers below approximately $\frac{1}{\pi}$.

Kao found that the linearly stratified region was divided into a flowing zone and a stagnant zone at a densimetric Froude number value of 0.345. The critical value was greater than $\frac{1}{\pi}$ because of the presence of an eddy zone above the flowing layer. His solution also showed that the densimetric Froude number remained constant and that changes in the rate of withdrawal were reflected as changes in the depth of the flowing zone. The flow

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5/"A Free Streamline Solution for Stratified Flow into a Line Sink," T. W. Kao, Journal of Fluid Mechanics, Volume 21, March 1965.

pattern as shown in Figure 6 is a nondimensional representation dependent on the depth of the flowing zone, d.

For a given linear stratification, the value of d can be found with the Froude number as defined above, set equal to 0.345. Having determined d, Figure 6 is used to determine the streamline locations and particularly the location of the dividing streamline. The temperature of the outflow can then be calculated. Kao's work was concerned with a line sink at the downstream bottom corner of the channel. The application described in this paper however, is for a circular sink located at some distance above the floor of the reservoir. It was assumed that the withdrawal layer would be equal to 2d, symmetrical about the level of withdrawal. Also, tests described earlier show that at a short distance from the orifice the withdrawal pattern is essentially two-dimensional with respect to temperature distribution.

A test was performed to determine the possible application of Kao's theory to approximately linear portions of the temperature profile. The theoretical withdrawal layer thickness of 5 inches is outlined on the photograph of Figure 7 along with the measured temperature profile. The arrow on the photograph shows the direction of flow and the height of the withdrawal orifice. The vertical dye streaks in Figure 7 were photographed immediately before withdrawal began. Figure 8 shows a displacement of the dye streaks about 6 minutes after the start of withdrawal. Figure 9 shows the dye

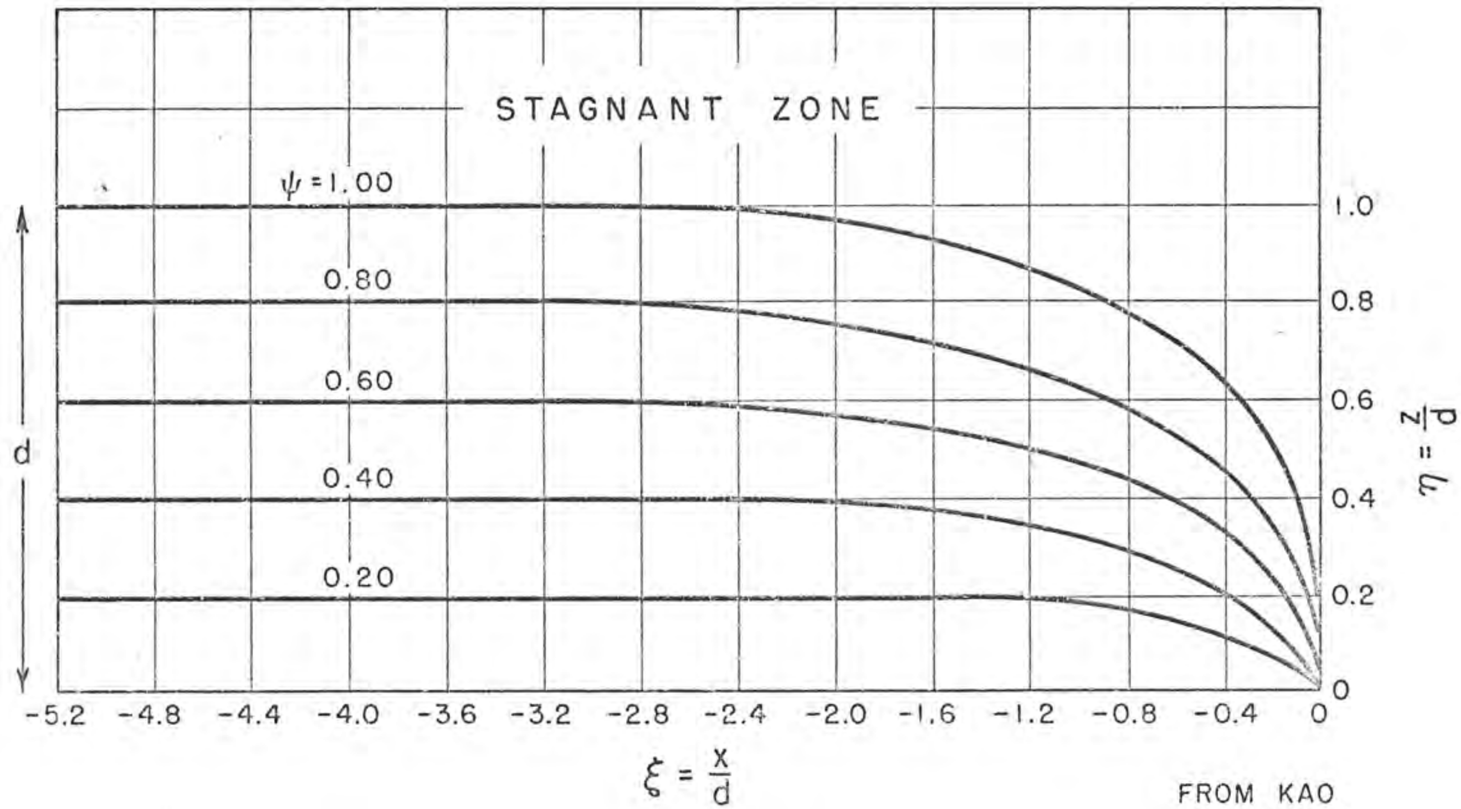

FIGURE 6. FLOW INTO LINE SINK FROM LINEARLY STRATIFIED FLUID

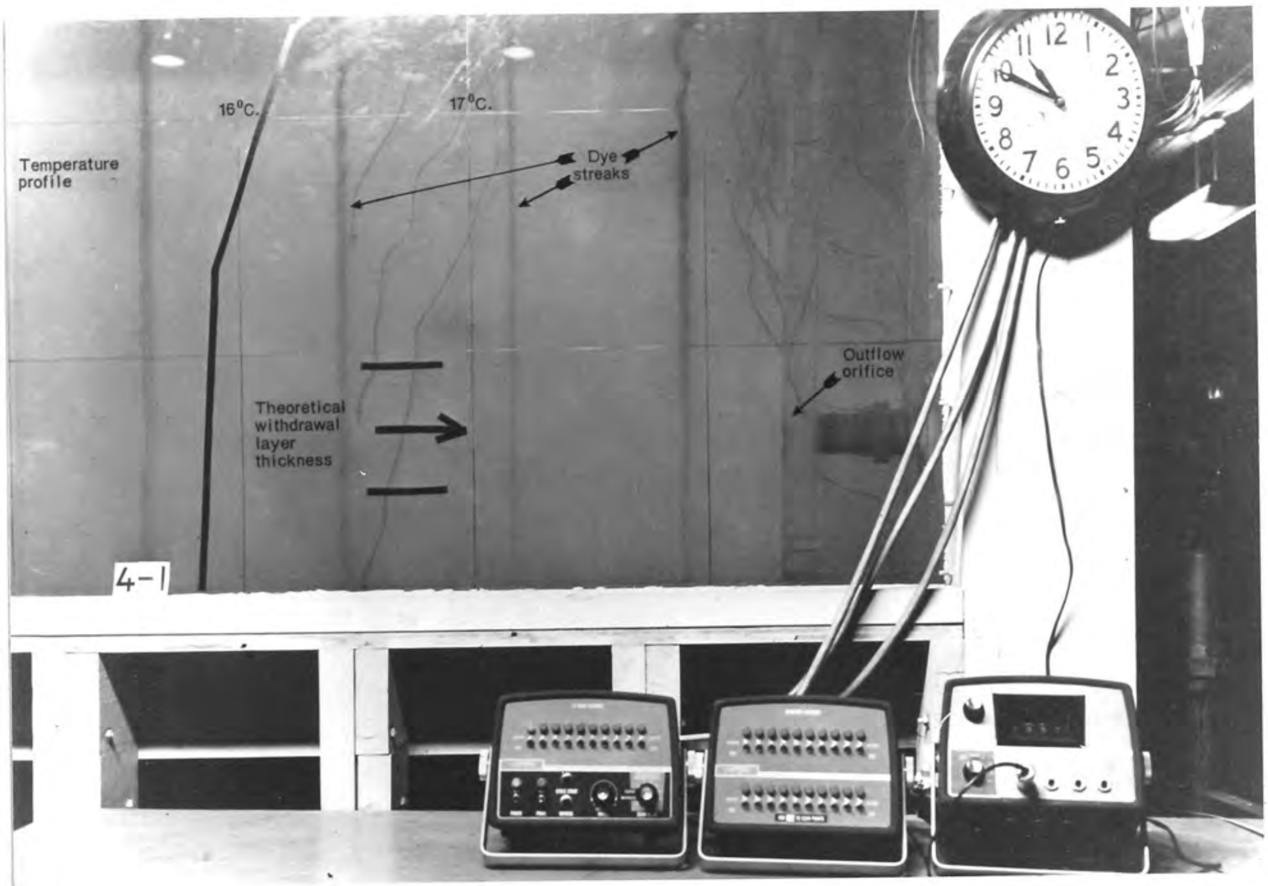

FIGURE 7. DYE STREAKS BEFORE START OF WITHDRAWAL TEST

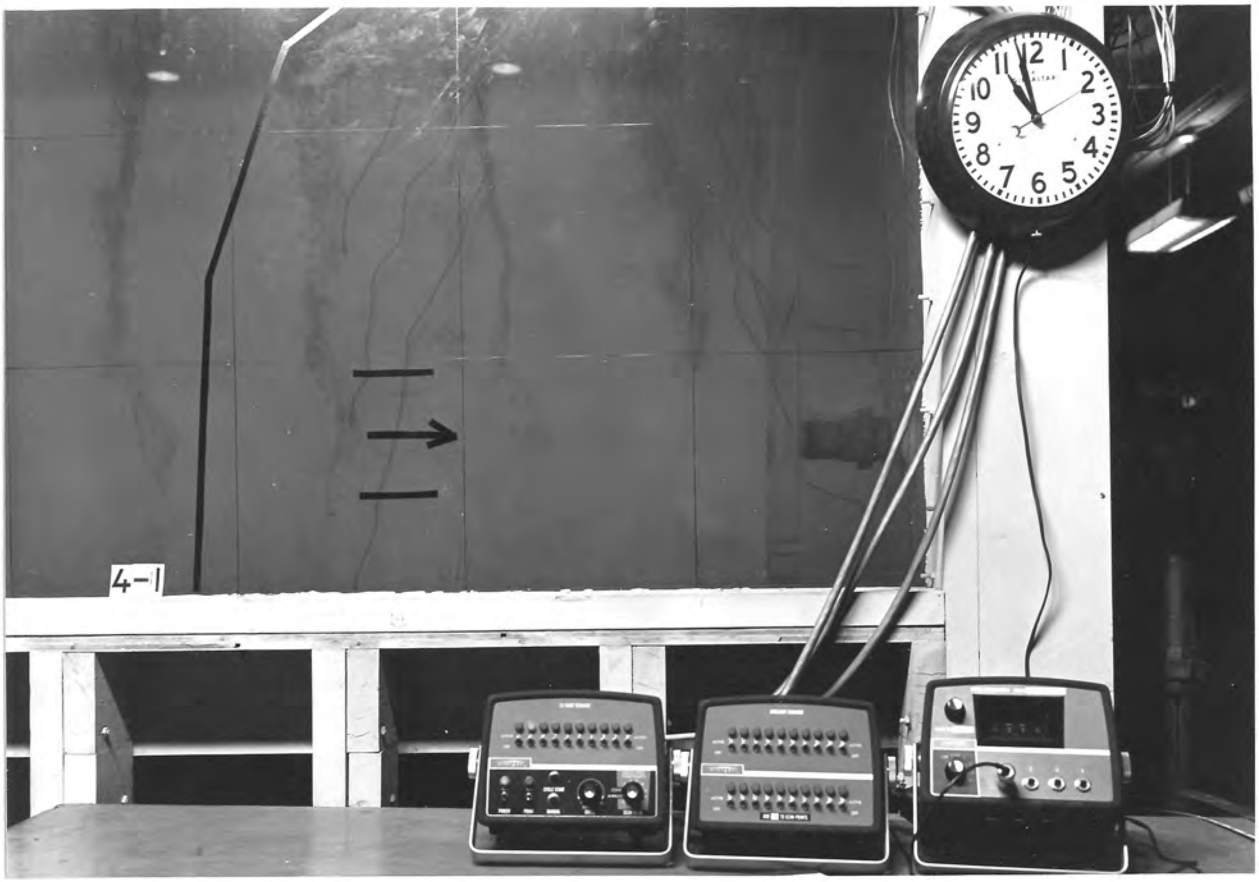

FIGURE 8. DYE STREAKS AT T - 6 MIN

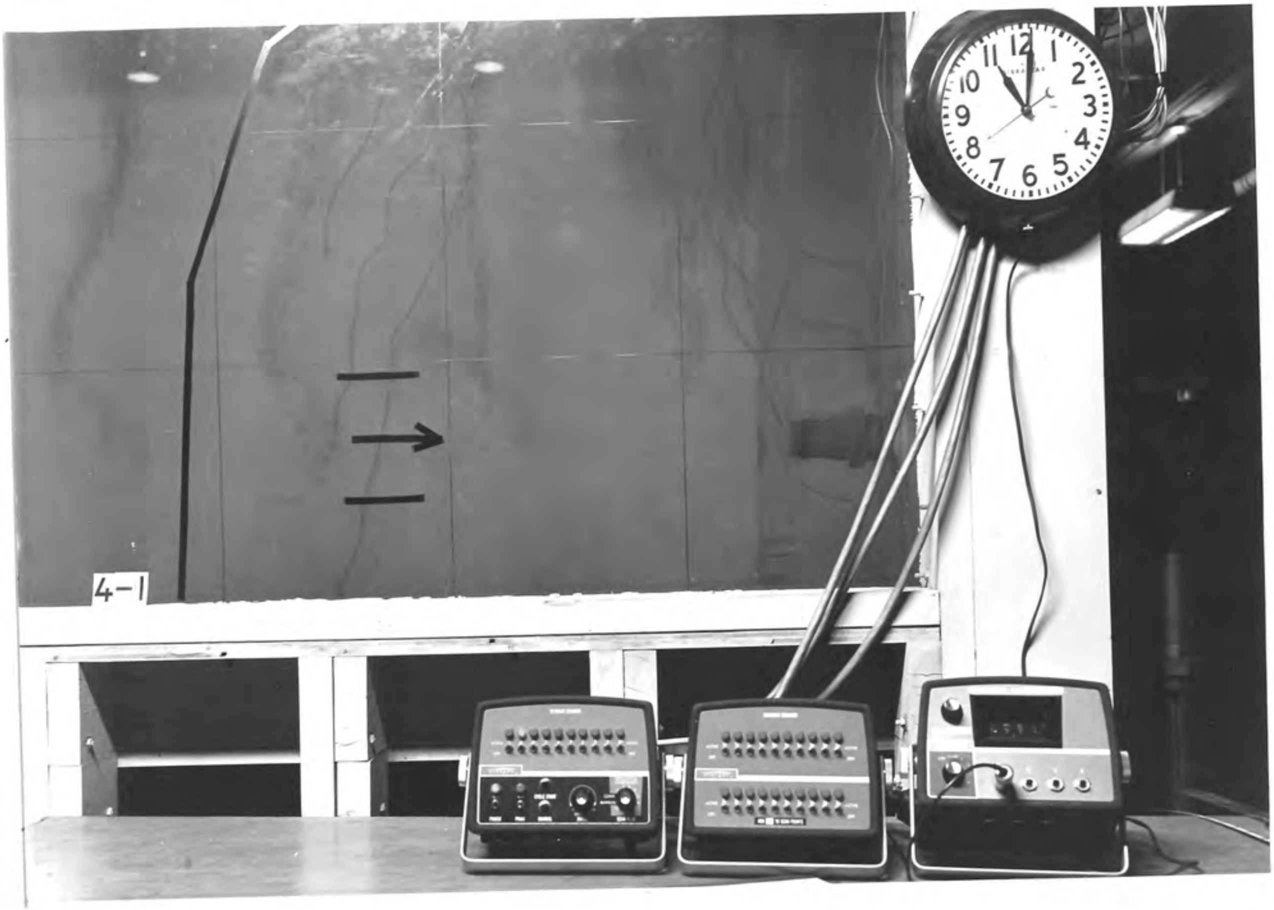

FIGURE 9. DYE STREAKS AT T - 9 MIN

streaks after about 9 minutes. The model results appeared to verify the application of Kao's theory to the three-dimensional case in a region of linear variation of temperature.

Harleman[6] points out that the important difference between stratified and free-surface flows is the effect of viscous resistance at the interface. No attempt has yet been made in the present study to measure the growth of the withdrawal layer due to interfacial mixing.

Experiments by Debler[7] indicated that viscous effects result in a critical densimetric Froude number of about 0.28, instead of the theoretical value of 0.345 determined by Kao. Since the withdrawal layer thickness varies inversely with the square root of the densimetric Froude number, the thickness predicted from Debler's value would be about 10 percent larger than that predicted from Kao's value. This is not an important limitation, considering other uncertainties involved, including prediction of the stratification pattern for new reservoirs.

Gelhar and Mascalo[8] developed a mathematical model which includes viscous effects. For a linearly stratified fluid, the model predicted

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6/"Stratified Flow," D. R. F. Harleman, Section 26 of Handbook of Fluid Dynamics, edited by V. L. Streeter, McGraw-Hill, New York, 1961

7/"Stratified Flow Into a Line Sink," W. R. Debler, Journal of the Engineering Mechanics Division, ASCE, July 1959

8/"Non-Diffusive Characteristics of Slow Viscous Stratified Flow Towards a Line Sink," L.W. Gelhar and D. M. Mascalo, MIT Hydrodynamics Laboratory Report No. 88, February 1966 a growth of the withdrawal layer directly proportional to the 1/4 power of the distance from the sink.

Discussion of the withdrawal layer thickness may be largely academic when applied to the prototype case. Discharges will usually be large enough to draw from the entire thickness of a specific layer such as the hypolimnion. Even with smaller discharges, growth of the layer by entrainment at the interface may result in withdrawal from the entire layer some distance upstream in the reservoir. This possibility will be investigated further. An understanding of the relative importance of precise prediction of withdrawal layer thickness is necessary in the formulation of mathematical models, where certain simplifying assumptions are required. Also, it may be unnecessary to provide complete selectivity in a withdrawal structure if two or three outlets will perform the same function.

PROTOTYPE TESTS

In addition to the observations reported by Austin, et al., in the paper cited above, some specific prototype tests have been made to evaluate the operation of existing selective withdrawal facilities and to obtain general information on the mechanics of prototype reservoirs.

Data have been collected for several years from Cheney Reservoir. Measurements of temperature and chemical quality have been made within the reservoir and quality at the outlet has been continually monitored. Evaluation of the data is presently underway to determine the performance of the selective outlets.

In 1967, the DWICA (Deep Water Isotope Current Analyzer) probe, owned by the Tennessee Valley Authority, was used to measure velocity in portions of Lake Mead. The primary purpose of the measurements was to detect possible short circuiting of polluted inflow to a municipal water intake. The measurements showed that the short circuiting did not exist.

The spiral effect observed in the laboratory flume also occurred in Lake Mead. As mentioned in the case of the laboratory flume, the currents might have been caused by horizontal temperature gradients which cause the reservoir to seek stability by convection. These horizontal gradients could be caused by reservoir inflows or weather differences at various points in the reservoir. Other reasons for the currents might be wind, the Coriolis effect, secondary currents caused by withdrawal, or a combination of these factors. Barometric pressure differences in a reservoir of this size could also be a contributing factor.

Measurements were also made in Lake Mead of unsteady flow in the withdrawal layer caused by discharge variations during generation of peaking power.

Evaluation of prototype structures and reservoirs is continuing.

FUTURE PLANS

Plans for future research include the formulation of a mathematical model or the use of an existing model to predict stratification and to evaluate selective outlet schemes. The hydraulic model will be used for verification of the mathematical model and for refinement of certain phases which are dependent on a detailed knowledge of flow conditions within the vicinity of the outlet. Simulation of specific prototype structures will be attempted.

The hydraulic research may also include tests on destratification of reservoirs or of portions of reservoirs in the vicinity of the outlets.

SUMMARY

The Division of Research of the Bureau of Reclamation in Denver, Colorado, is continuing a research program aimed at developing criteria for the design of selective outlet structures. A library study of the state-of-the-art was used as a basis for beginning hydraulic laboratory tests. General information on stratified flow patterns in the vicinity of outlets has been obtained from a temperature model and limited comparisons have been made with theory.

APPENDIX. - NOTATION

The following symbols are used in this paper:

d = thickness of withdrawal layer, ft

F' = densimetric Froude number, dimensionless

g = acceleration of gravity, ft/sec^2

g' = modified acceleration of gravity, $g\,\Delta\rho/\rho$, ft/sec^2

V = velocity of withdrawal layer, ft/sec

x = horizontal distance from sink, ft

z = vertical distance from sink, ft

η = dimensionless vertical distance from sink, z/d

ξ = dimensionless horizontal distance from sink, x/d

ρ = mass density, fluid in bottom layer in two-layered system, $lb\text{-}sec^2/ft^4$

$\Delta\rho$ = difference between mass densities of layers in two-layered system, $lb\text{-}sec^2/ft^4$

ψ = stream function

ABSTRACT

The Bureau of Reclamation is deeply involved in attempts to control water quality in streams and reservoirs. The use of selective withdrawal facilities is a primary method of such control. A library study has shown that more research to optimize intake design is needed. Basic studies are being conducted in the Research Division of the Bureau of Reclamation in Denver, Colorado. Early results of these studies and plans for future research are described in this paper.

Key words: hydraulics; research; outlets; hydraulic models; water quality; reservoirs; design criteria; temperature.