HYDRAULIC STRUCTURE AT MOUNT ELBERT POWERPLANT

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INTRODUCTION

The Fryingpan-Arkansas Project is a multipurpose transmountain diversion development. It will make surplus water from the western slope of the Rocky Mountains of Colorado (Colorado River drainage) available to inhabitants of the eastern slope of Colorado (primarily in the Arkansas River drainage). The water will be used for municipal, industrial, and irrigation purposes. As shown in figure 1, the diverted water is transported through a series of tunnels, reservoirs, canals, and powerplants. Mt. Elbert pumped-storage powerplant (figure 2) is one of two powerplants to be constructed in the project. These powerplants will produce power from the water as it descends to the eastern plains.

Mt. Elbert pumped-storage powerplant will eventually produce 200MW of power with two units. Each unit will be

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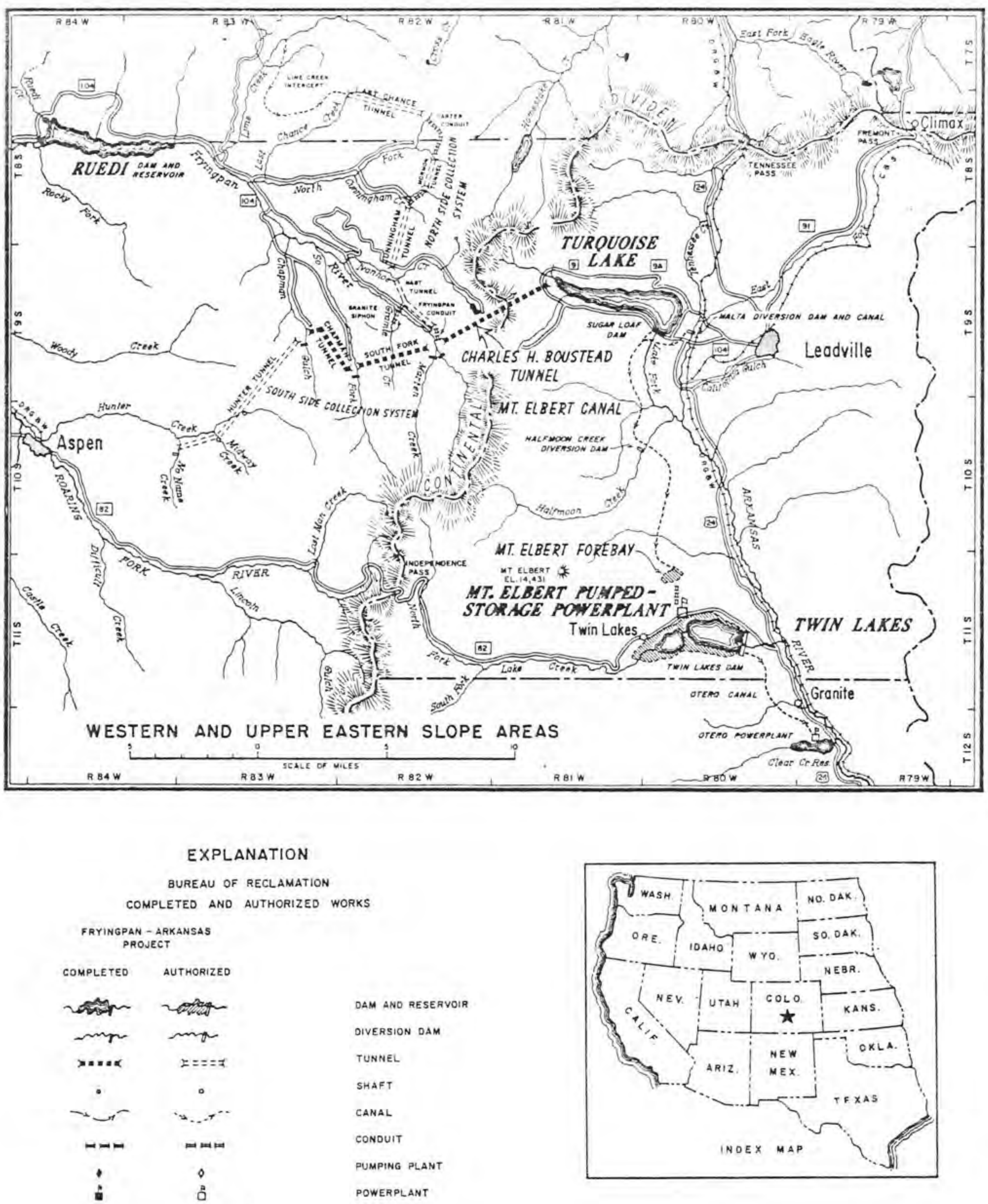
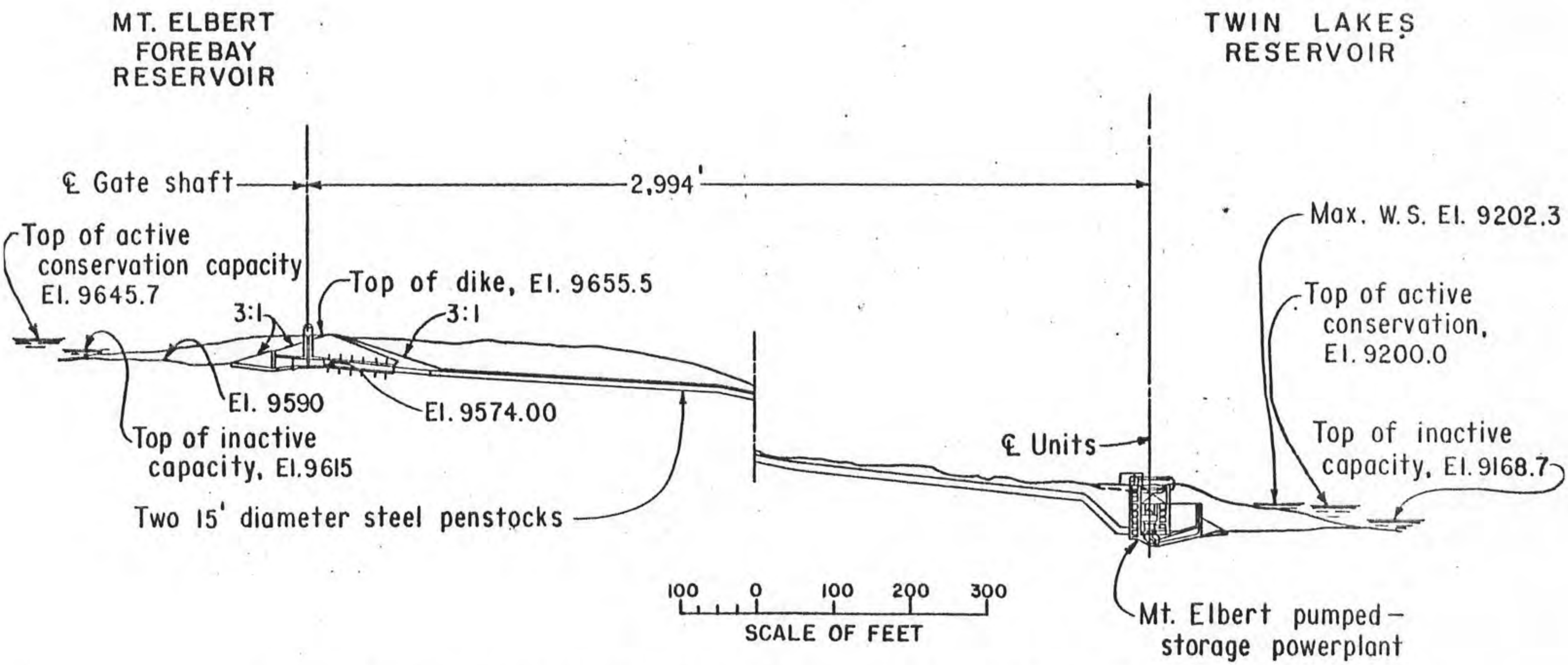


LOCATION MAP
FIGURE 1

fed from the 11,500 acre-ft (14,160,000 m^3) upper or forebay reservoir by a 15-foot (4.6m) diameter penstock. The length of each penstock will be approximately 3,000 feet (940m). The forebay reservoir will be created by the construction of a 90-foot (27.4m) high dam on a minor drainage. The forebay reservoir will have a compacted clay lining which is necessary due to the pervious nature of the in-place soils in the forebay area. The forebay reservoir will receive water from the pumping action of the powerplant and from the Mt. Elbert conduit. The Mt. Elbert conduit will have a maximum flow capacity of 370 Ft^3/s (10.5 m^3/s). The maximum water surface elevation of the forebay reservoir will be 9,647.0 Ft (2948.6m) while the minimum operating water surface elevation will be 9,615 feet (2930.7m).

The lower reservoir for the plant will be an expanded Twin Lakes (figure 2). The existing dam on the lower lake will be replaced by a new embankment with a maximum height of 52 feet (15.8m). This will combine the two existing lakes into a single 147,500-acre-ft ($1.8x10^8 m^3$) lake at the top of active conservation water surface. Twin Lakes has long been used as a recreational site. The lower lake contains an outstanding self-sustaining lake trout fishery. Twin Lake will receive water both from the diversion and powerplant and from Lake Creek, the mountain stream on which the lakes lie. Large areas of



PROFILE ALONG CENTERLINE OF PENSTOCKS SHOWING FEATURES OF THE MT. ELBERT PUMPED-STORAGE SCHEME

FIGURE 2

the lake bottoms are covered with glacial flour. Glacial flour is finely ground rock which has no cohesiveness and which is consequently easily disturbed by water movement. The top of active conservation water surface of Twin Lakes will be 9,200 feet (2804.2m) and the minimum active water surface will be at 9,168.7 feet (2794.7m). The maximum static head for the plant will therefore be 478.3 feet (145.6m). The maximum discharge through each penstock will be 3,600 Ft^3/s ($102m^3/s$) during the generating cycle and 3,090 Ft^3/s ($87.5m^3/s$) during the pumped cycle. It is expected that the first unit will be in operation by January 1, 1979. The second unit is to be constructed and in operation by February 1980.

In this paper the authors intend to discuss unusual design and construction hydraulic structure features of the power-plant. These are:

1. A baffled chute which will dissipate the energy in the canal water flowing into the forebay reservoir.
2. An upper inlet-outlet structure which will function with acceptable head loss, vortex-free inlet operation while yielding velocity head recovery and satisfactory flow velocities past the trashracks during outlet operation.
3. Penstocks designed to interact with the surrounding backfill when under pressure. Inclined

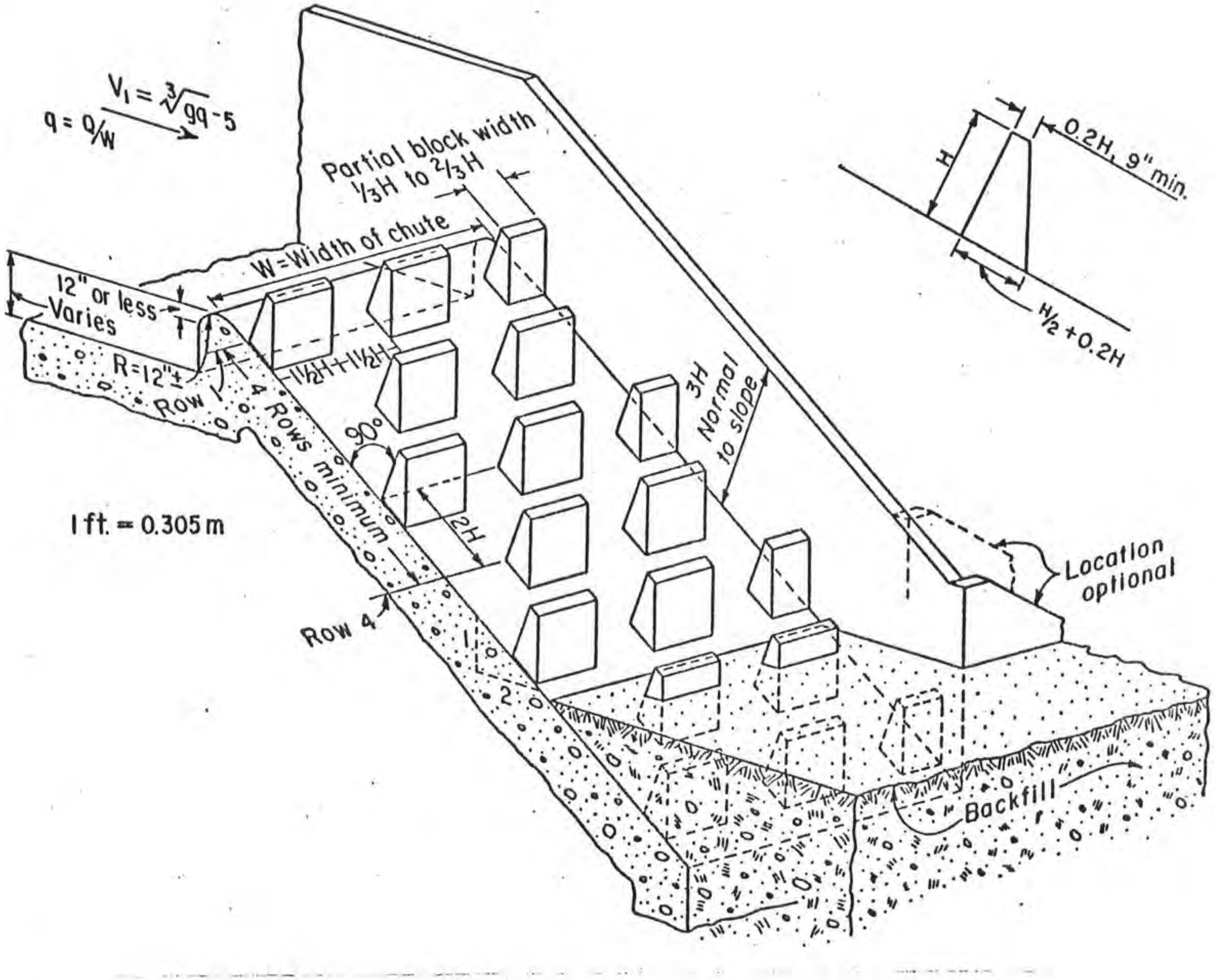
surge tanks, buried in the side of the excavation required for the penstocks, were selected to reduce visual impact.

4. A tailrace channel which will limit mixing affects of the powerplant on Twin Lakes. This will minimize the disturbance of the lake stratification and the glacial flour sediment which will in turn help to reduce the impact of the powerplant on the lake and the lakes fishery.

Baffled Chute

The baffled chute or apron drop shown in figure 3 was designed to dissipate the energy in the Mt. Elbert Canal flow as the flow drops into the forebay reservoir. Since the forebay reservoir water surface elevation can fluctuate over a 30-foot (9.1m) range, it is desirable to have an energy dissipator that will function satisfactorily no matter what the tailwater elevation is. Baffled chutes, because of their excessive roughness, are able to maintain relatively uniform, low velocity flow over their entire flow length. They can function with no tailwater although under such conditions some scour will occur at their base. They function equally well with higher tailwater, and scour is reduced or eliminated. Thus, the baffled chute is well suited for this Mt. Elbert application.

Baffled chutes have been used as canal drop structures by the Bureau of Reclamation for many years. They basically



TYPICAL BAFFLED CHUTE

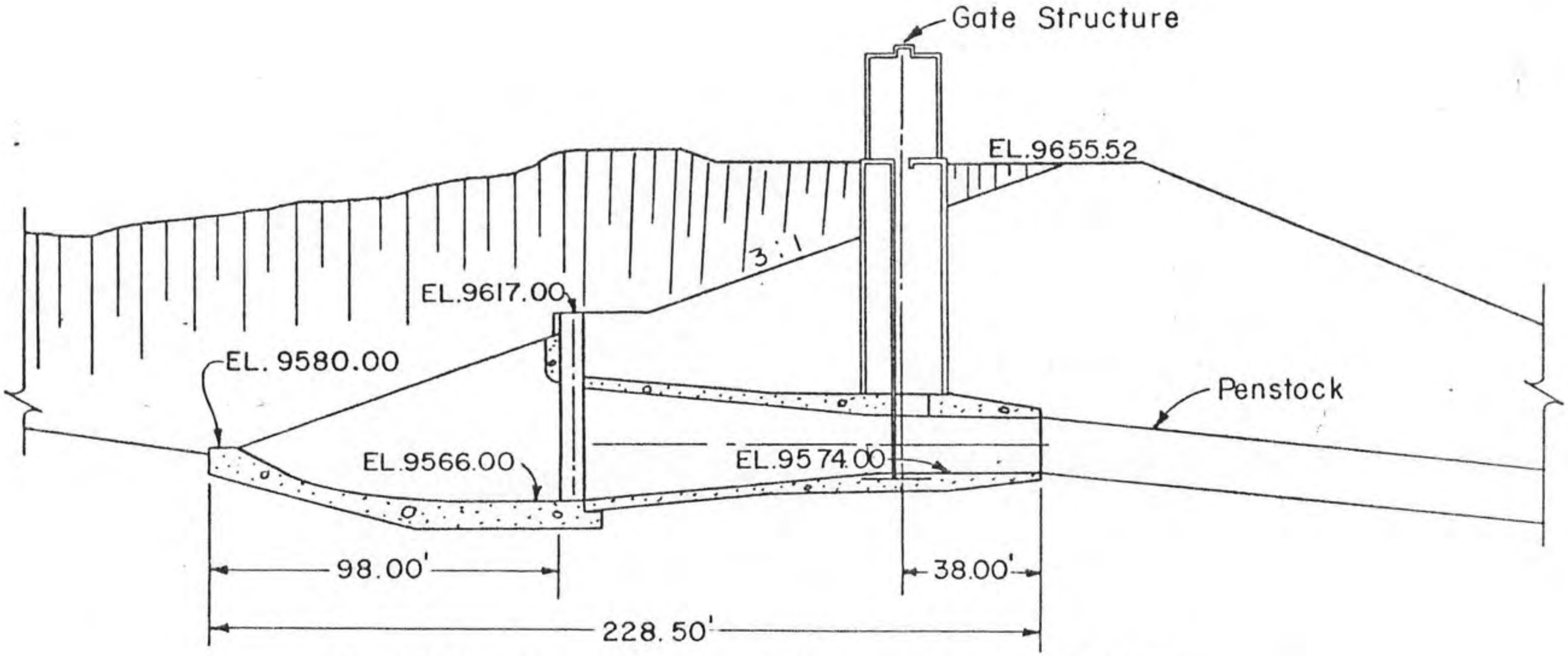
FIGURE 3

consist of a sloping apron, usually on a 2:1 or flatter slope, with multiple rows of blocks or baffle piers equally spaced along the chute. The flow passes over, around, and between the baffle piers and appears to slow down at each baffle pier and accelerate after passing the pier. The multiple rows of baffle piers on the chute prevent excessive acceleration of the flow and provide a reasonable terminal velocity, regardless of the height of drop. The extent of acceleration and the ultimate velocity at the base of the chute depends on the discharge and height, width, and spacing of the baffle piers. This type of drop has been used in a wide variety of structures with success and has been studied in detail by the Bureau of Reclamation's Hydraulics Laboratory. Presently used design standards are available in several publications (1,3,4).

Of prime importance during construction were the considerations to secure a smooth, dense finish for concrete surfaces adjacent to high-velocity water flow. Cavitation damage of such surfaces has been traced to surface irregularities or to poor quality of concrete in the surface.

Upper Inlet-Outlet Structure

The upper or forebay reservoir inlet-outlet structure (figure 4) functions to gradually accelerate or decelerate flows which in turn results in reduced vortex tendencies during



PRELIMINARY INLET – OUTLET STRUCTURE

FIGURE 4

the generating cycle and increased velocity head recovery during the pumping cycle. The flow deceleration effect of the structure also results in reduced flow velocities through the structures trashracks. This is desirable in that with the higher velocity flows a potential exists for strong vortex shedding and thus the resulting vibration which could result in fatigue failure of the trashracks.

Balanced against the above hydraulic considerations was the desire to minimize the size, complexity, and therefore the cost of the structure. In general a larger more gradually expanding structure has better hydraulic characteristics for both pumping and generating flow. During the generating cycle a slower flow acceleration would reduce the potential for vortex formation. Vortices with sufficient strength to entrain air are undesirable because of the resulting potential for blowback and because the passage of air through the turbine will result in rough operation. During the pumping cycle a longer structure would allow a more gradual expansion of the flow which would minimize flow separation and thus minimize turbulence and high velocity concentrations. This would in turn result in maximum velocity head recovery and a more uniform, low-velocity flow through the trashracks.

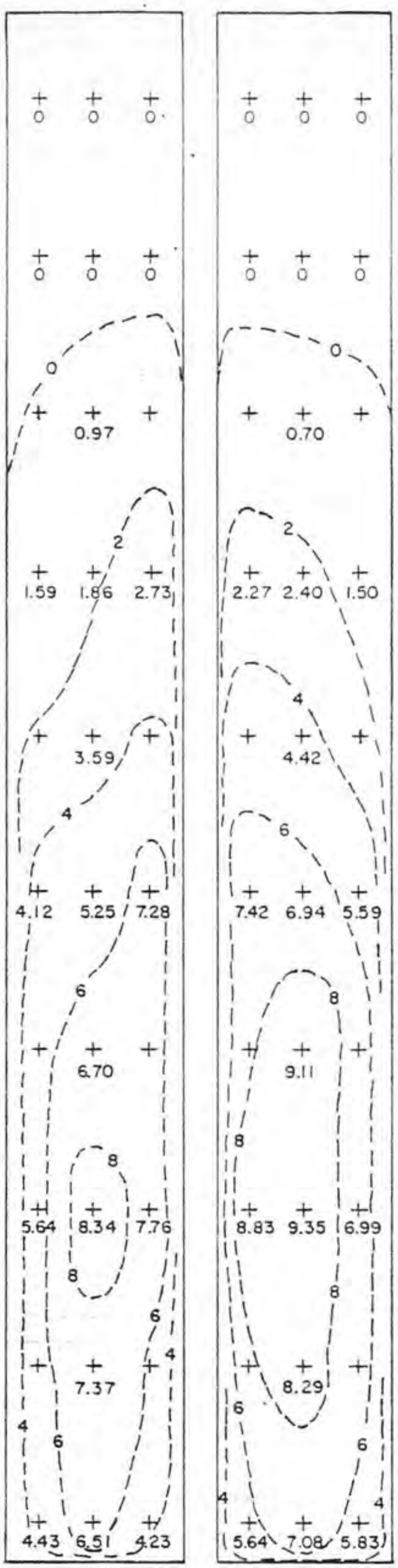
The structure length and expansion rate shown in figure 4 were determined by the designers to be economically feasible.

because it was realized that this does not represent an optimum hydraulic design, a hydraulic model study (2) of the structure was undertaken to verify and improve flow conditions as needed. The objectives of the model study were primarily to insure satisfactory flow velocities through the trashracks during the pumping cycle and to insure against generating cycle surface vortices which would have sufficient strength to draw air into the penstocks. Head loss through the structure for both cycles was also considered.

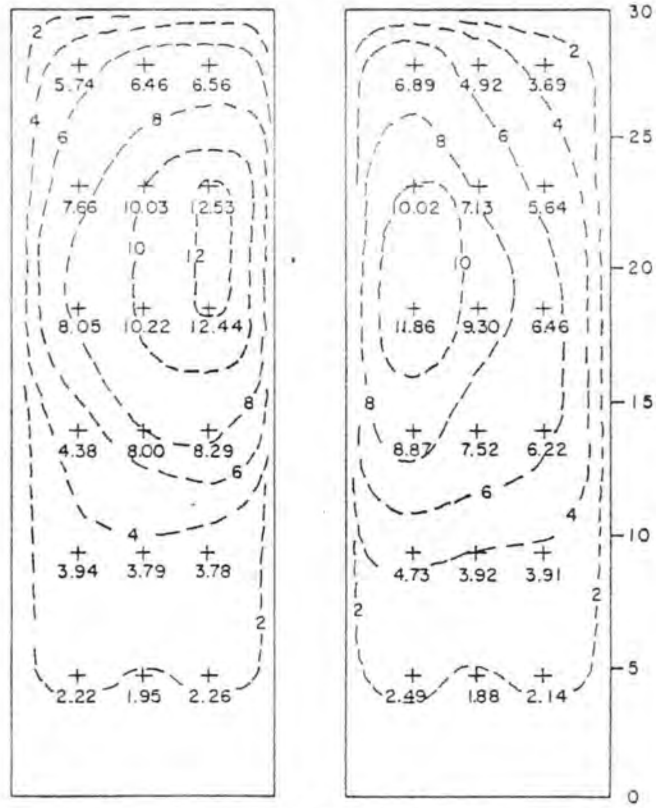
A 1:23.23 scale model was constructed. A 7.75-inch (197mm) diameter plastic conduit represented the 15-foot (4.57m) diameter penstock. The 3,600-Ft^3/s ($102m^3/s$) maximum generating discharge for each unit was modeled by a flow of 1.385 Ft^3/s (39.2 l/s). The model was arranged so that both pumping and generating flow could be studied.

In the model, velocity distribution data was collected at the trashrack section and at the section containing the stoplog slots. These data were collected for both the pumped and generating cycles. Velocity distributions during the generating cycle were quite uniform with only slight fluctuations, and consequently these flow conditions were determined to be satisfactory. The pumping cycle however, proved to be a different story. Flow direction and distribution were strongly influenced by the penstock orientation. A typical trashrack section velocity distribution is shown in figure 5. Note that not only were severe localized high-velocity regions observed, but also there was no flow passing through a significant portion of the trashrack section. The structure expansion was too large for the flow to follow. A deflector was then developed (figure 6) which dispersed the flow and yielded trashrack section velocity distributions similar to that shown in figure 6a. These velocities were considered to be low enough so that trashrack failure would not be a concern. The deflector structure was incorporated in the final design.

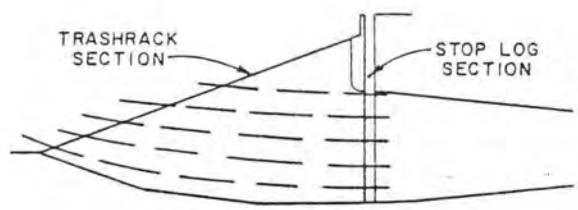
A combined Froude number-Reynolds number modeling criteria was used to study the vortex potential. Direct Froude modeling tends to underrepresent vortex strength. Use of discharges greater than those determined by Froude modeling will increase model vortex strength. The model was operated at discharges of up to 200 percent of design discharge. This created flow conditions that were felt to be as bad as, if not worse than, actual prototype conditions. Under the model operating conditions potential generating cycle vortices with sufficient strength to draw air into the penstocks were observed over a large range of reservoir elevations (figure 7). At design discharge the model showed vortices which would develop surface dimples but which would not draw air (figure 8). A lattice wall vortex



TRASHRACK SECTION VELOCITY DISTRIBUTION
LOOKING IN DIRECTION OF GENERATING FLOW



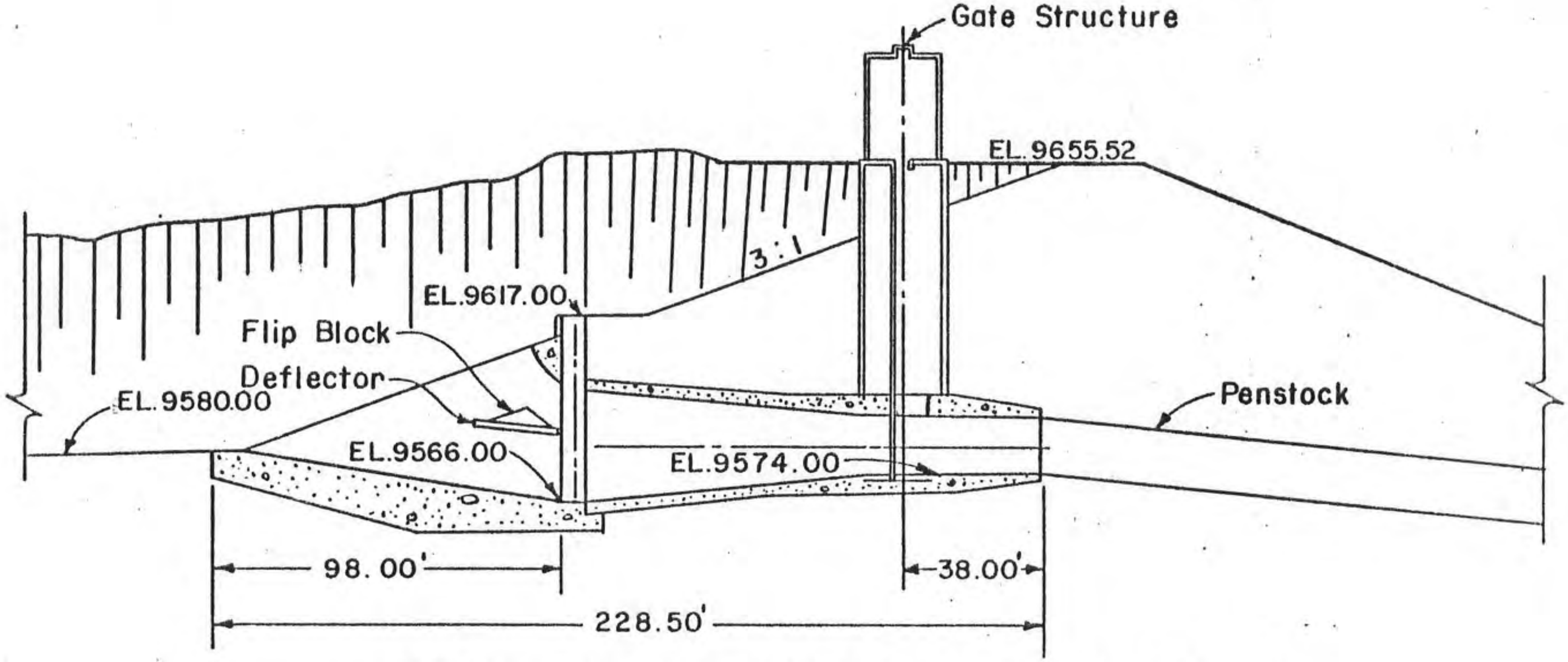
STOP LOG SECTION VELOCITY DISTRIBUTION
LOOKING IN DIRECTION OF PUMPED FLOW



APPROXIMATE STREAMLINES

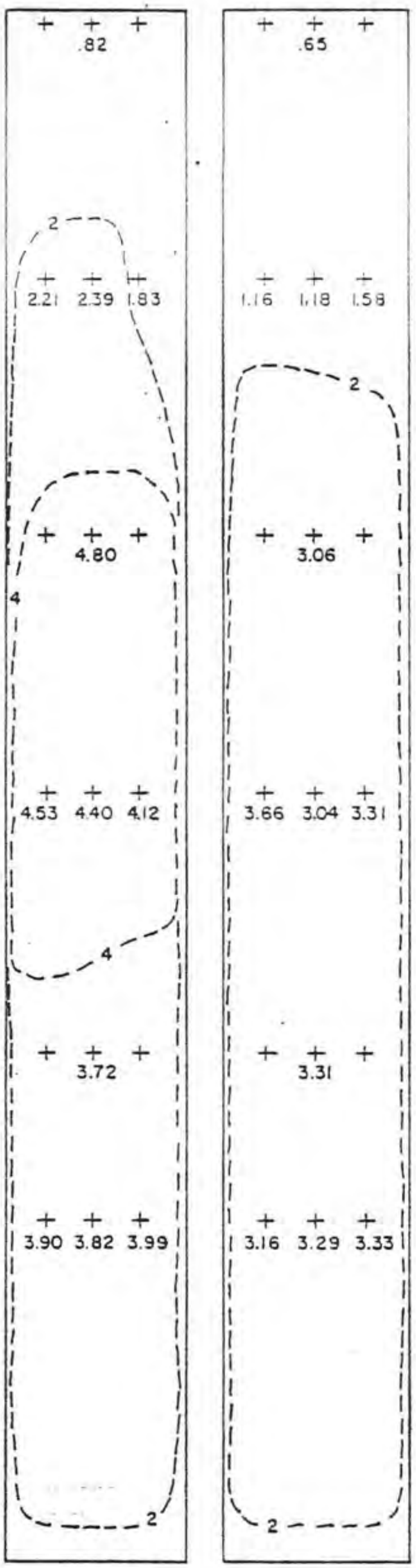
VELOCITY DISTRIBUTION
TRASHRACK AND STOP LOG SECTIONS
INITIAL INLET-OUTLET STRUCTURE
WITH CONCAVE FLOOR AND NO DEFLECTOR
PUMPED FLOW
VELOCITIES SHOWN ARE PROTOTYPE
VELOCITIES IN FEET/SECOND
2 FOOT/SECOND CONTOUR INTERVAL

FIGURE 5

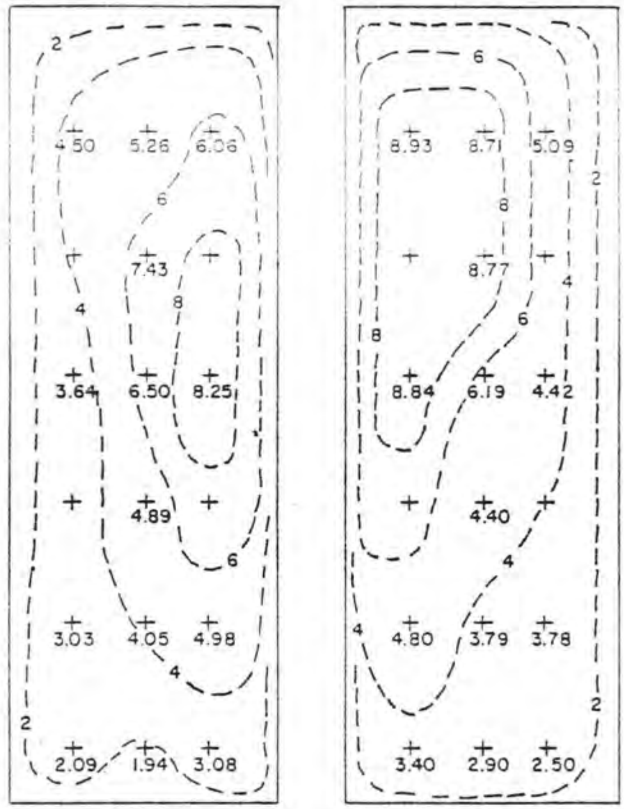


FINAL INLET — OUTLET STRUCTURE

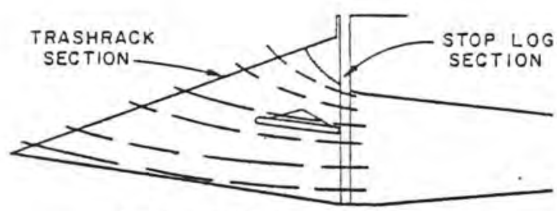
FIGURE 6



TRASHRACK SECTION VELOCITY DISTRIBUTION
LOOKING IN DIRECTION OF GENERATING FLOW



STOP LOG SECTION VELOCITY DISTRIBUTION
LOOKING IN DIRECTION OF PUMPED FLOW



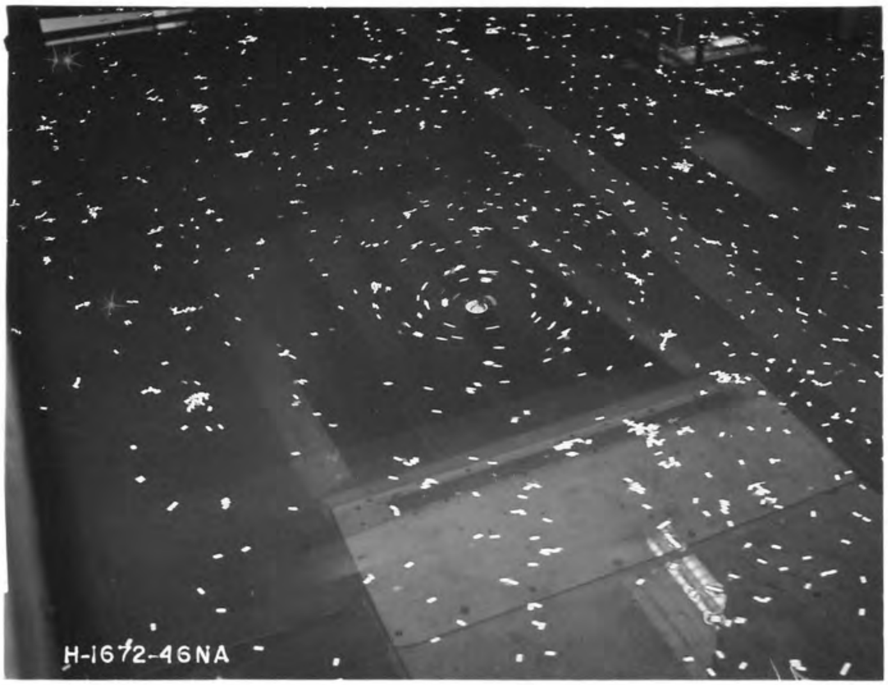
APPROXIMATE STREAMLINES

VELOCITY DISTRIBUTION
TRASHRACK AND STOP LOG SECTIONS
INITIAL INLET-OUTLET STRUCTURE
WITH STRAIGHT FLOOR AND DEFLECTOR
PUMPED FLOW
VELOCITIES SHOWN ARE PROTOTYPE
VELOCITIES IN FEET/SECOND
2 FOOT/SECOND CONTOUR INTERVAL

FIGURE 6a

VORTEX DEVELOPED BY PASSING 200% OF DESIGN GENERATING DISCHARGE

FIGURE 7



VORTEX DEVELOPED BY PASSING DESIGN GENERATING DISCHARGE

FIGURE 8

LATTICE WALL VORTEX SUPPRESSOR

FIGURE 9

suppressor (figure 9) was developed which prevented air core development for all flow conditions tested. Because of uncertainty about the strength of vortices that will occur in the actual structure, the inlet-outlet was designed so that the lattice wall suppressor could be easily added if operation shows that it is needed.

Head loss through the inlet-outlet structure and the connecting 124-foot (37.8m) length of penstock were evaluated to be 2.36 feet (0.719m) of water for the pumped cycle and 2.31 feet (0.704m) of water during the generating cycle.

Penstocks and Surge Tanks

The penstocks were designed to take advantage of the compacted backfill placed around them. There were no other unusual design considerations for the penstocks except for the surge tanks.

Studies conducted by the Special Studies and Testing Section of the Mechanical Branch, Division of Design, in the Bureau's Engineering and Research Center, indicated that control of hydraulic transients was necessary to keep both upsurge and downsurge within design limits for the penstocks. Using characteristics of the model of the installed pump-turbine, it was found that the design gradient could be seriously exceeded in some portions of the penstock, and that a condition of possible water column separation could occur due to downsurge.

The obvious and conventional solution was to place vertical surge tanks directly over each penstock. The tanks, however, would need to be approximately 150 feet (45.7m) high and 30 feet (9 m) in diameter to effectively control upsurge and to prevent water column separation.

Because the Mt. Elbert area is environmentally sensitive, alternatives to the very visible, 150-foot (45.7m) high vertical tanks were sought. After considering several alternatives, sloping surge tanks located laterally from the penstocks and buried in the side of a slope adjacent to the penstocks were selected as the best option available. This alternative had the advantages of the vertical tanks, could be constructed in an unobtrusive manner, and would relieve the upsurge and downsurge problems.

The basic dimensions of the tanks were determined from the hydraulic transient studies. Separate tanks for each penstock were selected to allow independent operation of either pump-turbine unit. Each surge tank consists of a 17-foot (5.2m) diameter steel line approximately 370 feet (112.8m) in length which leads to a vertical, reinforced concrete tank about 50 feet (15.2m) high and 40 feet (12.2m) in diameter. The steel lines will effectively act to control downsurge and will have maximum side support provided by compacted backfill placed to the top of the pipe. Because vertical risers from the steel pipes into the concrete tanks would require an elbow which would impede surge relief, direct side connections between the pipe and the tanks were provided.

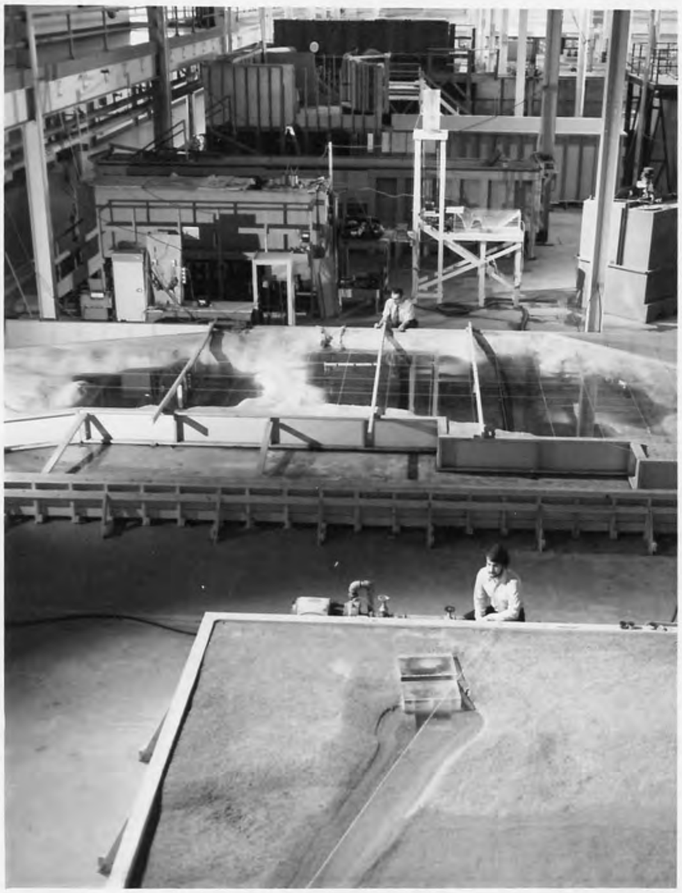
Powerplant Tailrace Channel

As previously stated, the bottom of Twin Lakes is covered with glacial flour, a substance which can be resuspended by minor flow disturbances. The lower lake also has a self-sustaining fishery which is noted for the large lake trout which it produces. The lake trout feed, during certain life stages, on a fresh water shrimp (Mysis Relicta) which was introduced to the lake in 1957 and which has become very abundant. Potential environmental effects of the pumped storage powerplant include: (1) Destruction of the summer thermal stratification, (2) Resuspension of the glacial flour with associated high turbidity, and (3) entrainment and passage of fish through the pump turbines. These factors could be expected to have direct adverse effects on the fresh water shrimp and the lake trout as well as direct or indirect effect on other biota. Secondary effects on the resort and recreation industry would result. Recognition of these potentially adverse environmental effects led to initiation of a major study of Twin Lakes. The study includes comprehensive biological assessment of preoperation conditions with associated studies of the lake thermal regime and lake hydrodynamics.

A Corps of Engineers modification of a model developed by Water Resources Engineers, Inc. was used to simulate thermal stratification in Twin Lakes. The model had been previously verified using data from two very different Bureau of Reclamation reservoirs. The model was applied using climatological and hydrological data collected at the site. Sufficient agreement between predicted and actually measured temperature profiles was obtained. The effects of plant operation were then incorporated in the program. Additional inflow and outflow points were designated to represent generating and pumping. The diffusion coefficient was varied from that used in the verification runs to show increased destratification effects due to plant operation. Because the question remains as to what diffusion coefficient value is truely representative of the effect of the plant, the mathematical model analysis is continuing.

Physical models were then used to evaluate the influence of the pumped storage powerplant on Twin Lakes. Three models were constructed (figure 10). The first, a distorted (1:84 vertical, 1:6000 horizontal) thermally stratified tabletop model was used to demonstrate and approximate the possible destratifying effects of plant operation.

A second distorted, thermally stratified model (1:100 vertical, 1:6000 horizontal) was used to study destrati-



TWIN LAKES MODELS

FIGURE 10

fication effects and circulation patterns in detail. The model included both lakes, the connecting channel, the inflow and outflow channels, and the Mt. Elbert plant. Plant operation was controlled by a minicomputer which also scanned water temperature monitoring thermistors. Velocities in the model were measured with an electromagnetic current meter, and circulation patterns and jet movement were determined by single-frame photography of dye clouds.

A third undistorted (1:100), homogeneous model was used to examine the near field characteristics of the tailrace flow and to develop the design of the tailrace channel. Velocities were measured with a miniature propeller meter and the electromagnetic current meter.

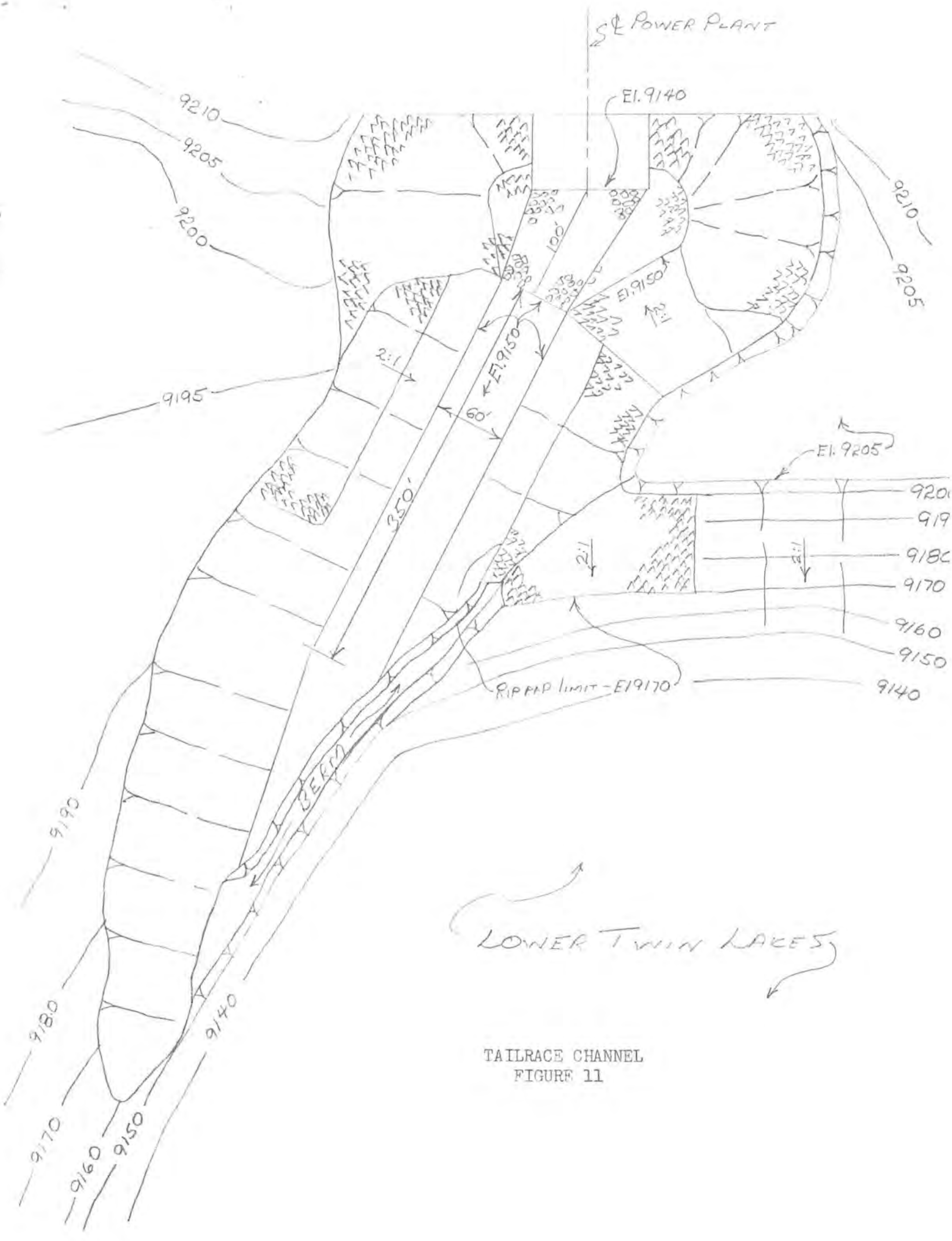
Operation of the tabletop model showed that the jet leaving the plant during the generating mode stayed close to the west shore then turned eastward when it reached the south shore of the lower lake. This model suggests that, beginning with a well defined stratification, the lake would be only weakly stratified after 30 days of either 1- or 2-unit operation. Movement of glacial flour was indicated.

Operation of the larger distorted model showed that the effect of the plant on Twin Lakes is strongly dependent on the relative temperatures of the generating cycle flow and the water in Twin Lakes. If generating flow is warmer than the lake water or the same temperature as surface lake water, it will tend to stay on the surface and consequently not affect bottom sediments. On the other hand, if the generating flow is as cold as or colder than the bottom lake water, the flow will tend to plunge and will quite likely disturb bottom sediment. These findings indicate that efforts should be made to use as warm as possible water for plant operation. With this objective design efforts have been directed towards drawing only the warm surface Twin Lakes water into the plant during the pumping cycle. The model indicated that the temperature of the water drawn into the plant during the pumped cycle roughly corresponds to the lake water temperature at the elveation of the bottom of the tailrace channel.

Finally using the undistorted model, efforts were directed towards developing the tailrace channel. Three channel configurations were tested; one was a direct extension along the plant centerline, the other two angled to the right toward the west shore of the lake. Velocity distribution readings taken during the generating cycle indicated that the configuration of the draft tubes concentrated the flow toward the centerline of the plant with very little dispersion. This gave the flow a higher energy flux at the point of entry into the lake. Bottom velocities seemed to be lower than intermediate depth and surface velocities. On the angled channels, the flow impinged on the left bank before turning and following the channel alinement. There was also some return flow and dead water areas, particularly with 1-unit operation. These trends occurred throughout the length of the excavated channel. Both 1- and 2-unit operation exhibited the same tendencies. Flow distribution was much better during the pumped cycle, particularly with the angled channels.

Based on the initial tests, an angled channel was studied in both the large distorted and the undistorted models for further investigation and refinement. The channel developed and included in the final design (figure 11) angled 27 degrees to the right of the plant centerline. The channel has a 60-foot (18.3m) bottom width with 3-to-1 side slopes. The invert is at elevation 9150 (2790m). At the end of the channel, where the channel enters the lake, a 5-foot (1.5m) high, 10-foot (3.0m) wide berm serves as an underwater barrier. The barrier encourages withdrawing water from a high level during the pumping cycle and influences the inflowing water during the generating cycle to have less tendency to move along the bottom of the lake.

The velocity distribution measurements, in the undistorted model, indicated that during the pumped cycle most of the flow entered the channel from along the north shore of the lake. The flow was evenly distributed and the velocity was about 1.2 Ft^3/s ($0.37m^3/s$.



TAILRACE CHANNEL
FIGURE 11

During the generating cycle flow was not evenly distributed near the plant but had attained an adequate distribution when it entered the lake where average velocities were usually less than 1Ft/s (0.30m/s). Velocities were slightly higher from mid-depth down.

Stratification was not affected by 2-unit operation although there was a tendency for the ambient temperature to be affected by the temperature of the generating flow. Over a two-week operating period, warm water inflow increased the temperature but the gradient remained essentially the same.

Time lapse motion pictures of colored water inflow showed movement of the generating influent generally toward the southeast and the pumping cycle intake generally originating along the north side of the lake. There was noticeable (but not appreciable) flow along the west side of the lake during the pumping cycle. This was not apparent during the velocity measurements in the undistorted model.

Dye tracers placed in the bottom of the lake in the vicinity of glacial flour deposits prior to operation did not move during the initial 2 or 3 days of operation but were gradually assimilated into the surrounding water.

In summary, the angled channel will provide satisfactory flow conditions, minor bottom disturbance, small changes to the natural stratification patterns, and a warming or cooling trend to the ambient lake temperature, depending on the temperature of the inflowing water.

Conclusions

1. Baffled apron chutes offer an energy dissipation structure which yields good hydraulic performance and good energy dissipation over a wide range of tailwater elevations. Consequently the structure is well suited to dissipated energy of inflows into pumped storage reservoirs which have large water surface elevation fluctuations.

2. Pumped storage inlet-outlet structures should and can be designed to yield optimum velocity head recovery, minimum intake head loss, operation free of air entraining vortices, with uniform low velocity flow through trashracks. These objectives can be sufficiently achieved while still designing an economically feasible structure.

3. The penstocks and the steel pipe portions of the surge tanks were designed taking into account the rigidity of the compacted backfill. To reduce visual effect in an environmentally sensitive area, the surge tanks were located laterally from the penstocks, inclined and buried within an existing slope, and terminated in vertical concrete tanks designed to blend with the surrounding landscape. The surge tank arrangement provides adequate

protection for the expected hydraulic transients both for upsurge and downsurge conditions.

4. At Mt. Elbert pumped-storage powerplant the tailrace channel has been designed to minimize the environment impact of the powerplant on its lower reservoir. The channel has been designed to minimize destratification effects of plant operation and to reduce the potential for mixing of glacial flour lake bottom sediments.

Appendix. - References

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