TABLE OF CONTENTS

HYDRAULIC ENGINEERING PROBLEMS ASSOCIATED WITH THE RACCOON MOUNTAIN PUMPED-STORAGE PROJECT

Rex A. Elder*

INTRODUCTION

Approximately six air miles west of Chattanooga, Tennessee, the Tennessee Valley Authority is constructing the Raccoon Mountain Pumped-Storage Plant, Figure 1. Nickajack Reservoir will serve as the lower pool and atop Raccoon Mountain the upper pool is being formed by building a dam across two small draws--dry creeks most of the time. There will be a little over 1,000 feet of differential between the upper and lower pools. The four pump-turbine units will have a maximum generating capacity of 1530 megawatts (mw).

This pumped-storage project will be particularly useful to TVA's power system, whose present installed capacity of 19,000 mw will increase to almost 29,000 mw within the next three or four years. Of this 29,000 mw only 4,000 mw, exclusive of the Raccoon Mountain Project, will be in hydro power.

Hydro is readily accessible, i.e., it can be turned on and off quickly. Steam power requires several hours to bring up the boilers, and they are not efficient if operated over wide load ranges. Nuclear power is even more of a problem in this respect for a nuclear power plant needs to run at nearly constant load 24 hours a day to operate efficiently.

With almost all of the increased load capacity in thermal power, the TVA system needs more relatively instantaneously available power to permit it to pick up its peak loads rapidly, loads that vary markedly, as much as 20 percent in two or three hours. This can be handled by pumped-storage which works in the following way: when the system load drops below the capability of steam units in the system the excess available electrical power can be used to pump water from the lower to the upper reservoir. Conversely, when the power demand exceeds the steam unit capability, the units can be reversed to generate. This provides the possibility of using excess power in periods of low power demand to produce the extra power needed to carry peak loads.

The upper reservoir of the Raccoon Mountain Pumped-Storage Project is designed to provide enough storage to permit weekly-cycle operations as well as daily-cycle operations. Studies show that power demands are at their lowest on Saturdays and Sundays. During the week the daily turbine discharge will exceed pumpage but Saturday and Sunday pumping will refill the reservoir with a time-elevation history similar to that shown in Figure 2.

The very large size of this project required careful study, evaluation, design, and in some cases, re-design of the hydraulic system. This paper

---

**Director, Engineering Laboratory, Tennessee Valley Authority, Norris, Tennessee*

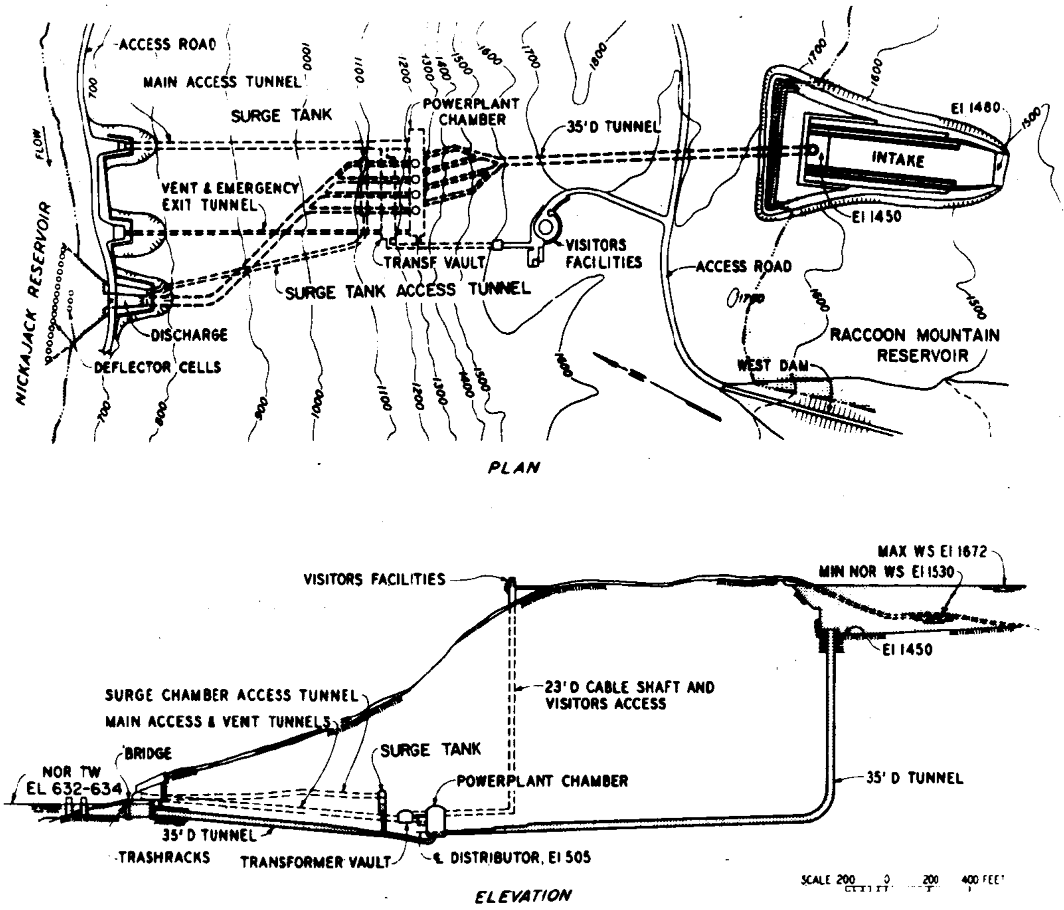


FIGURE 1 - GENERAL PLAN OF RACCOON MOUNTAIN PUMPED-STORAGE PLANT

is concerned with a few of these studies and their attendant problems.

LOWER RESERVOIR NAVIGATION STUDIES

The plant's inlet-outlet is to be situated in a reach of the lower reservoir which is only 600 feet wide and 80 to 100 feet deep--this reach in Nickajack has always been the most treacherous reach on the Tennessee River for commercial carriers to navigate. Commercial transport has already imposed on itself a no-passing policy in this area, i.e., carriers do not attempt to run this stretch of the reservoir both ways at the same time. These normal difficulties could be compounded by the installation of the Raccoon Mountain Plant with its discharge of 22,500 cubic feet per second (cfs) and withdrawal of 19,500 cfs. It was imperative, therefore, that an inlet-outlet be devloped which would eliminate interference with commercial and small craft navigation. To develop such a structure, a 1:90 scale model was designed and constructed for the one-mile reach of the reservoir in which the outlet is to be situated.

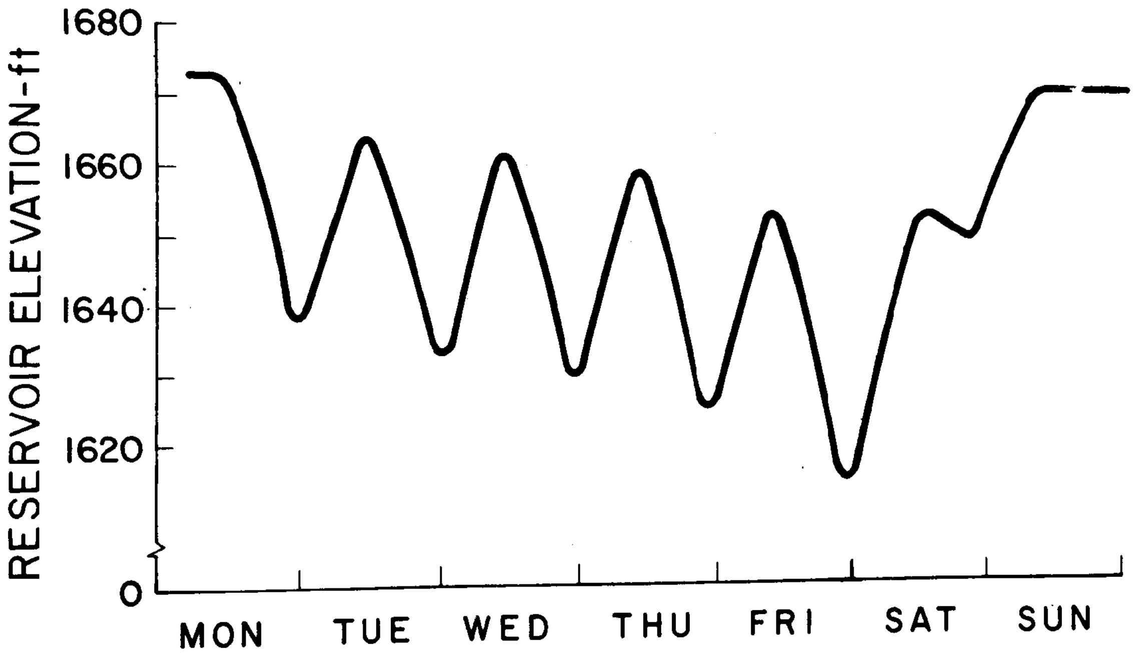


FIGURE 2 - SCHEMATIC PEAK WEEK OPERATION

Before the model could be used, it was necessary to verify that the model currents properly simulated those in the actual reservoir. The technique developed to obtain the necessary reservoir current data was as follows. Twenty-four 50-gallon drums were weighted so that only six inches remained above water when they were placed in the reservoir; after placement the drums followed prescribed paths and were photographed at five-minute intervals from an airplane. Each drum carried an identifying symbol. Over a period of time it was necessary to redistribute the floats. This was accomplished by means of a work barge. Reservoir flow patterns were easily defined from a composite plotting on which the drum positions were placed as photographed at the different specific times. Using this method sufficient reservoir current data were readily obtained over a sufficient range of flow conditions to allow the model to be properly adjusted to produce similar current patterns.

To determine the effect of the proposed structure on navigation, a 1:90 scale, remote-radio-controlled tow was used. This, too, had to be calibrated. To do this, the model tow pilot spent several days traveling up and down the area in question on commercial tows. The towing interests were very cooperative and permitted the operator to do this.

Back in the laboratory with his model tow, the operator ran the model reservoir until he could duplicate the maneuvers required by the prototype commercial tows in this zone. Although somewhat subjective, this is the fourth time this method has been used; the three preceding projects turned out very well.

With the reservoir model accurately simulating flow velocity and direction and the model tow simulating commercial navigation, the evaluation of various inlet-outlet orientations and structures could be carried out.

During previous tests with the model tow, evaluation depended upon observation of the tow's performance and discussion with its operator about his feeling and understanding of the relative navigational difficulties. This method was not entirely adequate because of its subjectivity and dependence on memory. Development of relatively inexpensive video-tape equipment provided a much superior evaluation technique for these tests. A remote auxiliary display panel was developed on which was shown the position of the tow's flanking and steering rudders, the speed and direction of the motors and the time associated with the model's digitally controlled discharges. By use of two video cameras and split-screen video-tape equipment, the tow's movements through the model and the remote display panel could be simultaneously recorded and observed. Thus, it was possible to make not only good comparisons of the relative navigational problems by simulataneously observing the data and the tow's movements on the auxiliary display panel but because the tape recordings from each run could be stored, comparisons of various schemes could be made over any period of time.

Owing to the S-shaped bend and the narrowness of the reservoir at the site the location of the outlet was extremely touchy. Figure 3 shows the outline of the model and the six positions of the outlet tunnel which were tested. At position 1 it was essentially impossible to move traffic upstream because the pilot had to be performing two opposing navigational maneuvers at the same time. Position 2 proved to have similar difficulties for traffic moving downstream. At position 6 with the structure shown in Figure 3 satisfactory conditions were achieved.

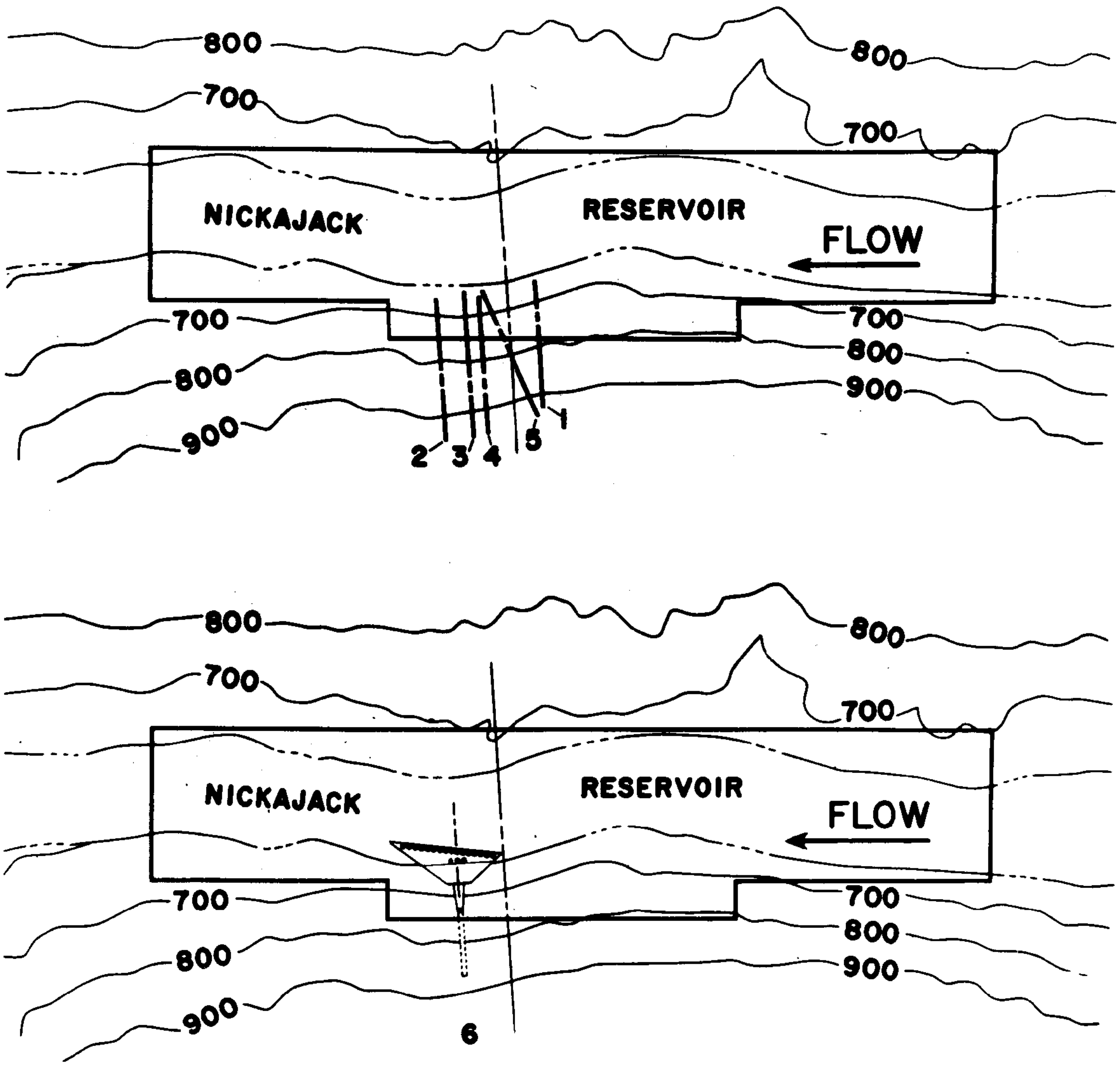


FIGURE 3 - NICKAJACK RESERVOIR INLET-OUTLET LOCATIONS

This structure eliminates navigational hazards for barges traveling on the normal sailing line either upstream or downstream during both the pumping and generating cycles. Barges traveling upstream off the normal sailing line are essentially unaffected by either cycle. Barges traveling downstream considerably off the sailing line could possible be pulled broadside into the inlet-outlet structure during the pumping operations. Because of this the structure was angled away from the shoreline to provide a very flat angle of strike thus minimizing damage to the structure and the tow. In addition, if a tow is pulled against the structure, it can pull away under its own power without running aground on the point which is situated downstream from the structure.

TRASHRACKS

Once the basic lower reservoir inlet-outlet structure site was established the problem of designing the structure presented itself. Because of geologic conditions the lower pool inlet-outlet could not be economically constructed to provide the usual relative low velocities associated with trashracks. To do so would require excessive rock excavation. Because the velocities were going to be high it was desirable to develop a velocity distribution as uniform as possible. Therefore, a 1:40 scale model was built of the inlet-outlet structure and the reservoir in its immediate vicinity on which to make these studies. The basic geometry of the inlet-outlet was determined by the navigation studies but it was possible to make internal modifications and several of these schemes were tested.

As expected, the velocities were lower and more uniformly distributed during the pumping cycle, with the generating cycle producing the more critical velocity distribution problems. When viewed from Nickajack Reservoir, the higher velocities occur at the right side of the structure. This flow concentration is caused by the bend in the 35-foot tunnel situated about 350 feet from the portal face.

The original structure, Figure 4a, showed a marked flow imbalance. Much of this was due to flow separation from the side walls. By flattening the angle of these walls, Figure 4b, a marked improvement was found with the maximum velocity during turbine discharge reduced from 16.3 to 15.0 feet per second (fps). A further improvement was achieved by sloping the floor at a 3° 15' angle, Figure 4c. This improved the distribution and reduced the maximum velocity to 14.5 fps. In all of these schemes, excessive uneven distribution occurred near the surface. This was improved by raising the structure and the tunnel invert 8.5 feet, Figure 4d. While this caused an increase in velocity to 15.4 fps the overall distribution was considerably better. Studies are still underway to further improve the velocity distribution.

UPPER RESERVOIR INLET-OUTLET STUDIES

The upper reservoir atop Raccoon Mountain will be formed by natural topography and an 8,000-foot long rock-filled dam. This inlet-outlet will be situated in the northwestern section of the reservoir, as shown in Figure 5, with its position fixed by the designers primarily on the basis of cost and geology. A 35-foot diameter vertical conduit will connect the upper and lower reservoirs, Figure 1.

As originally proposed, the approach channel was bathtub-shaped with a bottom width of 200 feet and with a bell-mouth entrance. On the basis of past experience, air-drawing vortices were considered to be the major problem and were to be avoided. A 1:100 scale model of the reservoir was

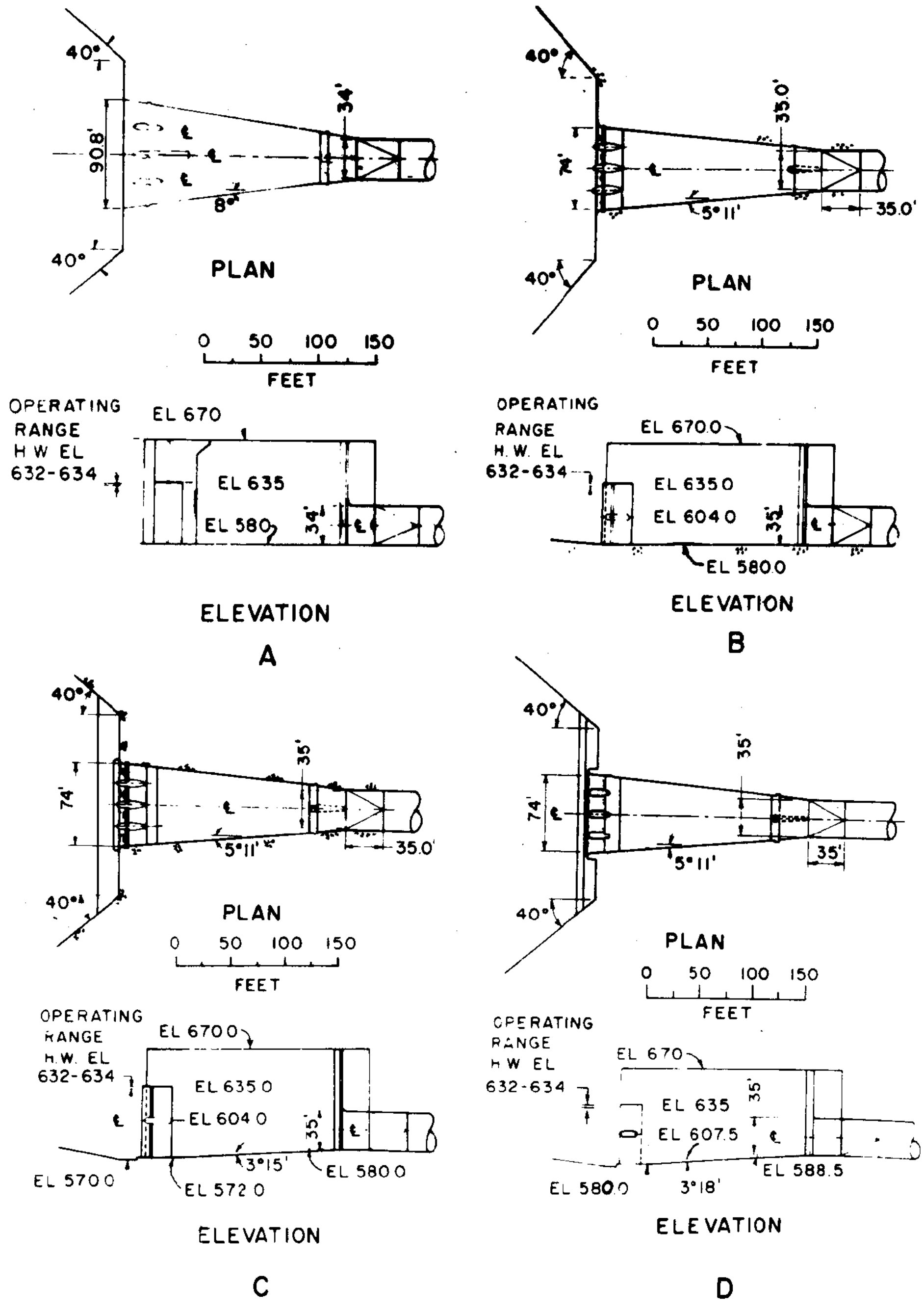


FIGURE 4 - NICKAJACK RESERVOIR INLET-OUTLET STRUCTURE

constructed to develop an inlet-outlet which would be free from air-drawing vortices. Since vortex action was to be studied, a large model would have been more advantageous but space was unavailable for a model larger than 50 feet by 60 feet.

Tests on the original design quickly showed that this design was very productive of vortices and would have to be modified. The vortex action occurred roughly over the upper one-third and lower one-third of the reservoir head range and was not only a function of the extremely large discharges but very decidedly of the reservoir and intake geometries.

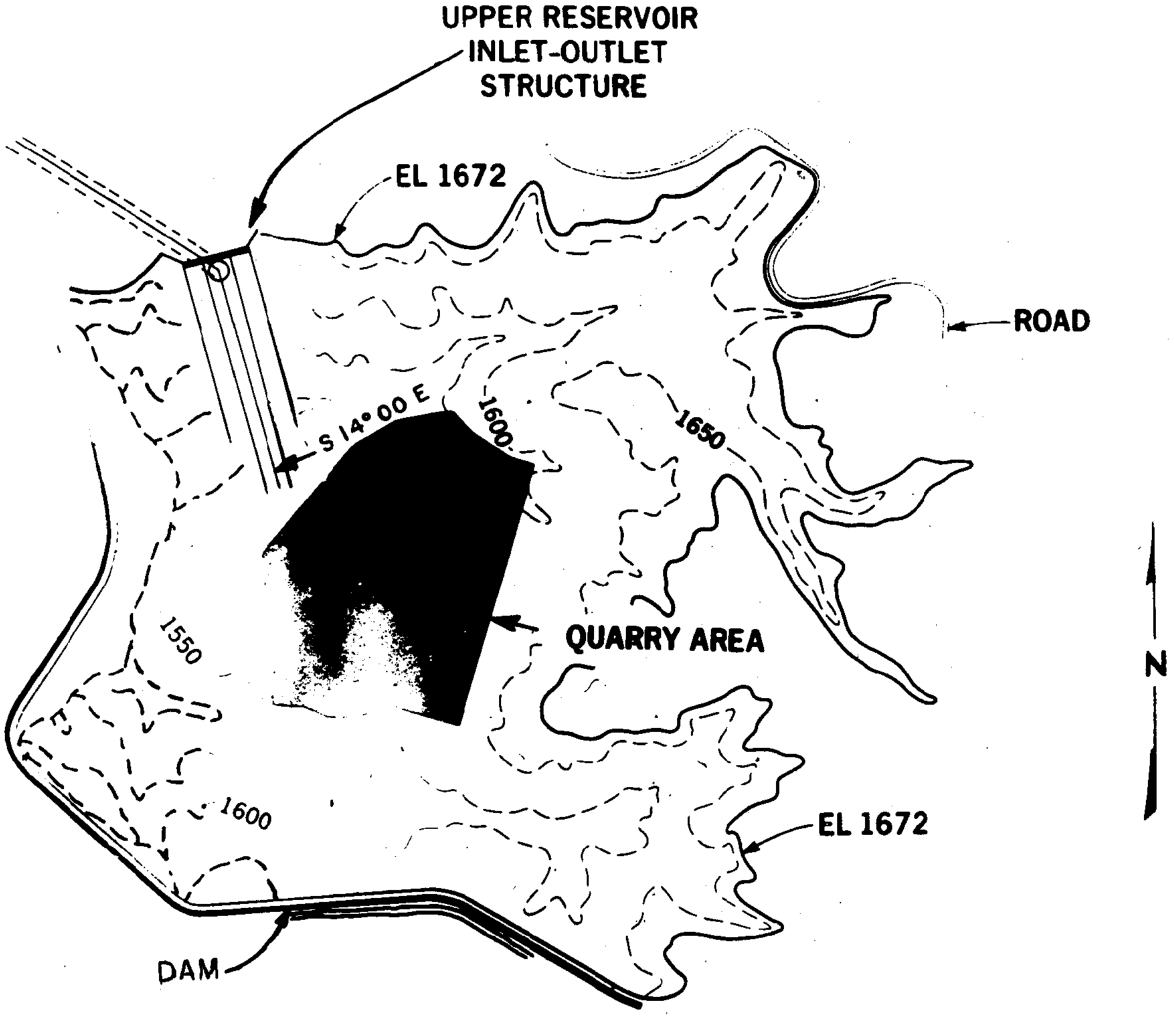
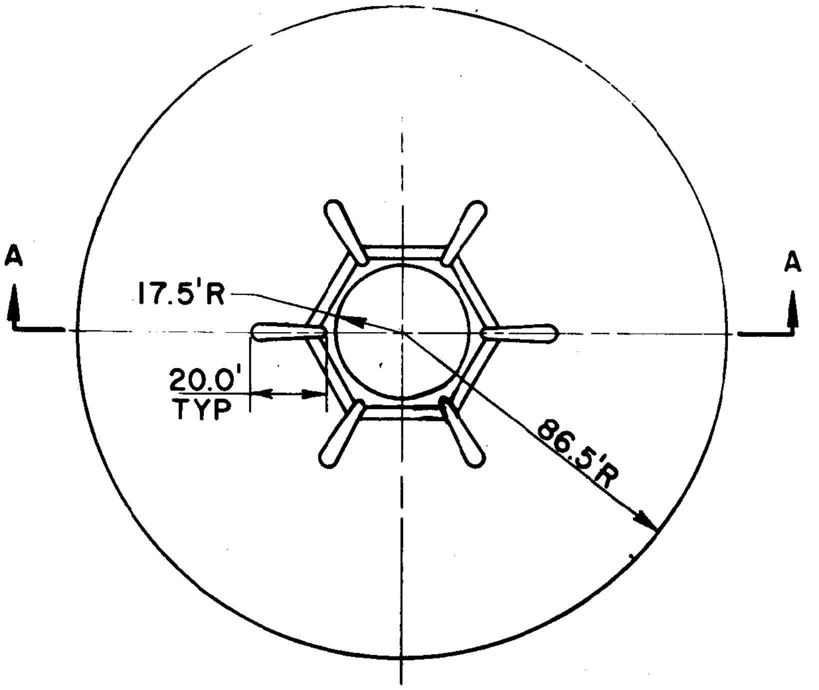
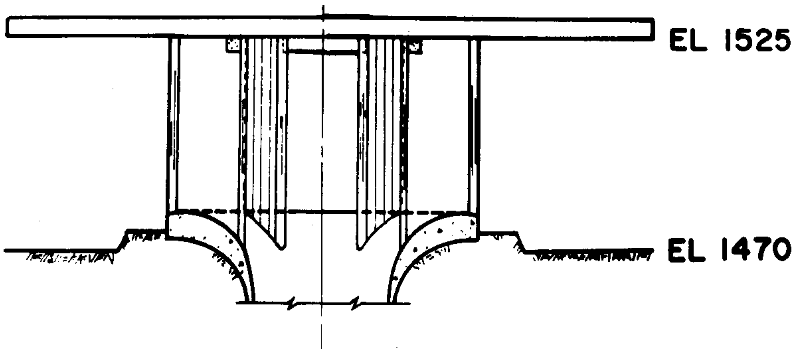


FIGURE 5 - UPPER RESERVOIR INLET-OUTLET LOCATION



PLAN



SECTION A-A

FIGURE 6 - DEEP WATER INLET

In the course of testing, every design which has been recorded in the literature was tried: Morning-glory shapes with or without piers failed; vertical openings of all types failed; all types of entrance channel designs failed. The only satisfactory designs were an entrance in the deepest water covered with a large flat plate, Figure 6, and a silo-like structure, Figure 7, 230 feet high with a semi-cylindrical front, performed by 117 holes 8 feet wide by 16 feet high. The first structure was rejected because of the cost of excavating the additional 1,000 feet of tunnel. The second structure has been accepted. The success of this structure requires that a cut off or similar device be present to prevent flow around the back of the entrance and careful adjustment of the intake channel design to ensure that adverse currents will not develop into vortices inside of the structure.

In evaluating all of these structures, the major problem was the proper technique for scaling vortices. A review of the world's literature showed that vortex scaling is a profession-wide problem. There are some meager data, but they are not conclusive. The only half-way good model-prototype data available are on the Kinzuna Project in northern Pennsylvania. Some work has also been carried out at Wallingford and at the British Hydro Research Association in England, and at the University of Strathclyde in Glasgow, Scotland. However, their information is far from definitive. In view of all this, a couple of observations can be made: a vortex model cannot be operated according to the Froude scaling laws. Viscous forces play an important role in vortex formation and a Froudian model does not properly simulate viscous forces. To compensate, the models may be operated at discharge rates greater than those determined by Froude's criteria. Some studies indicate that prototype velocities must be used. A simplified mathematical anaylsis of vortices indicated that a 1:100 model, when operating with Froudian relationships, may underestimate the size of the vortex by a factor as great as 100. It is necessary, therefore, to interpret model results very conservatively.

In this case, to evaluate the upper reservoir model a technique was used which consisted of dropping dye into the vortex; if a dye tube developed which extended down into the intake it was considered to indicate an air-drawing vortex in the prototype and was judged unsatisfactory. On this basis the design of Figure 7 was developed and adjudged satisfactory.

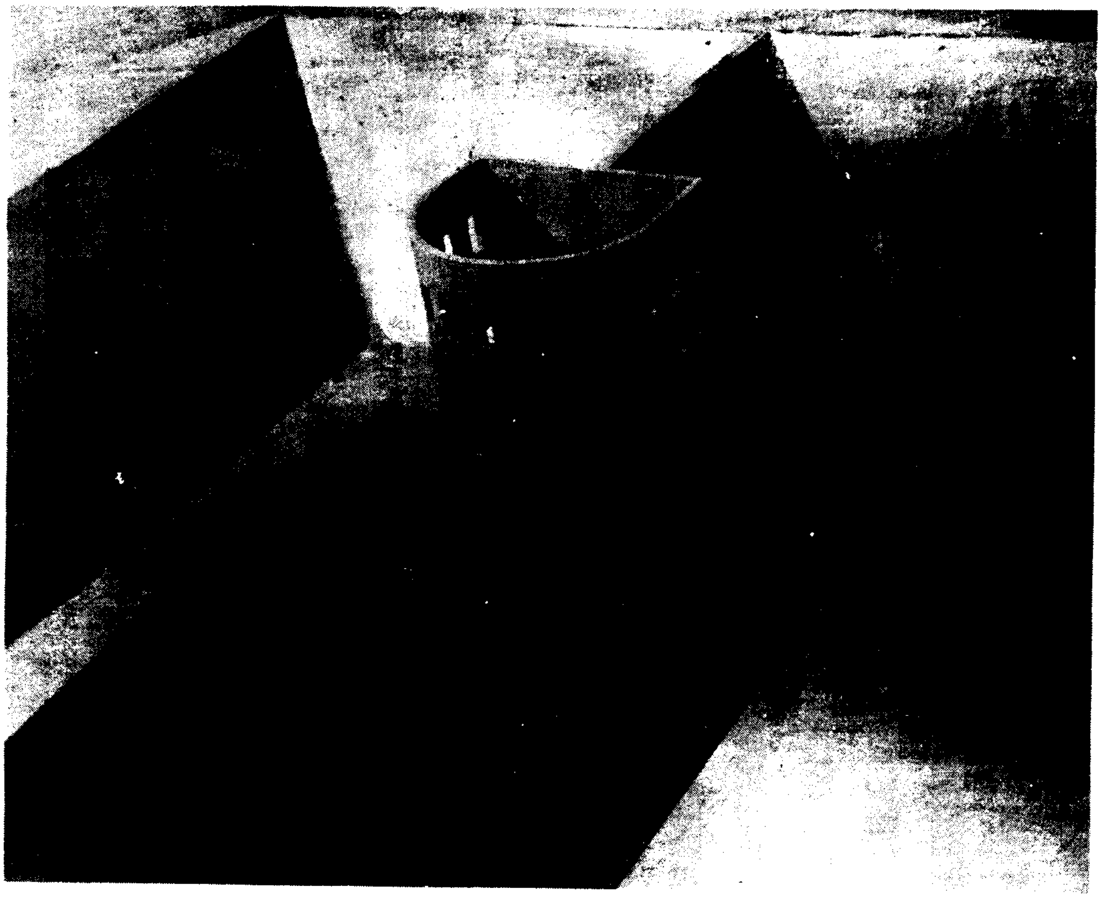


FIGURE 7 - SILO INLET

A TWO-DIMENSIONAL TEMPERATURE MODEL FOR A THERMALLY LOADED RIVER WITH STEADY DISCHARGE

Nobuhiro Yotsukura*

INTRODUCTION

Waste heat released into a river is attenuated mostly by the natural processes of mixing with cold ambient water and dissipation from water surface to air. This report presents a model in which the excess temperature distribution is calculated by combining analytical solutions to an approximate convective diffusion (mixing) equation with an exponential heat dissipation equation at the air-water interface. Both river discharge and waste discharge are assumed steady. The model is useful in predicting distribution of excess temperature in a downstream region where temperature is almost uniform in the vertical direction while it is still markedly non-uniform in the transverse direction.

The report is an excerpt of a comprehensive report to be published later by the U. S. Geological Survey.

A SOLUTION TO TWO-DIMENSIONAL HEAT TRANSFER EQUATION

A two-dimensional equation of conservation of thermal energy may be written for a steady uniform flow in a natural channel as:

$$\frac{\partial T}{\partial t} + u(z)\,\frac{\partial T}{\partial x} = \frac{\partial}{\partial x}\,(D(z)\,\frac{\partial T}{\partial x}) + \frac{1}{Y(z)}\,\frac{\partial}{\partial z}\,(\varepsilon(z)Y(z)\,\frac{\partial T}{\partial z}) + \frac{H}{\rho c_p Y(z)} \qquad (1)$$

in which T is the depth-averaged water temperature, u(z) is the depth-averaged velocity in the downstream direction, D(z) is the dispersion coefficient induced by the vertical variation of velocity from u (1), $\varepsilon_z(z)$ is the depth-averaged transverse diffusion coefficient, H is heat flux at the water surface, ρ is water density, c_p is the specific heat of water, and Y(z) is the total depth measured from the water surface. The coordinate x is directed toward the downstream direction and z in the transverse direction. The transfer of heat at the channel bottom is neglected.

Equation 1 is applicable to both thermally loaded temperature and natural temperature. An equation for excess temperature may be derived by subtracting from Equation 1 a similar equation written for natural temperature, T_n. Prior to this, however, it is convenient to express the surface transfer of heat by a linearized form:

$$H(T,t) = H(T_b,t) - \rho c_p K(T_b,t)(T-T_b) \qquad (2)$$

where T_b is an arbitrary reference temperature chosen close to T (2) and K is the surface transfer coefficient. Defining $T_e = T - T_n$ and completing

---

U. S. Geological Survey, Washington, D. C.

the above subtraction, the equation for T_e is obtained as:

$$\frac{\partial T_e}{\partial t} + u(z)\,\frac{\partial T_e}{\partial x} = \frac{\partial}{\partial x}\left(D(z)\frac{\partial T_e}{\partial x}\right) + \frac{1}{Y(z)}\,\frac{\partial}{\partial z}\left(\varepsilon_z(z)Y(z)\,\frac{\partial T_e}{\partial z}\right) - \frac{K(t)T_e}{Y(z)}. \tag{3}$$

If the release rate of waste heat is steady and Equation 3 is applied at a large time t, the longitudinal dispersion term may be neglected. It is also seen that, if heat were conservative (K=0), the terms $\frac{\partial T_e}{\partial t}$ and $\frac{KT_e}{Y}$ drop out of Equation 3 and the resulting solutions are for a steady-state distribution. In order to utilize such steady-state solutions, assume that Y(z) in the surface-transfer term is approximated by $\bar{Y}$, the width-averaged depth. Then it can be shown that

$$T_e(x,z,t) = T_e'(x,z)\,\exp\left(-\int_0^t \frac{K(t)}{\bar{Y}}\,dt\right) \tag{4}$$

is a solution to a simplified form of Equation 3, or

$$\frac{\partial T_e}{\partial t} + u(z)\,\frac{\partial T_e}{\partial x} = \frac{1}{Y(z)}\,\frac{\partial}{\partial z}\left(\varepsilon_z(z)Y(z)\frac{\partial T_e}{\partial z}\right) - \frac{K(t)T_e}{\bar{Y}} \tag{5}$$

provided that T_e' is a steady-state solution to

$$u(z)\,\frac{\partial T_e'}{\partial x} = \frac{1}{Y(z)}\,\frac{\partial}{\partial z}\left(\varepsilon_z(z)Y(z)\,\frac{\partial T_e'}{\partial z}\right). \tag{6}$$

As long as the discharge rates of river and waste heat are steady, Equation 4 shows that the excess temperature T_e' is simply obtained at a point (x,z) by multiplying a time-dependent loss factor to the steady-state solution T_e. Note, however, that Equation 4 does not apply to the condition that K is nonzero constant and $\frac{\partial T_e}{\partial t}$ is zero in Equation 5.

No analytical solution is currently available for Equation 6 in which u(z) and Y(z) vary transversely as in a natural stream. However, Yotsukura and Cobb (3) found that an analytical approximation to Equation 6 is quite feasible in such conditions. Defining the cumulative discharge as a new variable

$$q = \int_0^z uY\,dz, \tag{7}$$

and replacing z with q, Equation 6 is transformed into a form in which u and Y appear only in the diffusive flux term. By assuming furthermore that the variation of diffusivity in the transverse direction has small effects on the solution, Equation 6 is approximated by

$$\frac{\partial T_e'}{\partial x} = \overline{\varepsilon_z uY^2}\,\frac{\partial^2 T_e'}{\partial q^2}, \tag{8}$$

where the diffusion factor $\overline{\varepsilon_z uY^2}$ is a constant defined by

$$\overline{\varepsilon_z uY^2} = \frac{1}{Q}\int_0^Q \varepsilon_z uY^2 dq \tag{9}$$

An analytical solution to Equation 8 for a line source extending from q_{s1} to q_{s2}, where $(q_{s2} - q_{s1})$ is equal to the waste water discharge Q_s, is given by a set of error functions as follows:

$$\begin{aligned} T_e(\alpha,q') = \frac{T_{es}}{2}\Bigg[& \sum_{n=0}^{\infty}\sum_{j=1}^{2}\Big\{ \operatorname{erf}\frac{\alpha(q'_{s2} + 2n + \delta_j q')}{\sqrt{2}} - \operatorname{erf}\frac{\alpha(q'_{s1} + 2n + \delta_j q')}{\sqrt{2}}\Big\} \\ & + \sum_{n=1}^{\infty}\sum_{j=1}^{2}\Big\{ \operatorname{erf}\frac{\alpha(q'_{s2} - 2n + \delta_j q')}{\sqrt{2}} - \operatorname{erf}\frac{\alpha(q'_{s1} - 2n + \delta_j q')}{\sqrt{2}}\Big\}\Bigg] \end{aligned} \tag{10}$$

Summation with respect to the index j is defined by $\delta_1 = +1$ and $\delta_2 = -1$. The symbols q', q'_{s2}, and q'_{s1} are all fractional values relative to Q, T_{es} is the excess temperature at the waste release site, and α is a nondimensional parameter,

$$\alpha = \sqrt{\frac{Q^2}{2x\,\overline{\varepsilon_z uY^2}}} \tag{11}$$

Yotsukura and Cobb verified by tracer experiments that Equation 10 is quite satisfactory for a number of straight uniform natural channels. They also found that it is usable in a moderately meandering reach of the Missouri River. The nondimensional diffusion coefficient, $\varepsilon_z/\bar{Y}U_*$, was found to range from 0.23 for the straight channels to 0.7 for the Missouri reach. The symbol $U*$ designates the average shear velocity.

The derivation of the surface transfer coefficient, K, is based on a commonly used surface transfer equation,

$$H(T,t) = H_r(t) - \varepsilon\sigma(T+\delta)^4 - \beta\lambda U(t)(E(T)-E_a(t)) - \beta\lambda\gamma P(t)U(t)(T-T_a(t)) \tag{12}$$

In Equation 12, the first term, H_r is the total incoming radiation, the second term is the loss due to back radiation from water to air, the third term is the loss due to evaporation, and the fourth term is the loss due to conduction from water to air. A linear approximation of H in the form of Equation 2is accomplished by expanding Equation 12 by a first order Taylor series around T_b (2,4). Thus

$$K(T_b,t) = \frac{1}{\rho c_p}\left[4\varepsilon\sigma(T_b + \delta)^3 + \beta\lambda U \frac{\partial E}{\partial T}(T_b) + \beta\lambda\gamma PU\right] \tag{13}$$