UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

HYDRAULIC MODEL STUDY
OF STRATIFIED FLOW OVER A WEIR

Hydraulic Laboratory Report Hyd-425

DIVISION OF ENGINEERING LABORATORIES

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HYDRAULIC MODEL STUDY OF STRATIFIED FLOW OVER A WEIR

PURPOSE OF STUDY

The purpose of this study was to observe by means of a hydraulic model the pattern of flow over a weir in regard to the proportionate contributions made to the outflow by various levels of waters in a reservoir. This study was one part of a comprehensive consideration of a proposal that reservoir evaporation losses might be reduced and water quality influenced by attempting to withdraw only the surface layer of water from a reservoir having a temperature-induced density stratification.

ACKNOWLEDGMENT

This study was performed through cooperative efforts of engineers of the Hydrology Branch and Hydraulic Laboratory Branch.

INTRODUCTION

In the final report on Lake Mead evaporation studies, a section was devoted to the "Theoretical aspects of the withdrawal of water from the surface of Lake Mead." In this section it was concluded that if it were possible to withdraw water of the highest temperature from near the surface, a saving of approximately 8 percent in evaporation would be realized. During the period chosen for study, July 9, 1952, to June 29, 1953, evaporation loss from Lake Mead was computed to be approximately 900,000 acre-feet for which a saving of 8 percent would amount to 72,000 acre-feet of water. The importance of saving water and the controversial nature of the hydrodynamics of surface withdrawal prompted studies to indicate whether only surface water would be withdrawn from a reservoir or would the outflow be supplied from the entire depth.

To help visualize what takes place when water is withdrawn from a reservoir, several electric analogy tray studies were performed by the General Engineering Branch. These included two, 2-dimensional models and one, 3-dimensional model. A weir near the surface and a slot at mid-depth of the reservoir were used for the 2-dimensional models and a single morning-glory spillway was used for the 3-dimensional model. All three models represented crest lengths of 500 feet which would require a 5-foot head to discharge

19,200 cfs, the average withdrawal rate from Lake Mead in the period July 1952 to June 1953. For all three models, the depth of the reservoir was taken to be 400 feet. The "surface" layer over which the temperature was nearly constant was taken as 33 feet or approximately one-twelfth of the total depth.

The following conditions, which were based on a solution of Laplace's equation were assumed for all three models: a homogenous fluid possessing the same temperature, density, salinity, silt content, and viscosity at all points. It was also assumed that the reservoir remained at the same level, and that the momentum of inflow did not carry through to the point of discharge.

The results of these analogy studies showed that the flow was essentially parallel and uniform in each of the three models, except in the immediate vicinity of the spillway. Furthermore, each of the stream tubes furnished an equal volume of water regardless of its depth in the reservoir. The proportion of the "surface" layer of water to the total withdrawal would depend on the ratio of the depth of the "surface" layer to the total depth. Thus, in the electric analogy models of Lake Mead, since the "surface" layer was taken as one-twelfth of the total depth, the layer would account for 8-1/3 percent of the total discharge in each of the three models. The analogy studies indicated water would be withdrawn from all reservoir levels and not from the surface layer alone.

The analogy studies idealized the flow pattern to an extent that did not meet conditions encountered in a reservoir. Representation of the density and viscosity variation with depth from the reservoir surface was not practicable in the analogy and therefore an hydraulic experiment was proposed to further aid in the visualization of the hydrodynamics of surface withdrawal.

MODEL STUDY

Procedure

The problem encountered in establishing a procedure for the experiment was a means to represent in the model the density-viscosity relationship of the water below the surface of Lake Mead. For example, the average density profile based on water temperatures for the period July 1952 to June 1953, showed a variation of approximately 0.15 percent, expressed relative to density at 4° C, from the surface to the bottom at approximately 400 feet, Figure 1. The temperature range for this depth was from 78° F near the surface to 53° F at the lower depths. For this range of temperature, the water viscosity increased by approximately 22 percent. The density, as noted from Figure 1, did not change in an abrupt manner but gradually increased with depth and the decrease in temperature. Thus, there was no distinct stratification in either density or viscosity until a depth of approximately 170 feet below the surface was reached. Withdrawal from below the surface layer of the reservoir would be resisted by both an increase in density and viscosity with depth. The denser and more viscous water near the bottom of the reservoir would require a greater lifting force than would be the case in a homogenous reservoir. It could be reasoned that, in the presence of stratification, there would be expected a difference in the response and in the proportionate contribution of the lower part of the reservoir. Because of the impracticability of experimentally reproducing the density curve, an attempt was made to find liquids that would produce two strata in which the lower layer would have both a greater density and viscosity than the upper layer.

Water was selected for use as a fluid in the experiment because of its availability and occurrence in the reservoir. A search was made for an additive material that would produce between two layers the density-viscosity relationship of the reservoir.

Several solutions were considered of which glycerol produced a relationship in the desired direction. For the reservoir, the density ratio of the 53° F and 78° F water was approximately 1.0015 which could be obtained with an approximate 1 percent glycerol solution. The relative viscosity increase of the solution to that of water was approximately 1.02 compared to the increase of 1.22 for the reservoir temperature range. Because of the difficulty in detecting the quantity of glycerol in the effluent from the flume and because only a small percent increase could be obtained in the viscosity without a highly disproportionate increase in the relative density, it was decided to limit the study to the withdrawal flow pattern caused by a difference in density.

The desired density ratio could be readily produced with sodium chloride salt and the chloride ion was detectable to small percentages by chemical analysis. The two layers of the experiment, fresh and salt water, were nearly homogenous with respect to viscosity because of the small quantity of added salt. Thus, the experiment departed from the actual viscosity conditions of the reservoir, and its assumed effect of diminishing the quantity of water withdrawn from lower parts of the reservoir.

The experiment was divided into two parts, the first of which has been called, "flow pattern with two layers," and, the second, "flow pattern with continuous variation of density." The distinguishing feature between the parts was the establishment of the density layer before starting the inflow to the flume. In the first part, the inflow was released to the flume to fill the volume between the upper surface of the salt solution and the surface of flow over the weir. In the second part, to obtain a variation of salt content with depth, the salt from the lower layer was allowed to diffuse through the upper layer. The upper surface of this layer was below the weir crest. Fresh water was then allowed to flow into the flume to overflow the weir and establish the flow pattern.

Euipment

A flume 6 feet long, 4 inches wide inside and 13 inches deep was constructed from 1/4-inch thick clear plastic, Figure 2. A constant head tank containing a circular overflow weir supplied water to the flume through plastic tubing. At the upstream end of the flume a 4-inch square by 9.64-inch deep compartment was provided to dissipate the energy of the inflowing water. The dissipator was of the type known as a vertical stilling well in which the water was discharged from a pipe ending near the floor of the well, Figure 2. The water flows from the end of the pipe to spread radially on the floor to the walls where it was deflected upward. Energy of the inflow was dissipated by the decrease of velocity from the pipe to the well and the internal turbulence of eddies caused by deflecting the water upward. Water flowed over the downstream wall of the compartment into the test section. Discharge through the flume was controlled by the elevation of the tank and a hose clamp on the plastic tubing.

A suppressed weir 11.64 inches high was placed 6 inches upstream of the end of the flume to control the depth and the outflow of water. Water passing the weir was conveyed by a trough to a 3-liter beaker used for volumetrically measuring the flow.

Time increments of the experiment were recorded from an electric clock. Temperatures of the liquid were measured with a mercury bulb thermometer. A system of coordinate lines to aid in comparing flow patterns was established with taut strings. The horizontal lines were spaced at 1-inch intervals with the lowest 6 inches from the flume bottom. The vertical lines were spaced at 6- and 12-inch intervals with the first line 6 inches upstream of the weir.

To prepare the model for the experiment, salt in the quantity of approximately 3.5 grams per liter was dissolved in water contained between the downstream wall of the energy dissipator and the weir. The depth of water was 9.5 inches which gave a volume of 38.62 liters. A methyl violet dye was added to the salt solution to distinguish the layers of salt and fresh water.

After the salt solution had reached a quiescent state, water was slowly released from the constant head tank to fill the flume and overflow the weir. Samples of the effluent were taken at intervals depending upon the rate of change of the flow pattern. Photographs recorded the flow pattern at the time of the samples.

The samples were analyzed to determine if portions of the lower strata were withdrawn by the shear of the upper strata. Chloride content of the inflow and outflow was determined by the Mohr method in which the sample was titrated with 0.05 N silver nitrate solution using potassium chromate as an indicator.

Flow Pattern with Two Layers

The density layer prepared for Part 1 of the experiment contained 60.20 milli-equivalents per liter of chloride ion or 3.51 grams per liter of sodium chloride as analyzed from a sample obtained before inflow to the flume. The conversion may be made by the equation, grams of sodium chloride per liter equals milli-equivalents per liter times one-one thousandth of the molecular weight of sodium chloride,

$$\text{G of NaCl/l} = \text{m. e l} \times \frac{58.5}{1000}$$

The specific gravity of the salt solution at the experiment temperature of 28° C was 1.0023.

After the layer had reached a quiescent state, the flume was filled to the crest of the weir over a period of 1 hour with tap water containing 0.09 m.e./l of chloride ion. As the water began to overflow the weir, the discharge was gradually increased to 42 cubic centimeters per second. Because of the small quantity of discharge used in the experiment, the nappe did not spring free of the weir but was held against the downstream face by surface tension. The velocity of outflow was 0.038 feet per second based on a depth of 0.26 inches above the weir crest and the 4-inch width of the flume. A 250-milliliter sample was obtained from the initial flow from the flume. Samples and photographs were taken continually over a period of approximately 5-1/2 hours for which the flow patterns are shown in Figures 3, 4, and 5, and the chemical analysis results in Figure 6A.

An undulation of the fluids occurred for a short period in the initial stages of the flow pattern establishment. As the flume filled, surface tension caused the water surface to rise above the weir crest. The sudden breaking of the tension produced an acceleration of the flow which was transferred to the lower layer, Figure 3A and B. This undulation persisted for approximately 15 minutes after the initial outflow. The pattern was essentially stabilized after 21 minutes of operation, Figure 3C. A slight disturbance of the interface was caused by the inflow of water at a velocity of 0.0064 fps over the downstream wall of the dissipator. This disturbance continued to produce a slight undulation of the interface after 1 hour and 20 minutes, Figure 4A. Immediately upstream of the weir the shear of the upper layer produced a turbulent intermediate layer of lesser density than the lower layer, Figure 4B. Thus, the flow pattern was unstable in this region. The drag of the upper layer at times produced an eddy of the fluid upward toward the crest and at other times an eddy downward toward the flume bottom. This action produced a variable chloride ion content in the outflow which amounted to approximately 45 percent of the average content dependent upon the phase of flow at the time of the sample, Figure 6A. The average chloride content of the effluent was approximately 0.4 of 1 percent of the initial content of the lower layer.

A gradual decrease of the interface height at the upstream end of the test section occured in the remaining 4 hours of the experiment, Figure 5A. This indicated the lower layer was being withdrawn from the flume by the upper layer of fresh water. The shape of the flow pattern immediately upstream of the weir as indicated by the interface of the fresh water and the intermediate layer only slightly changed with the increase in time. This change was a gradual decrease in the height of the interface above the flume bottom, Figures 4B and 5B. The intermediate layer retained approximately the same degree of turbulence.

The limiting height to which a part of the lower layer could be raised by a discharge of 42 cubic centimeters was not determined because of the gradually changing density of the lower layer. Nevertheless, it was concluded that the outflow from the flume contained not only the water equal to a depth of 0. 26 inch above the weir crest but also contributions from the density layer 2. 90 inches below the surface.

Flow Pattern with Continuous Variation of Density

A continuous variation of density for the second part of the experiment was obtained by allowing the model to stand for a period of 67 hours and 20 minutes with diffusion taking place between a salt and fresh water layer. Samples from the flume showed the following chloride ion variation: 11 inches from the bottom of the flume, Figure 7, 14. 72 milli-equivalents per liter; 8 inches from the bottom of the flume, 41. 30 m. e. /l; and at the bottom of the wall separating the dissipator and test section, 55. 40 m. e. /l. The 55. 40 m. e. /l or 3. 24 grams per liter corresponded to an approximate relative density of 1. 0020 compared to the inflow water. Density variation of the above chloride ion content was not uniform from the surface to flume bottom. The variation was less over the first 8 inches from the bottom than in the remaining 3 inches to the level of the upper sample. This was considered agreeable to the experiment as evidenced by the relative density profile of Figure 1.

To reduce turbulence observed near the upstream end of the test section for a discharge of 42 cubic centimeters per second, Figure 4A, a discharge of 10 cc per second was used in the second part of the experiment. Initial inflow to the flume produced a clockwise rotation of the fluid between the surface and the 8-inch level in the flume. As the water flowed over the wall separating the test section and dissipator, it drew with it a portion of the more dense fluid from the lower layer, Figure 8A. The interface thus formed between the 10- and 11-inch level, was quite stable showing no tendency to undulate as previously described for the 42 cubic centimeter discharge.

During the first 6 minutes after the initial outflow which contained 14. 26 m. e. /l of chloride ion, an intermediate layer formed to rise toward the weir crest counter to the rotation of the sublayer, Figure 8B. The chloride ion content of the effluent after 6 minutes was 9. 58 m. e. /l, Figure 6B. Immediately upstream of the weir the shear of the fresh water produced the turbulent mixing that was observed in the first part of the experiment. The pattern of flow in this region was unstable with currents rising and falling back from the weir crest, Figure 9. Four distinct layers were formed in the first 30 minutes of the test, a layer caused by the inflow, an intermediate layer rising to the crest, and 2 sublayers below the level approximately corresponding to the height of wall between the dissipator and test section, Figure 9B. Withdrawal of the fluid from above the 8-inch level was rapid during this time.

In 2 hours and 14 minutes after initial outflow, an intermediate layer rising to the weir was still visible, Figure 10, but the chloride ion content of the effluent had decreased to a value of 0.56 m.e./l. The chloride content continued to diminish until after 4 hours 15 minutes, the effluent content was 0.26 m.e./l, Figure 6B. There was no visible intermediate layer rising to the weir crest, Figure 11A.

The experiment was continued for a total time of 21 hours and 36 minutes but after approximately 5 hours there was no measurable change in the chloride content of the effluent which reached a minimum of 0.21 m.e./l. This value was equal to the minimum obtained in the experiment with 2 layers for 42-cc discharge. After 21 hours and 36 minutes, the flume continued to show a clockwise rotation of the fluid, Figure 11B. A measurement of the chloride ion content of the fluid at the bottom of the wall separating the dissipator and test section disclosed an increase from 55.40 m.e./l at the start of test to 56.80 m.e./l at the end. Because of the high concentration of chloride ion and the dilution necessary for titration of the sample by the Mohr method, this apparent increase of approximately 2.5 percent in concentration was attributed to experimental error. The concentration values could have easily occurred reversed. Samples of lower concentration not requiring dilution were a quite reliable measure of the chloride content.

In the second part of the experiment the chloride content of the effluent reached a minimum equal to the minimum of the first part of the experiment. This could result from several causes; namely a mechanical mixing of the fresh inflow and saline sublayer at the entrance to the test section, a molecular diffusion between the two layers through the test section, a continued lifting of the saline sublayer by the drag of fresh water near the weir, or a combination of all three. Because of the clockwise rotation of the fluid in the lower part of the flume some mixing at the inlet could have occurred. Evidence of this action in the first part of the experiment appears in Figures 3C and 4A. The rising intermediate layer and the undulating interface upstream of the weir in Figures 4B and 5B indicates that the drag of fresh water would contribute to the effluent chloride content. In the second part of the experiment, the flow entering the test section was tranquil without undulations, but some turbulence could be noted in the intermediate layer at the weir (Figure 9A). In the final stages of the second part, no intermediate layer was evident at the weir, but a layer that could produce mixing was evident at the point of inflow at the upstream end of the test section Figure 11B. The molecular diffusion would seem subordinate to the mixing because the effluent concentration did not increase with the decreased discharge and reduced velocity of flow through the test section in the second part of the experiment. This factor may have been counteracted by the decrease in concentration of the saline solution which reduced the diffusion potential between the fresh and saline water. The extent of time for which an outflow would continue to withdraw saline water from the lower depths and the maximum height to which it could be lifted thus could not be determined from the experiment. Nevertheless, the experiment did demonstrate that the outflow from the flume would contain contributions from strata of fluid below that which was equal to the depth of flow over the crest of the weir.

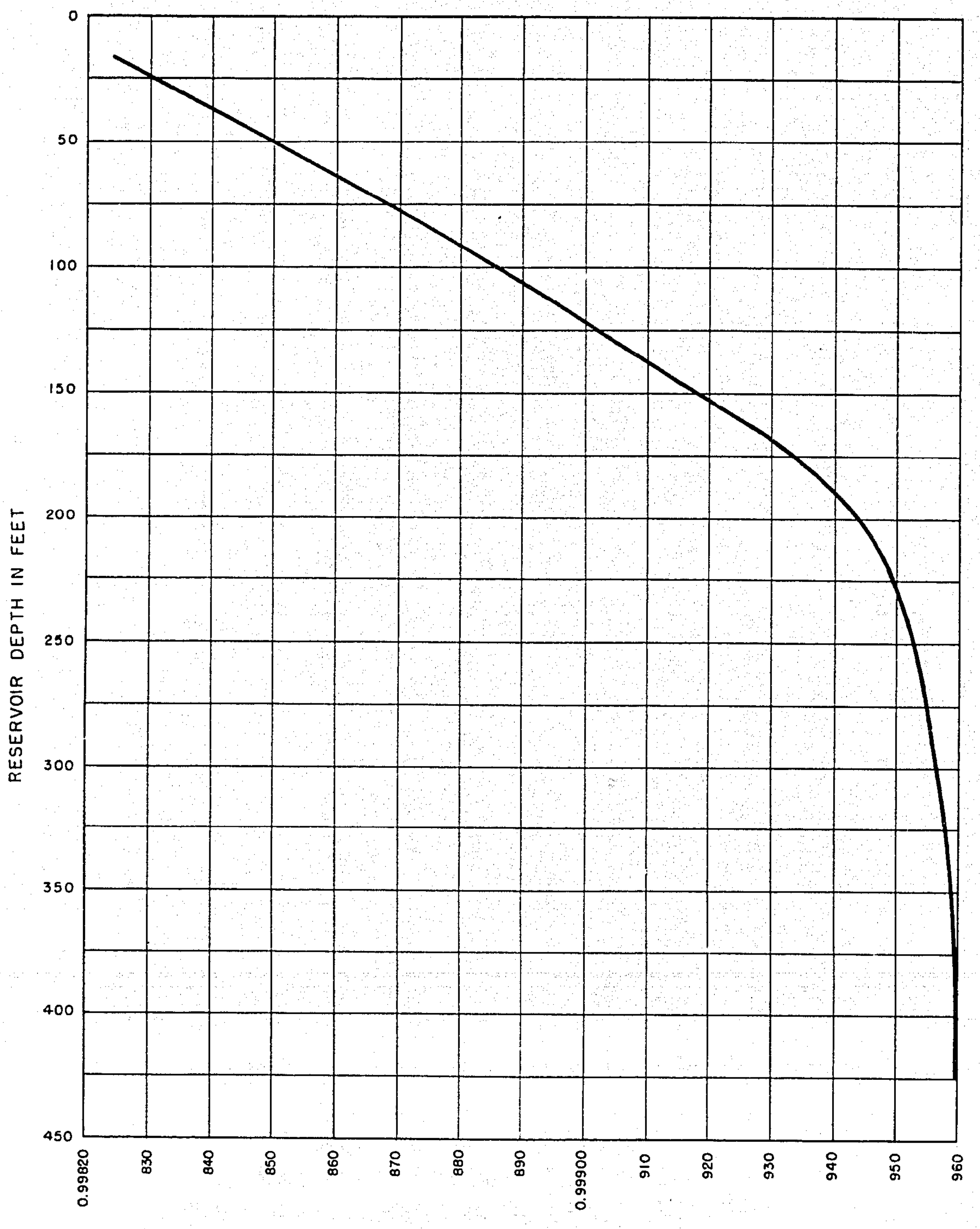
CONCLUSIONS

1. The experiment demonstrated that withdrawals of water over a crest or weir in a reservoir would be composed of not only the surface water equal to the depth of flow over the control but also contributions from underlying strata.

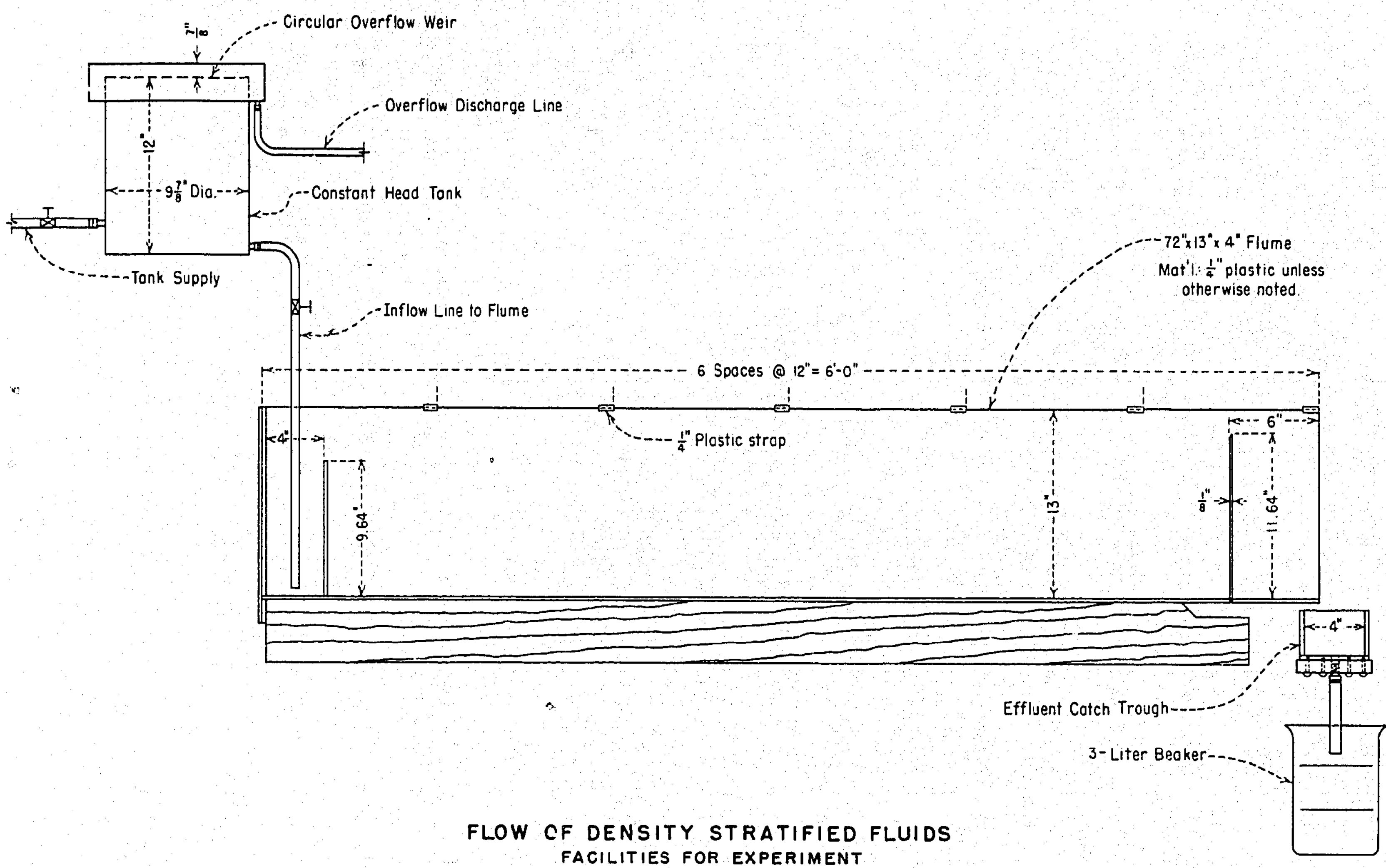
2. The effect of the increasing viscosity with depth, although not a predominant factor of withdrawal, would be to lessen the contribution of the lower strata to the total outflow.

3. The contribution from lower strata of the reservoir would reduce the effectiveness of surface withdrawal on evaporation losses by decreasing the average temperature of the outflow water.

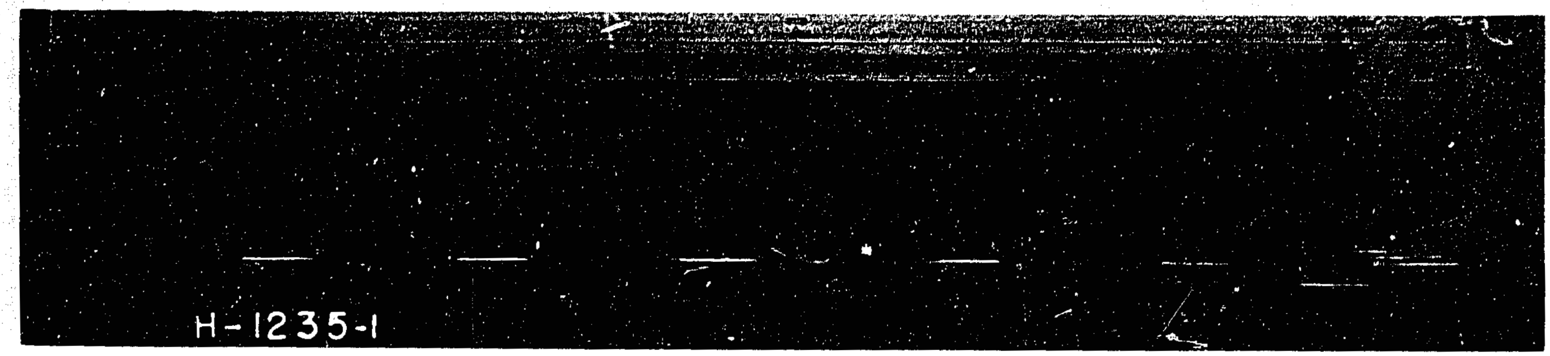
4. The contributions from lower strata would limit the effective upstream reach of the withdrawal by reducing the surface velocity, and thus, there would be a tendency for surface water temperature to remain high with little reduction in evaporation loss.



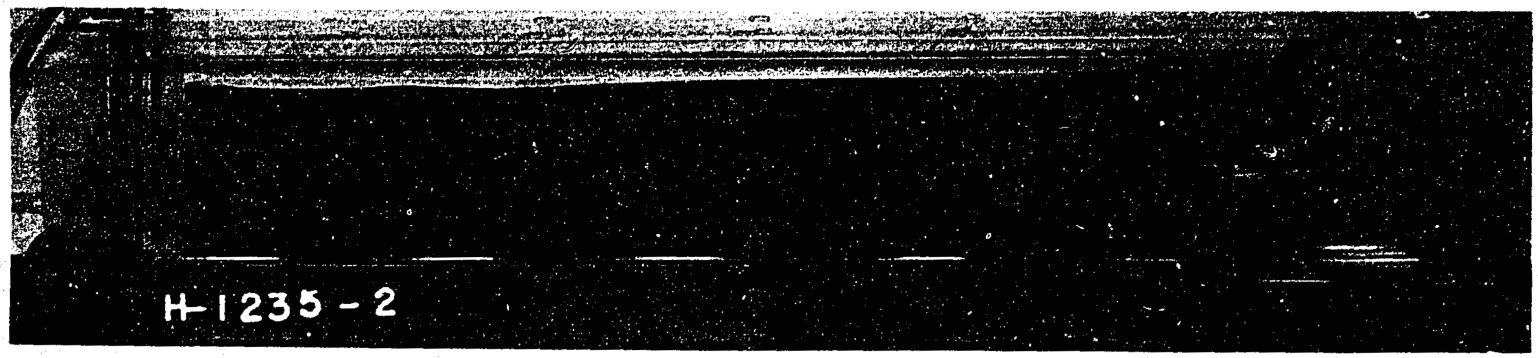
FLOW OF DENSITY STRATIFIED FLUIDS
AVERAGE DENSITY PROFILE OF LAKE MEAD
PERIOD JULY, 1952 TO JUNE, 1953



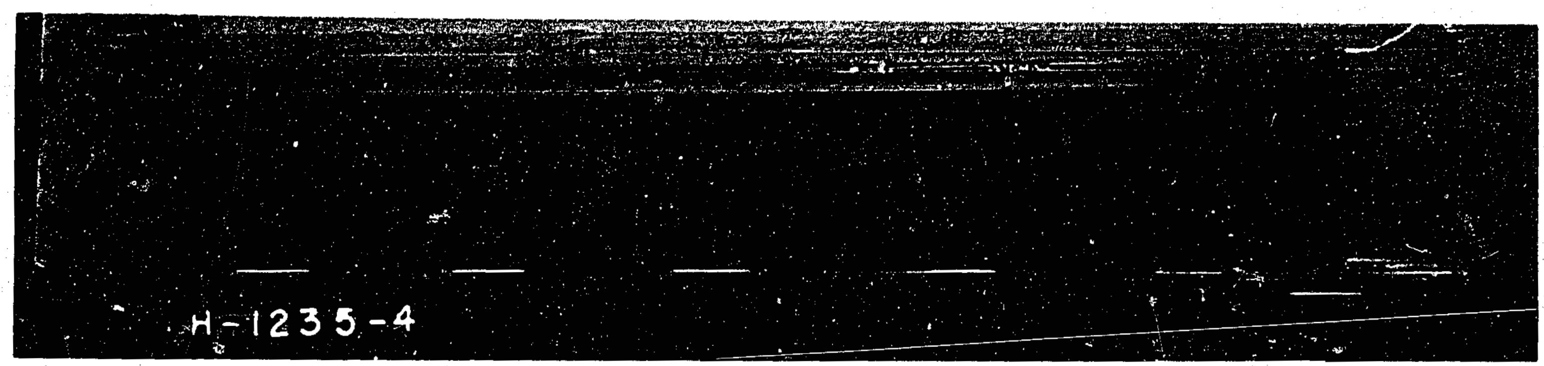
FLOW OF DENSITY STRATIFIED FLUIDS
FACILITIES FOR EXPERIMENT



A. Flow Pattern 6 Minutes After Initial Outflow



B. Undulation of Interface 7 Minutes After Initial Outflow



C. Flow Pattern 21 Minutes After Initial Outflow

FLOW OF DENSITY STRATIFIED FLUIDS
Flow Pattern Initial Stages Two Layer Stratification
Discharge 42 Cubic Centimeters Per Second

FIGURE 3
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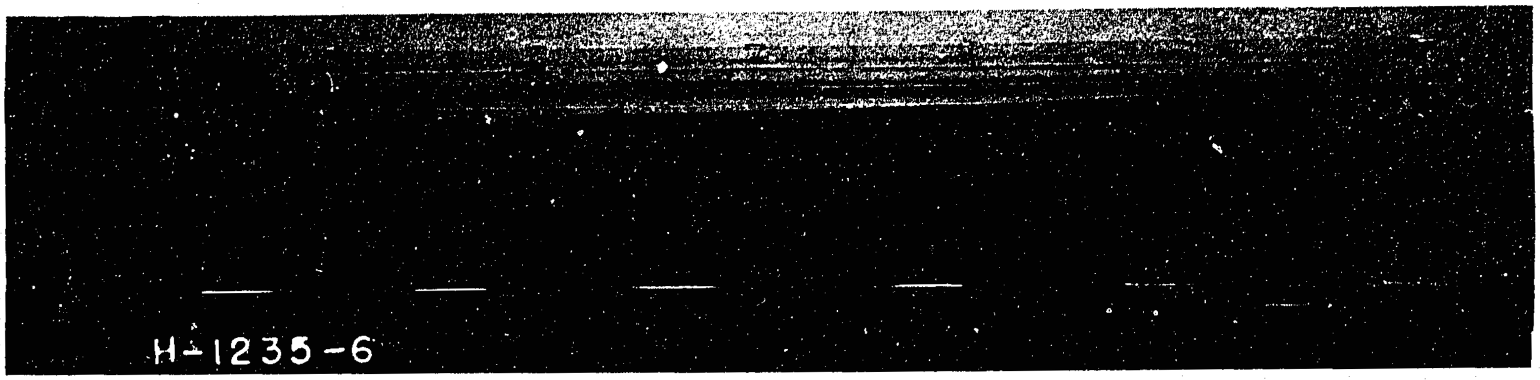
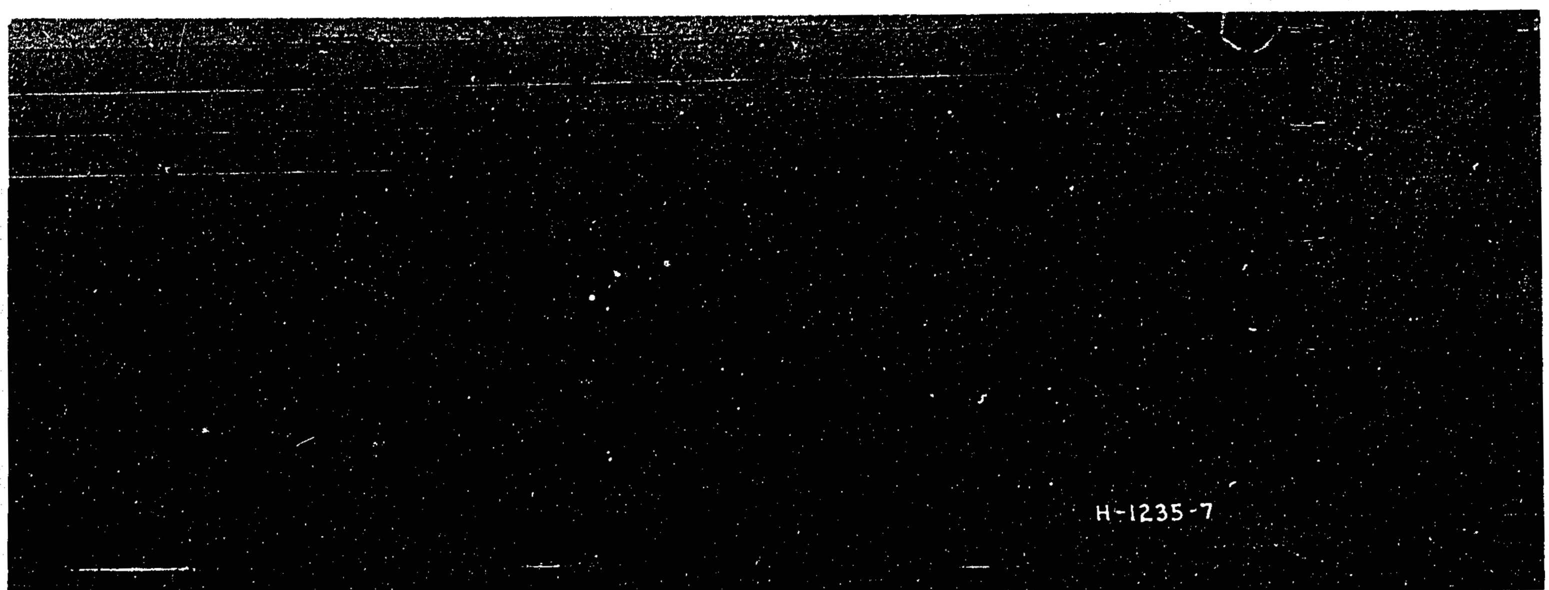
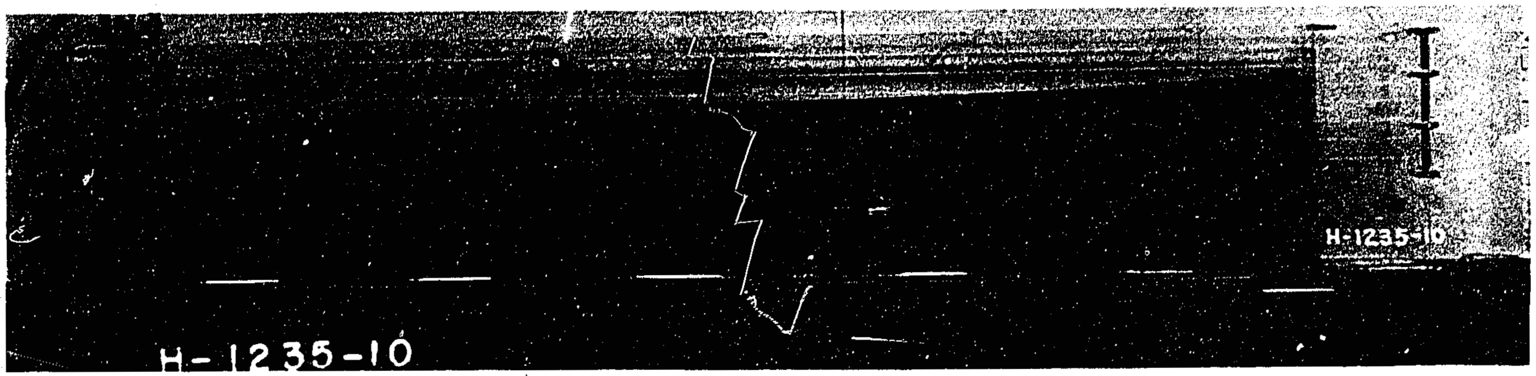


A. Undulations Produced by Inflow

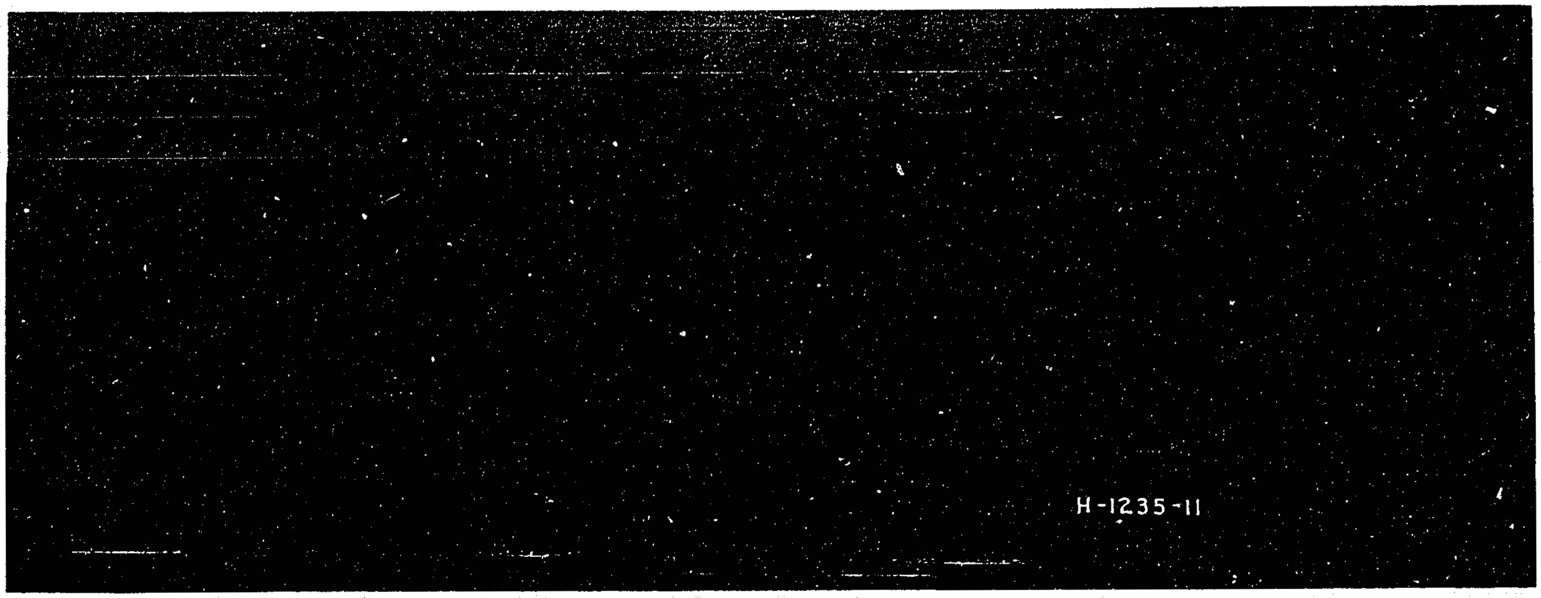


B. Undulations Adjacent to Weir Caused by Outflow

FLOW OF DENSITY STRATIFIED FLUIDS
Flow Pattern 1 Hour 20 Minutes After Initial Outflow Two Layer Stratification
Discharge 42 Cubic Centimeters Per Second



A. Diminished Depth of Lower Layer



B. Intermediate Layer Adjacent to Weir

FLOW OF DENSITY STRATIFIED FLUIDS
Flow Pattern 4 Hours 53 Minutes After Initial Outflow Two Layer Stratification
Discharge 42 Cubic Centimeters Per Second

FIGURE 5
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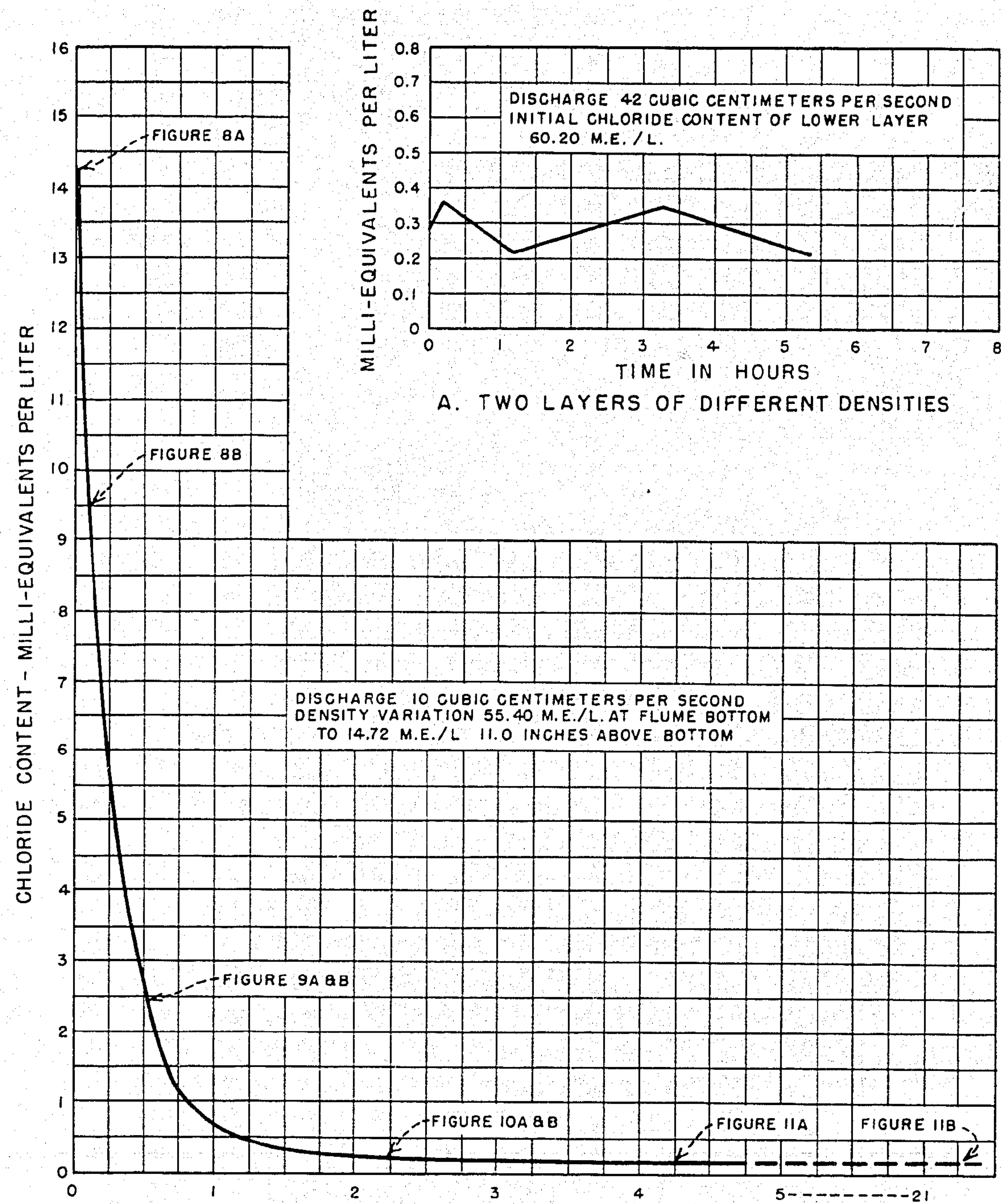
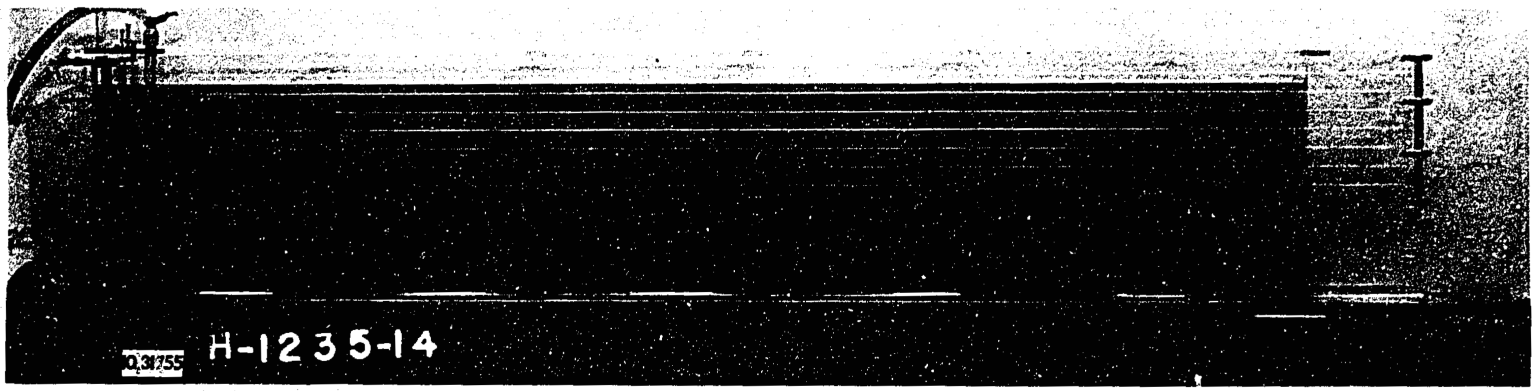


A. TWO LAYERS OF DIFFERENT DENSITIES

B. CONTINUOUS VARIATION OF DENSITY

FLOW OF DENSITY STRATIFIED FLUIDS
CHLORIDE CONTENT OF OUTFLOW

566



Milli-Equivalents Per Liter of Chloride Ion 11 Inches from Bottom, 14.72-8 Inches from Bottom, 41.30- and at Bottom of Wall Separating Dissipator and Test Section, 55.40 Period of Diffusion 67 Hours and 20 Minutes.

FIGURE 7
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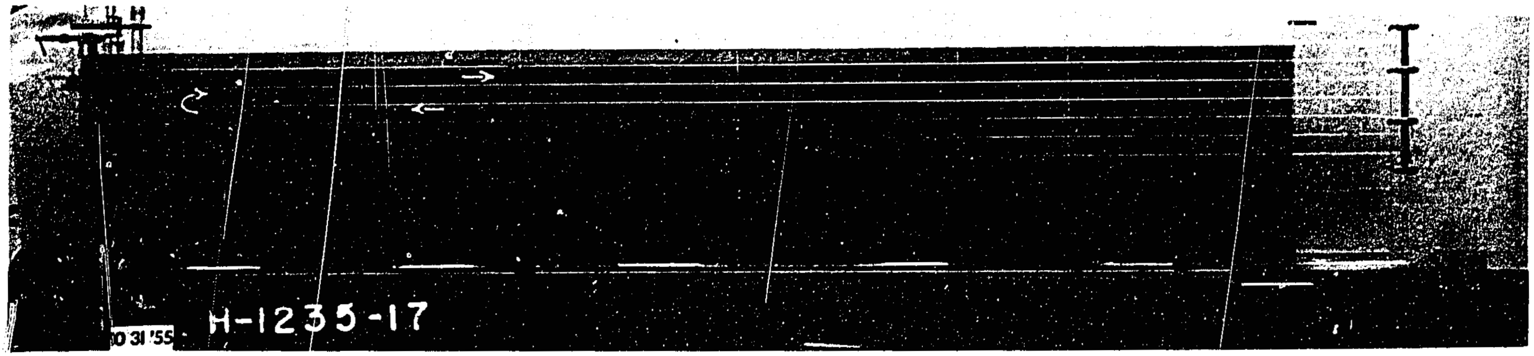
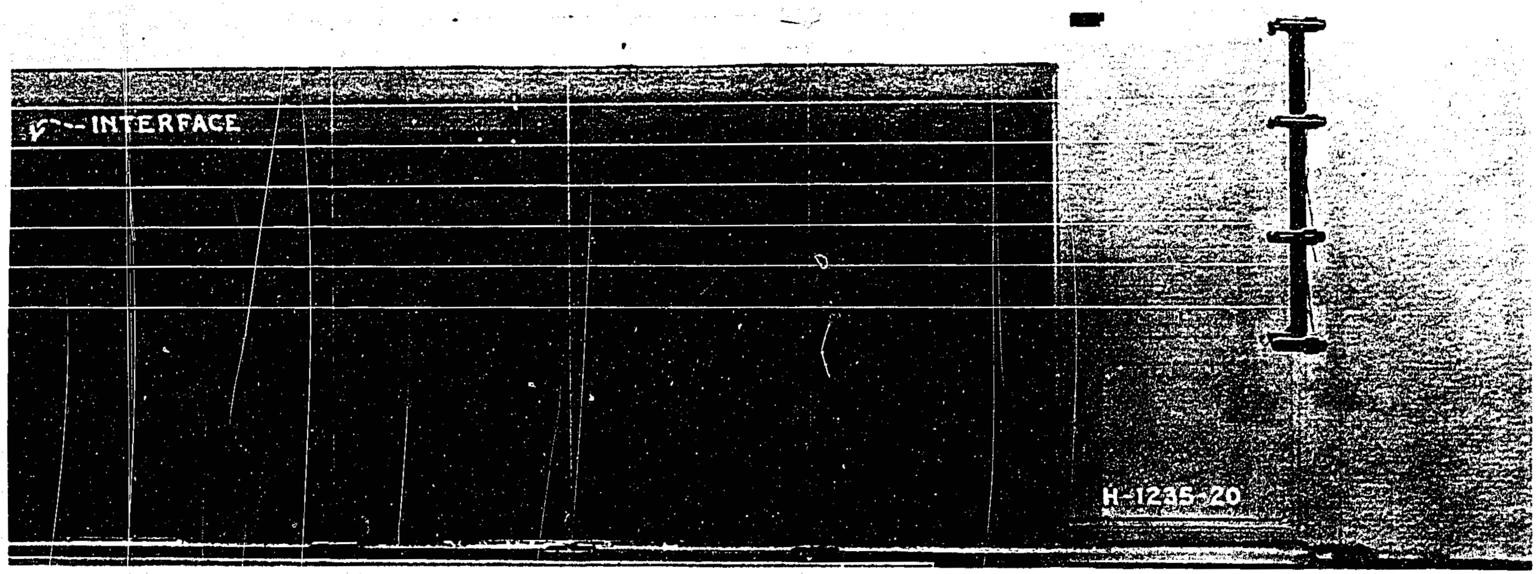
FLOW OF DENSITY STRATIFIED FLUIDS
Flume Prepared for Experiment with Continuous Variation of Density



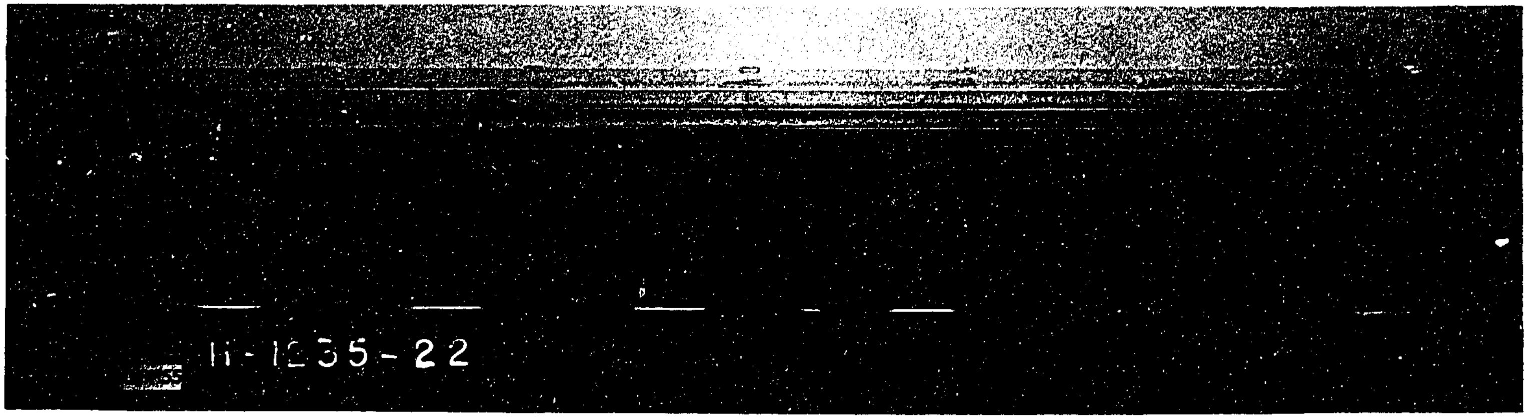
A. Flow Pattern at Time of Initial Outflow - Arrows Denote Rotation of Fluid Above 8-inch Level



B. Flow Pattern Upstream of Weir 6 Minutes After Initial Outflow

FLOW OF DENSITY STRATIFIED FLUIDS
Flow Pattern Initial Stages with Continuous Variation of Density
Discharge 10 Cubic Centimeters Per Second

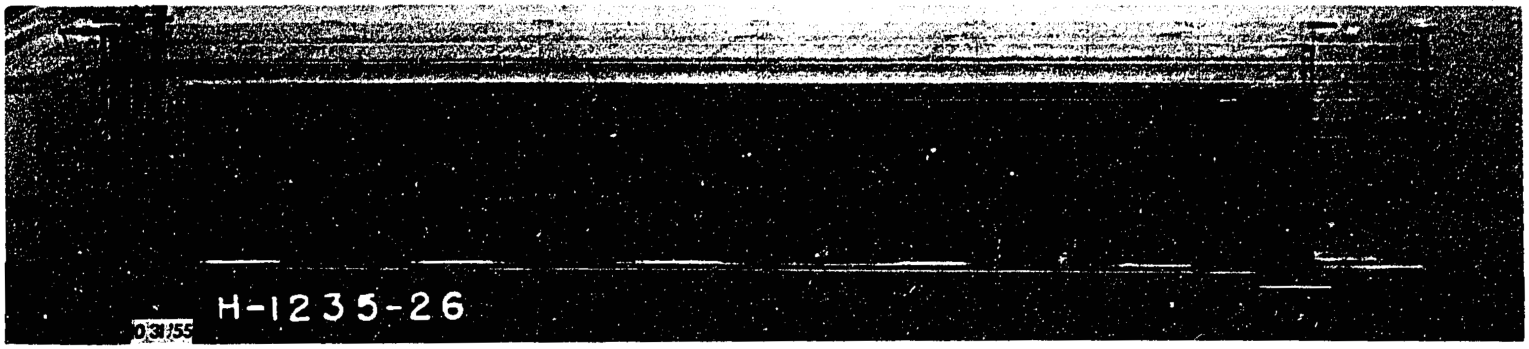
FIGURE 8
Report Hyd 425



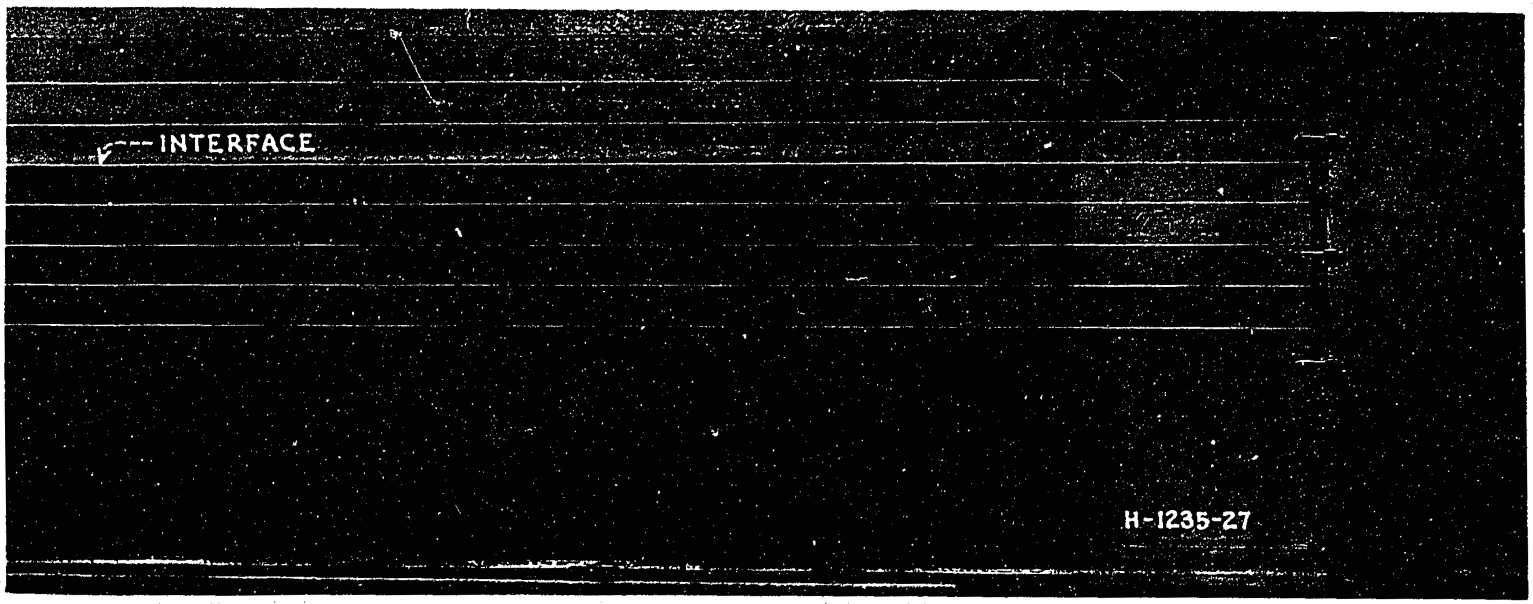
A. Flow Pattern with Clear Upper Layer, Intermediate Layer Rising to Weir, and Two Sublayers

B. Stratification of Flow Immediately Upstream of Weir

FLOW OF DENSITY STRATIFIED FLUIDS
Flow Pattern 32 Minutes After Initial Outflow Continuous Variation of Density
Discharge 10 Cubic Centimeters Per Second



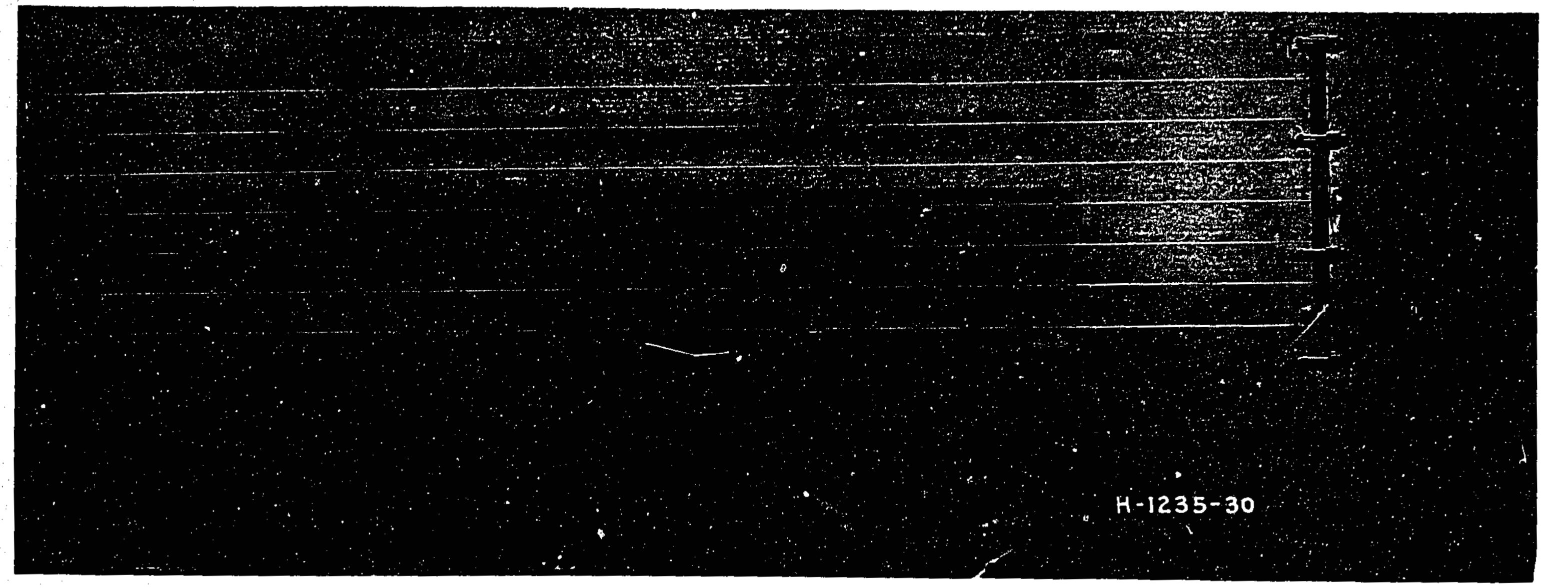
A. Decrease in Height of Interface Between Clear Water and Intermediate Layer



B. Slightly Rising Intermediate and Clear Water Interface Upstream of Weir

FLOW OF DENSITY STRATIFIED FLUIDS
Flow Pattern 2 Hours 14 Minutes After Initial Outflow Continuous Variation of Density
Discharge 10 Cubic Centimeters Per Second

FIGURE 10
Report Hyd 425



A. Flow Pattern After 4 Hours 15 Minutes No Visible Flow of Density Layer Over Weir

B. Flow Pattern After 21 Hours 36 Minutes - Milli-Equivalents Per Liter of Chloride Ion at Bottom of Wall Separating Dissipator and Test Section 56.80 - Effluent Content 0.21 M.E./L.

FLOW OF DENSITY STRATIFIED FLUIDS
Flow Pattern in Final Stages of Experiment - Continuous Variation of Density
Discharge 10 Cubic Centimeters Per Second

FIGURE 11
Report Hyd 425