THERMAL DENSITY UNDERFLOW DESIGN AND EXPERIENCE

REX A. ELDER

Tennessee Valley Authority

INTRODUCTION

Since 1952 the Tennessee Valley Authority has designed and built two structures and assisted in the design of a third structure which permit withdrawal of cold bottom water from thermally stratified reservoirs. These structures, which have been termed "skimmer walls," were built at TVA's Kingston [1] and Gallatin Steam Plants and at AEC's Oak Ridge facilities. The Gallatin plant is located on the Old Hickory Reservoir of the Cumberland River approximately 20 miles northeast of Nashville, Tennessee; the Kingston and Oak Ridge facilities are on the Clinch River arm of the Watts Bar Reservoir approximately 30 miles west of Knoxville, Tennessee. The flows through each of these reservoirs, during the summer months, are controlled, not by natural runoff, but by releases from high-head storage dams located upstream. Since these storage dams release cold water during the summer months, the reservoir flows become thermally stratified and normally the flows pass through the reservoir as stratified underflows. A

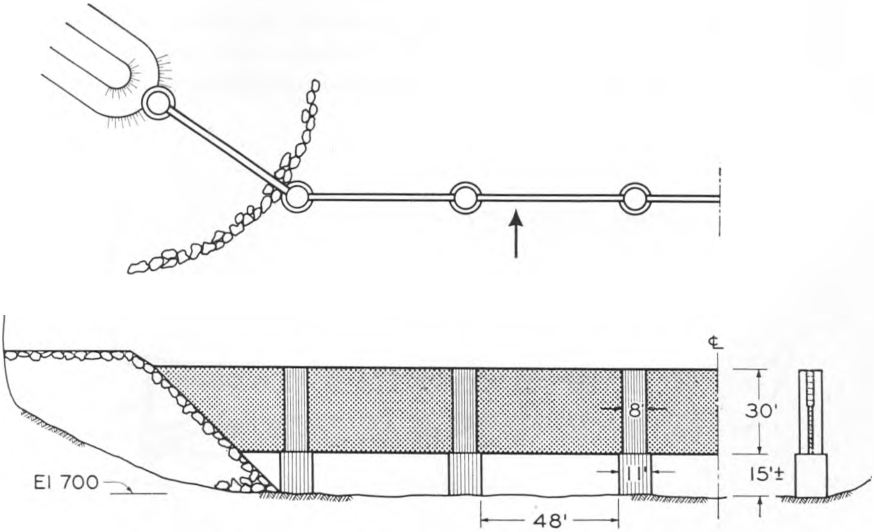

FIG. 1. KINGSTON SKIMMER WALL—HALF PLAN AND ELEVATION.

complete description of these phenomena was presented in a paper at the Minnesota International Hydraulics Convention in August 1953 [2].

At installations such as steam-generated electric power plants, where cold water results in actual financial gains, a skimmer wall structure such as shown in Fig. 1 has been proven effective in preventing essentially all but the cold bottom waters from being drawn into the intake pumps [1]. The Gallatin and Oak Ridge skimmers were built on the reservoir banks and thus draw their water directly from the passing underflow. The Oak Ridge installation has the pumps directly downstream from the wall and is shown in elevation in Fig. 2. The Gallatin design placed the pumps at the end of a 2600-foot canal as shown in Fig. 3. The bottom of this canal is 16.5 feet above the top of the wall opening. The Kingston installation is considerably

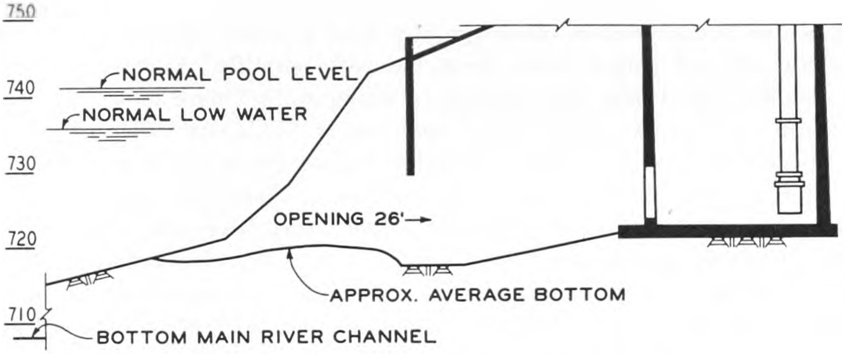

FIG. 2. OAK RIDGE UNDERFLOW DIVERSION WORKS.

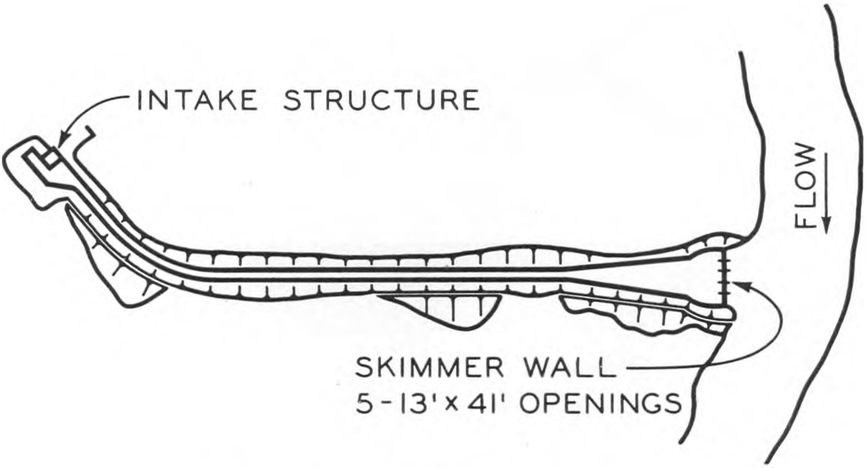

FIG. 3. GALLATIN UNDERFLOW DIVERSION WORKS.

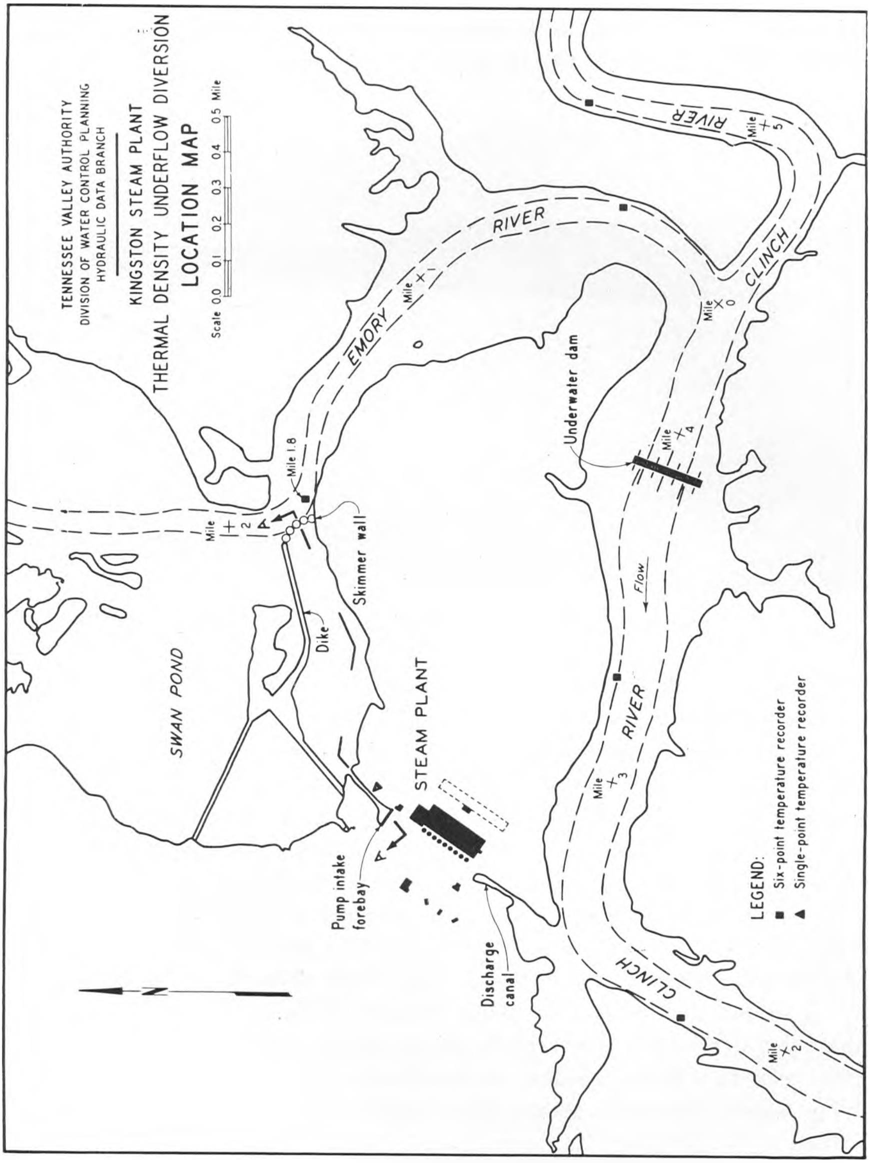

FIG. 4. LOCATION MAP—KINGSTON UNDERFLOW DIVERSION WORKS.

more complex than either of these two, as can be seen from Fig. 4 which shows the general layout of the project and Fig. 5 which shows the skimmer wall and diked-off channel. The underflows are diverted up 1.8 miles of the Emory River channel to the skimmer wall site by means of an underwater dam at Mile 3.8 on the Clinch River [1]. After passing through the wall, the flow goes into a one-mile channel whose bottom is 5 to 10 feet above the top of the wall opening.

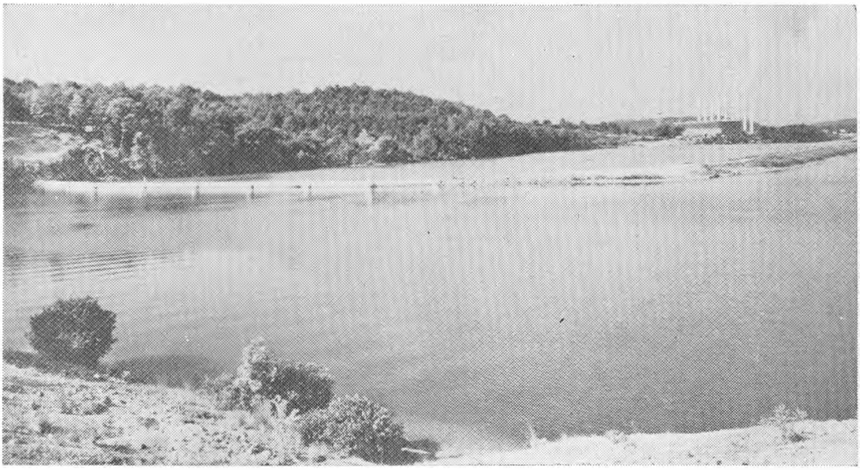

FIG. 5. KINGSTON SKIMMER WALL AND SWAN POND DIKE.

At the time these designs were conceived, very little information was available on the diversion of density underflows through a submerged wall opening. TVA had available a large number of field measurements of the flow of thermal density currents obtained in Watts Bar and Fort Loudoun Reservoirs. An analysis of these data indicated that, in reservoir channels such as those at the project sites and for thermal stratifications of the magnitude expected, a relationship exists between the maximum velocity at which density underflow can occur and the depth of the underflow [1].

A second item of data available from the TVA field measurements was that, at water intakes, the velocity in the intake could be double the underflow velocity without breaking the stratification and pulling in warmer overlying waters. Velocities greater than double appeared to break the stratification.

These two field data relationships were used in establishing the preliminary design for the three projects. The designs were then checked and found to be adequate by the preliminary results from a series of studies sponsored by TVA at the Massachusetts Institute of Technology, Hydrodynamics

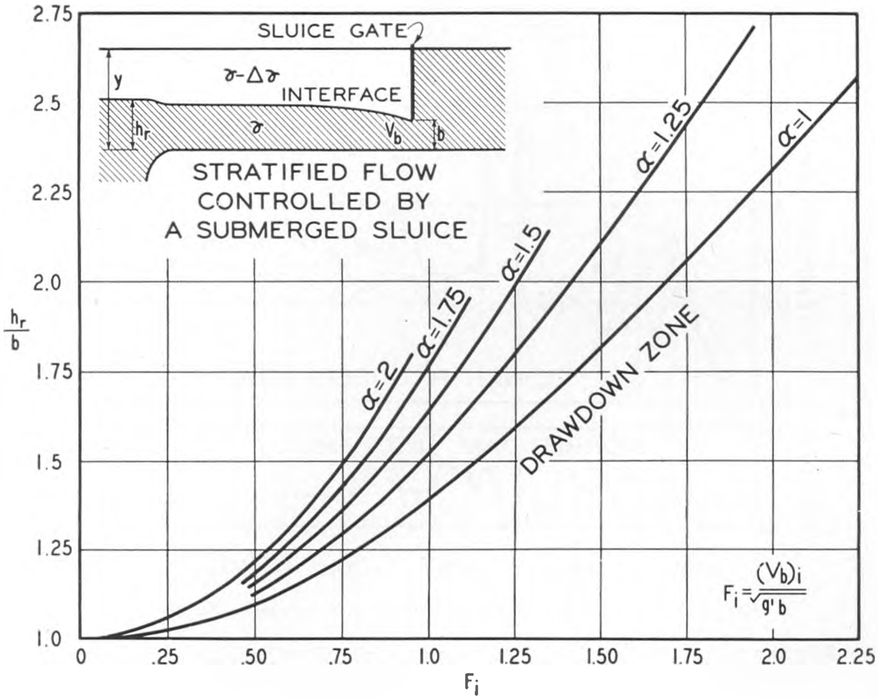

Fig. 6. Sluice Characteristics at Incipient Drawdown.

Laboratory. MIT later amplified these studies and in 1958 published a final analysis of the laboratory data [3]. Figure 6 reproduces the MIT curves for the relationships which exist at the point of incipient drawdown, i.e., the point where the lighter overlying water starts to be drawn through the opening. $(V_b)_i$ is the velocity through the wall opening at the incipient drawdown point and $g' = g\Delta\gamma/\gamma$ where $\Delta\gamma$ is the difference in specific weights of the fluids in the two strata and γ is the specific weight of the lower fluid. α is the kinetic-energy correction factor.

Performance Characteristics

This paper presents data to show how each of the three skimmer wall structures has performed and how the actual performance agrees or disagrees with the design criteria obtained from the MIT data. Specific problems associated with the use and operation of these structures are also cited.

Kingston

The performance of the Kingston installations, shown in Figs. 4 and 5, has been reported in detail for the years 1955 and 1956 [1] and can

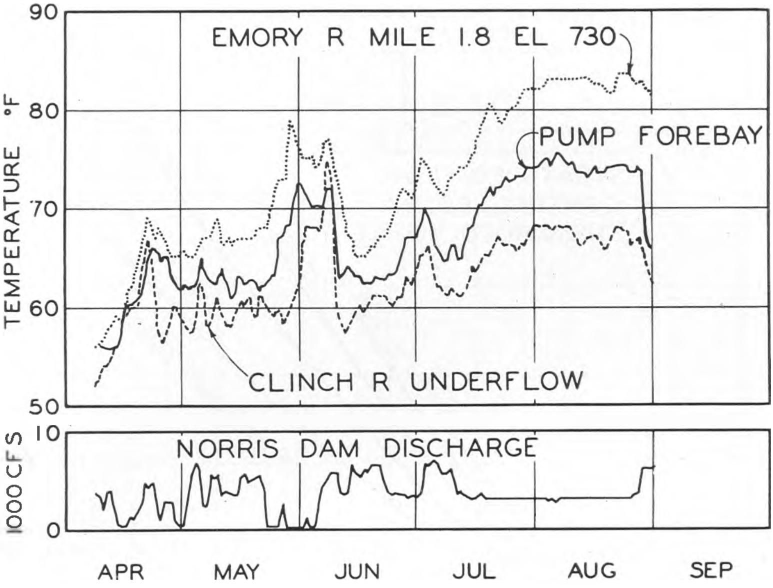

FIG. 7. EFFECTIVE TEMPERATURES—KINGSTON SKIMMER WALL, 1955.

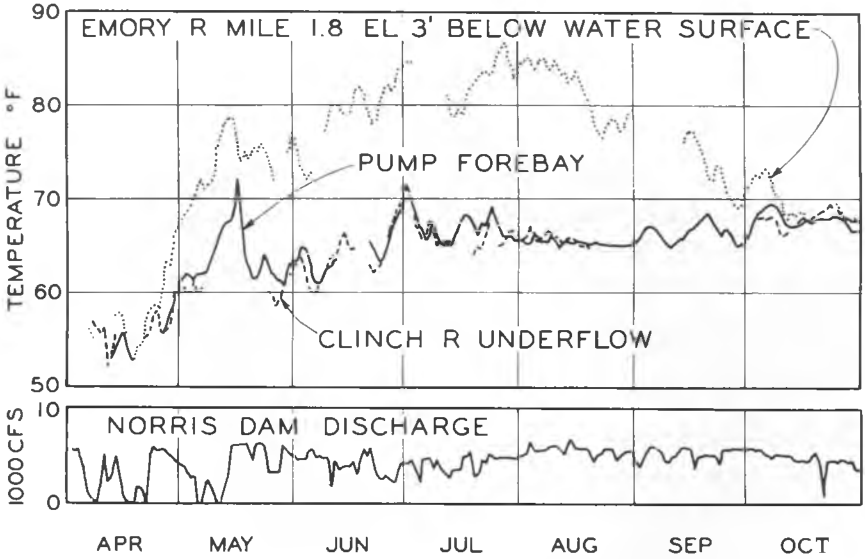

FIG. 8. EFFECTIVE TEMPERATURES—KINGSTON SKIMMER WALL, 1956.

be summarized by Figs. 7 and 8. The underwater dam had not been built in 1955; therefore, in that year the pump forebay temperature ran several degrees warmer than the Clinch River underflows since full utilization of

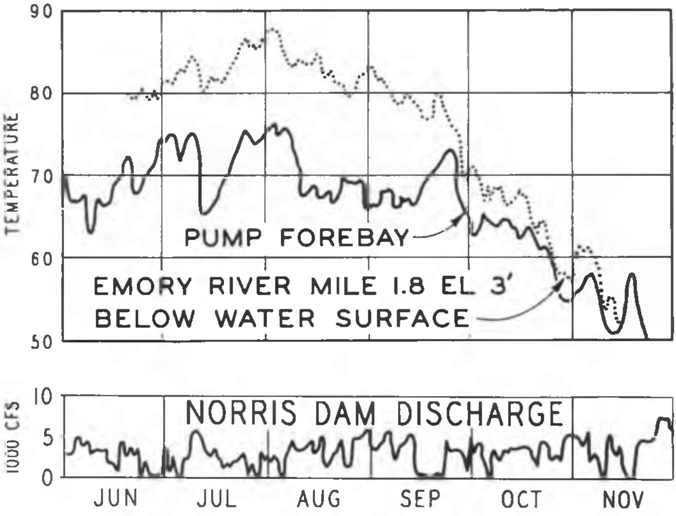

Fig. 9. Effective Temperatures—Kingston Skimmer Wall, 1957.

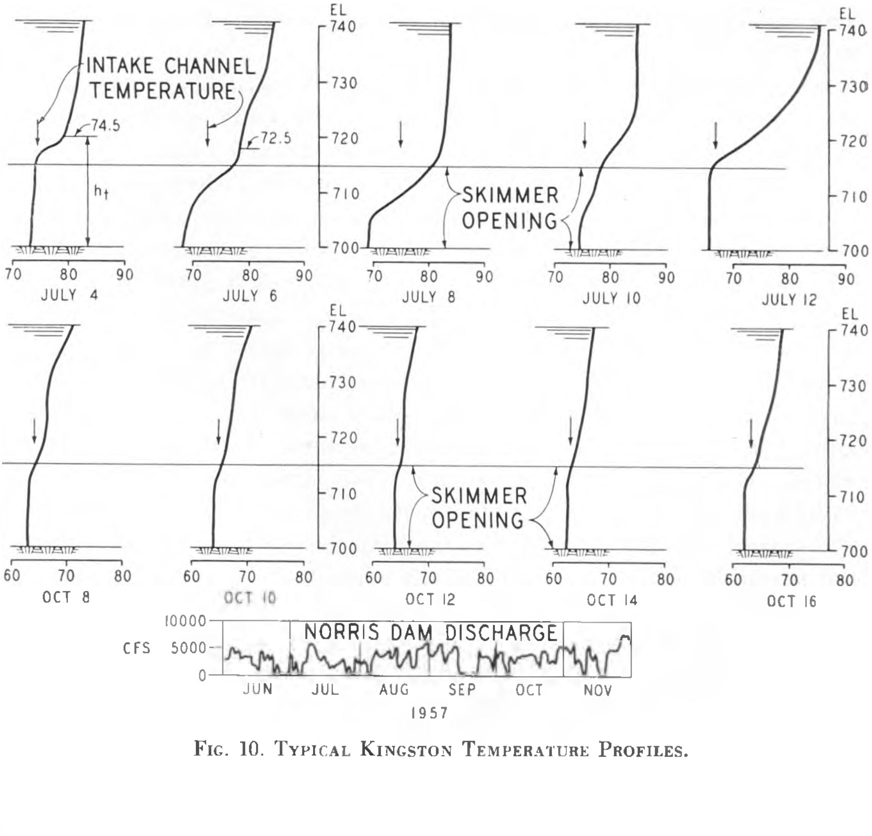

Fig. 10. Typical Kingston Temperature Profiles.

the available cold Clinch water could not be obtained. The 1957 record, Fig. 9, is also worth presenting, since the Norris releases were considerably smaller and, as a consequence, on several occasions the cold underflows were insufficient to supply the condenser demand. The periods of the first part of July, the end of July and the first of August, and the end of September constitute specific examples of insufficient Clinch River flow to meet the demands. The Clinch River underflow temperature is not shown in Fig. 9 since the underwater dam results in full use of the Clinch flows as can be seen from Fig. 8.

A 6-point temperature recorder is maintained at Emory River Mile 1.8, as shown in Fig. 4, to monitor the temperature profiles immediately upstream from the skimmer wall.

Comparison of the temperature profiles of July 6, 8, and 10, with July 4, and 12, Fig. 10, shows conclusively that the rising intake temperatures were due to depletion of the cold waters. The cold bottom waters of July 4, were those released from Norris on June 30, and July 2. On July 3, 4, and 5, essentially no releases were made at Norris and, as a consequence, the Kingston demand continually depleted the cold water from July 6 to 10. The increase at Norris on July 6, showed up at Kingston four days later and by July 12, fully stratified underflow withdrawal was again occurring.

It is interesting to note that in July, when large top-to-bottom temperature differences existed, Norris discharges essentially equal to or only slightly greater than the 2310 cfs condenser demand resulted in perfect underflow withdrawal. However, as the temperature differences decreased, the withdrawal approached the incipient drawdown stage. The profiles of October 8, 10, 12, 14, and 16, Fig. 10, show that for comparable or even somewhat higher discharges than those that gave nearly perfect withdrawal on July 4, and 12, but with lower top-to-bottom temperature differentials, the withdrawal was essentially at the incipient drawdown stage.

When the idea of bottom withdrawal of thermally stratified water was first considered, one of the problems which arose was the degree of stability that could be expected. With the incoming underflow rate varying almost continually and with possibilities of rather sudden shifts in the withdrawal rate due to unit shutdowns, the question of stability of stratification seemed significant. Soon after the Kingston plant was placed in nearly full operation, a test was run to determine the effect of starting and stopping one unit. No effect could be ascertained. Additional proof of stability is seen in the operational results shown in Fig. 8. These data conclusively prove that stability of underflow is no problem since, within the limits of instrument error and local heating and cooling effects in the 5000-foot channel between the skimmer wall and the intake thermometer, the under-

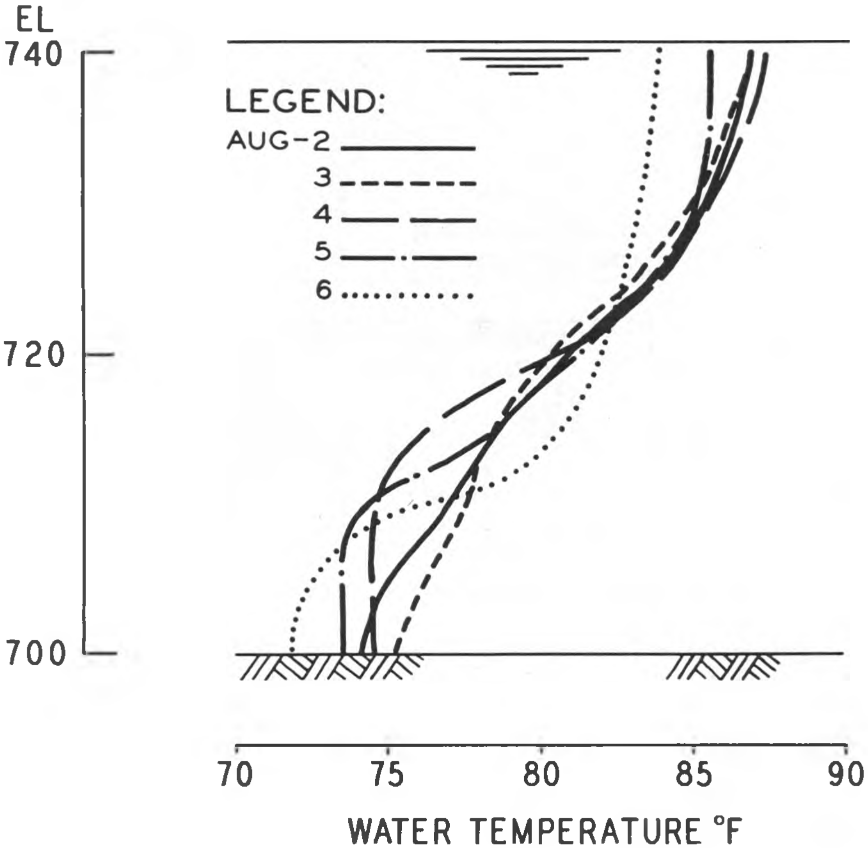

FIG. 11. KINGSTON TEMPERATURE PROFILES, AUGUST 2 TO 6, 1957.

flow and intake temperatures are identical. Actually, the underflows are remarkably stable as can be seen by the profiles for August 2, 3, 4, 5, and 6, Fig. 11. The slight decrease in the upper water temperatures on August 5, and 6, was due to a rain which produced surface cooling and a relatively small Emory flow at about 80-82° F. Recognizing this factor, it can be seen that the large variations in underflow conditions had no effect above elevation 722.

Gallatin

The Gallatin system was designed to provide water for five 250,000-KW generating units. To date only two of the units have been placed in operation; therefore, no data are available on performance at or near capacity. The efficacy of the design for reduced discharges is shown by the 1957 performance data of Fig. 12.

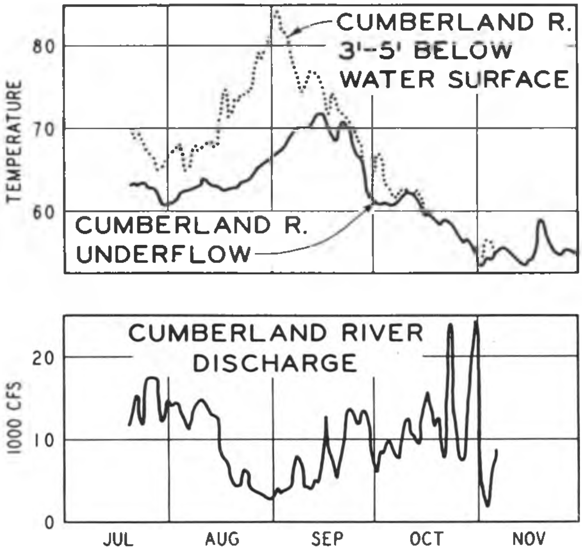

FIG. 12. EFFECTIVE TEMPERATURES—GALLATIN SKIMMER WALL, 1957.

Due to the reduced discharge operation, the Gallatin system has not been studied in detail. However, field tests made in mid-July 1957, revealed one interesting factor. At the time of the tests the Cumberland River discharges were fairly high and, as a consequence, the duck-under point, i.e., the upstream point where stratification starts, was in the immediate vicinity of the project. Flow conditions were not clear cut and no definite duck-under point could be established. Actually, large cells of hot or cold water existed at random over a mile or more of the river length. The hot water cells were up to 20 or 25 feet in depth. Since the top of the skimmer wall opening was 31 feet below the surface, no detrimental action occurred. It would appear that operation in the vicinity of the duck-under point may be more difficult to predict than that in locations where definitely stratified flow exists.

Oak Ridge

The Oak Ridge skimmer was built primarily because of a local artificial stratification condition. A large steam-generated electric plant is located 1.7 miles upstream from a cooling-tower make-up water inlet. The steam-plant condenser cooling water is discharged into a small tributary stream 1.1 miles upstream from its mouth. The mouth of the stream in turn is 0.4 mile upstream from the make-up water intake. The condenser effluent is 12 to 18 degrees hotter than the normal river flows; therefore, it flows back into the river as a top stratified flow. Thus, during all periods of the

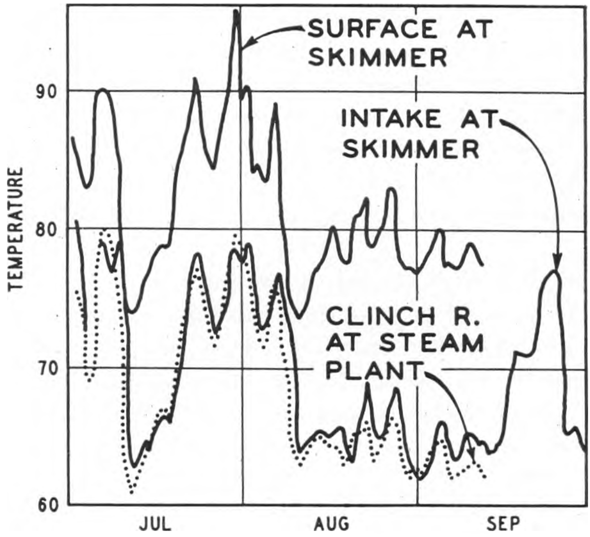

FIG. 13. EFFECTIVE TEMPERATURES—OAK RIDGE SKIMMER WALL, 1957.

year, stratified flow exists at the make-up water site. During the summer months the duck-under point for the cold Norris releases normally would be downstream from this site but for low releases may be upstream from it.

Figure 13 shows the 1957 data available on operation of the Oak Ridge intake. This intake operates continually at essentially design capacity. The 1957 data prove therefore that with the normal summer pool which ranges from elevation 740 to elevation 741, the skimmer wall successfully draws directly from the passing underflow. Comparison of Fig. 13 with Fig. 9 will show the temperatures of the flow into the Oak Ridge and Kingston intakes to be identical.

MODEL-PROTOTYPE COMPARISON

Comparisons of field data with the MIT laboratory data can only be obtained for the Kingston project since the Gallatin intake has never operated near design capacity and insufficient field data are available for the Oak Ridge intake.

At Kingston a 6-point temperature recorder has been located at Emory River Mile 1.8, see Fig. 4, since inception of the design and a single-point recorder in the pump intake forebay since the plant has been in operation. These two installations make it possible to study the Kingston performance for comparison with the model data. It is important to later discussions of the data to note that the two temperature recorders are located over a mile apart and further to note that, for most of the distance, the incoming water flows in an unstratified manner.

Thermal density stratification produces a much more complex stratification pattern than did the chemical densities used in the MIT studies. In place of a nearly sharp interface, the thermally stratified medium has gradually changing "interfaces." The temperature profiles of Fig. 10 show this clearly. As a consequence, a clear-cut, definite comparison of the Kingston operational data with the laboratory data is essentially impossible. However, an approximate method was developed which produced some interesting comparisons.

Referring to the profile for July 4, this method can be described as follows: It will be assumed that the flow velocities approaching the skimmer are uniform throughout the underflow section and that the width is constant throughout the flow depth. Both of these assumptions were found to be essentially true by field measurements. On the basis of these assumptions, the average intake temperature can be computed by averaging the temperature over the flow depth. Therefore, the flow depth, which is to be termed h_t , will be computed by determining the depth at which the average underflow temperature equals the measured pump forebay intake temperature. As can be seen in Fig. 6, the value of h_t will be equal to h_r at the incipient drawdown point. A plotting of h_t/b vs. **F**, where

$$\mathbf{F} = \frac{V_b}{\sqrt{g'b}} \quad \text{and} \quad g' = g\,\frac{\Delta\gamma}{\gamma}$$

and the other symbols have been previously defined or are shown in Fig. 6, should therefore produce some form of model-prototype comparison provided the type of flow for each prototype point can be identified. Since the temperature-profile data give a reasonably clear indication of the type of flow, only a method of computing the Froude parameter **F** must be developed. The steam plant records can be used to find the total number of pumps operating at any specific time. This knowledge allows calculation of V_b. To obtain g' , specific temperature values for the underflow and for the stagnant overlying waters are required. These can be developed from the Mile 1.8 temperature profiles by arbitrarily assuming that the temperature for the underflow will be the temperature of the most nearly vertical portion of the underflow profile. As an example from the profiles of Fig. 10, on July 4, t will be taken as 73.7° F and for July 6, t equals 68.5°. The temperature for the stagnant layer will be assumed to be the average above h_t. Using temperatures taken from the field data on these bases, the values of $\Delta\gamma/\gamma$ and thus g' can be calculated.

The temperature profiles can be broadly cataloged into three characteristic types of inflow patterns into the skimmer wall openings; drawdown flow in which the warmer overlying waters were definitely mixing with the cold bottom waters; incipient drawdown flow in which the warmer waters are just barely mixing; and isothermal underflow in which no warm water is drawn through the wall. The profile of July 8, illustrates the drawdown case, and the profiles of October 8, and 10, represent the incipient drawdown case (see Fig. 10). The July 4, profile is a typical isothermal underflow type.

Values of h_t/b, $\mathbf{F}$, and flow type were determined for 56 trial periods taken at 2-day intervals during the summer and early fall of 1957. This period was chosen since each of the three basic types of flow, i.e., drawdown, incipient drawdown, and underflow, occurred frequently. The calculated data are plotted on Fig. 14. Since h_t is equivalent to h_r of Fig. 6 at the point of incipient drawdown, the curves of Fig. 6 should delineate the division between the points of drawdown flow and isothermal underflow. The points of incipient drawdown flow should lie along the curves. Only the curves for the kinetic energy correction factor α equal to 1.0, 1.1, and 1.2, are shown since the prototype values should be within this range. On Fig. 14 the drawdown points should be expected to fall to the left of the curves and the isothermal underflow points to the right of the curves.

At first examination, the prototype comparison did not appear very good. However, after study it was found that all of the points representing the isothermal underflow condition which are to the left of the curves occurred during periods of very high air temperatures and solar radiation values. This condition would result in heating of the flowing water as it passed through the channel from the skimmer wall to the pump intake forebay. Since the intake temperature was measured at the pump intake forebay, the temperature applied to the profile data must be corrected for any increase occurring after the inflows pass the skimmer wall. An exact correction to the recorded intake temperature value cannot be made due to lack of complete data, but estimated corrections indicate that each of these points would shift below the curves if the intake temperatures were corrected for the increase which must occur in the 5000 feet of channel. A similar reasoning applied to the incipient drawdown points lying to the left of the curves can shift all but three of the points into the general region of the curves. The incipient drawdown points lying to the right of the curves and forming a reasonably good curve in themselves were found to have occurred during periods when the air temperature, incoming solar radiation and evaporative heat losses would be expected to decrease the temperature of the water in the 5000-foot channel. Again, estimated corrections would indicate that all the points except the one at $\mathbf{F} = 1.84$ belong in among the three curves. With these interpretations to the prototype data, it appears that good agreement exists between the laboratory and prototype data and that the curves of Fig. 6 can be used with confidence in designing intakes for the complex case of thermally stratified flows.

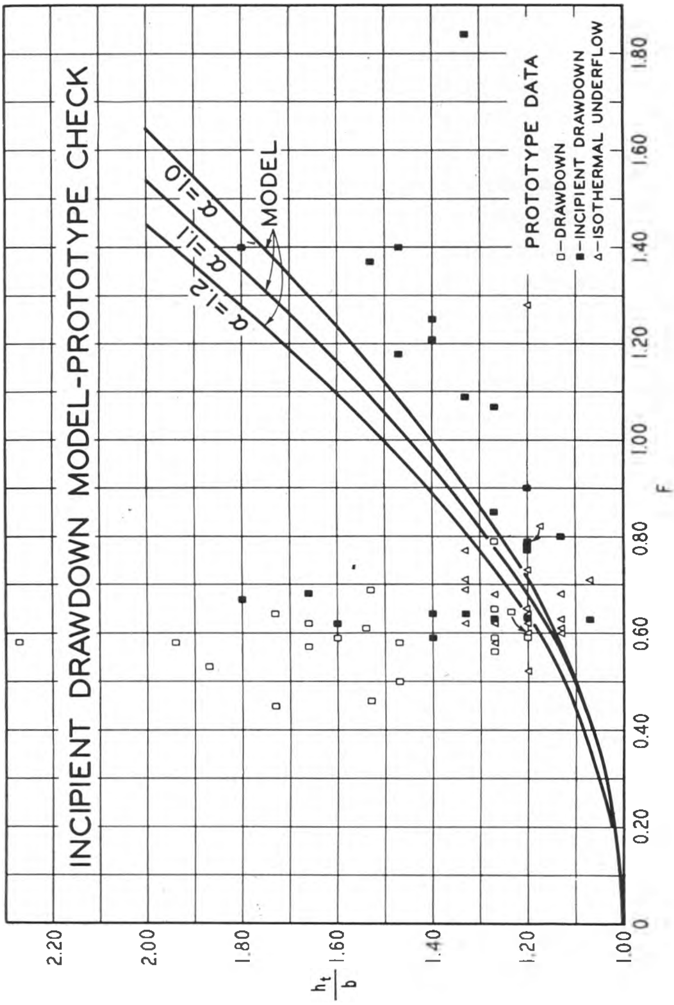

FIG. 14. KINGSTON MODEL-PROTOTYPE COMPARISON.

OPERATIONAL PROBLEMS

In general, the skimmer wall structures and their related canals have performed as well or better than the most optimistic predictions made for them. However, three possible sources of troubles arising from such structures have shown up. At Kingston a very minor secondary benefit arises due to the skimmer wall normally excluding any surface waters impounded in the Emory River arm of the reservoir. The Emory waters are almost always warmer and furthermore they may contain wastes discharged from a paper mill some 9 miles upstream from the skimmer wall, and it is, therefore, advantageous to exclude them from the plant. On rare occasions during a cold winter, the Clinch River flows may drop below 40° F, while the impounded Emory flows will drop to about 40° F. Since 40° water is denser than water below 40°, the warmer water will drop to the bottom taking the paper mill wastes with it and thus allow the wastes to be drawn into the condensers.

At Gallatin a potentially more important problem is presenting itself. Over the past year from 1 to 1½ feet of silt has been deposited on the floor of the intake channel, upstream from the wall, under the wall, and downstream from the wall. While the present intake velocities are extremely low, the Cumberland River carries a considerably heavier silt load than does the Clinch arm of the Tennessee system, so silting at Gallatin and not at Kingston could be expected. These data indicate that some maintenance on this type of intake may be required at locations where silt is prevalent.

Although field data are meager both from the Gallatin and Oak Ridge installations, they show indications that structures located immediately below the point of formation of a stratified flow may be in a zone where fully stable stratified flows do not always occur. The data on this action are certainly inconclusive but until more complete data are available, such sites should be studied very carefully.

CONCLUSIONS

1. Over five structure-years of operation with three skimmer walls have definitely proven that this type of structure is highly effective in making all of the colder bottom waters available.

2. The skimmer wall operation is equally effective whether the water is drawn directly from the river or through a side canal before entering the skimmer wall.

3. The skimmer wall operation is also equally effective whether the water passes from the wall directly to pumps or flows through channels at considerably higher elevations than the top of the wall opening and of considerable length.

4. The model data of Fig. 6, when properly applied, can be expected to produce a satisfactory hydraulic design for a skimmer wall opening.

5. Silting may present a maintenance problem in regions of high silt load in the streams.

6. If the skimming action is to be used the year around and water temperatures below 40° F can be expected, the problem of the waters at 40° being more dense than those below 40° may require consideration.

ACKNOWLEDGMENTS

Mr. C. E. Blee was Chief Engineer for TVA during the development of the TVA designs described in this paper. Mr. George K. Leonard has been Chief Engineer during most of the operational phases of the Kingston and Gallatin plants. The concept of the TVA works and the studies leading to their design were performed under the general direction of Mr. Albert S. Fry, Chief, Hydraulic Data Branch, TVA, and under the immediate direction of the Hydraulic Laboratory staff which is headed by the author. Acknowledgment is made to Mr. A. A. Meyer, formerly Chief, Civil Design Branch, TVA, for helpful cooperation in achieving the desired objective through appropriate design of the unprecedented and unique works. Dr A. T. Ippen, Professor of Hydraulics, MIT, was consultant to TVA on the design of the TVA work. Mr. W. J. Holland, Superintendent of Mechanical Engineering, and Mr. Robert Orin, Design Engineer, Union Carbide Nuclear Company, assisted the author in obtaining operational data on the Oak Ridge installation.

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DISCUSSION

Donald Harleman thanked the speaker for correlating the extensive field data with the MIT laboratory studies and pointed out that the curves on Figs. 6 and 14 were derived analytically and not experimentally. The analytic expressions were derived in order to predict the point of incipient drawdown, and then laboratory tests were made to see if the analysis was any good. The laboratory tests, however, were on an extremely small scale with only laminar or maybe very-low-Reynolds-number turbulent flows. For that reason the analytical expression on which Fig. 6 is based had as one of its variables the term α which is a kinetic energy correction factor applied to the velocity head derived from the mean velocity at the gate. This factor varied from 2 which would be expected to be true for laminar flow to 1 which would be approached in turbulent flow. The laboratory study verified the high values of α , that is, near 2 and 1.5 so that confidence could be felt in the lower values of α derived from the same analytical expression. In this particular case neither analytical work nor laboratory work alone would have been satisfactory. A way of predicting the change between the laboratory results and what might be expected in the field was needed.

Norman Brooks inquired if h_r as shown on Fig. 6 was the actual depth of the cold-water flow or if it was the depth of incipient flow determined from the MIT curves. The speaker replied that actually these are the same thing since the laboratory varied the depth of the dense underflow (h_r) until the depth reached the point of incipient drawdown. However, h_r did not have to be the depth for incipient drawdown. Its real definition is the depth of the available understratum. In reply to a further question as to how h_t , the flow depth, could be less than h_r , the speaker said that it might be a matter of definitions and assumptions. He said that mixing definitely did not occur once the draft started on the overlying water. That did not occur in the laboratory even with two very definite strata. In nature there was no such definite interface between layers of different temperature hence it was necessary to make some assumptions in order to make any comparison at all. The questioner then remarked that the limiting stream line could not pass through the middle of the opening in the skimmer wall. The speaker replied that it was quite conclusive that all of the available cold water was being drawn into the intake channel.

Maurice Albertson said that in diversion of water for irrigation clear water is desired instead of sediment laden water; so an effort is made to divert the water at the outside of the bend so as to take advantage of the secondary flow that moves the sediment across the bottom on the inside of the bend. He inquired if the stratification was strong enough to cause a similar condition that would help move the cold water. The speaker replied that the cross-sections at the Kingston plant showed a definite slope across the bend, but that there are many factors involved. For example, even with 15° or 20° F difference between top and bottom the effect of gravity is about 0.005 fps^2; so that although it is definitely possible that the cold water rolls up on the inside or outside of the bend it is quite difficult to obtain depths or other data.