UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

MODEL STUDIES OF THE DRAFT TUBE CONNECTIONS AND SURGE CHARACTERISTICS OF THE TAILRACE TUNNELS FOR OROVILLE POWERPLANT, CALIFORNIA DEPARTMENT OF WATER RESOURCES STATE OF CALIFORNIA

Hydraulics Branch Report No. Hyd. 507

Division of Research

OFFICE OF CHIEF ENGINEER
DENVER, COLORADO

April 26, 1963

ARTIST'S CONCEPTION
of
OROVILLE DAM

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
OFFICE OF CHIEF ENGINEER

IN REPLY
REFER TO:

BUILDING 53, DENVER FEDERAL CENTER
DENVER 25, COLORADO

April 26, 1963

Mr. William E. Warne, Director
Department of Water Resources
State of California
Sacramento 2, California

Dear Mr. Warne:

I am pleased to submit Hydraulics Branch Report No. Hyd. 507 which constitutes our final report on studies conducted on the draft tube connections and tailrace surge problems of the underground power station of Oroville Dam. I believe you will find this report interesting and informative, and it will satisfy the requirements of your office for a comprehensive discussion of the extensive test program.

Sincerely yours,

B. P. Bellport
Chief Engineer

Enclosure

PREFACE

Hydraulic model studies of features of Oroville Dam and Powerplant were conducted in the Hydraulic Laboratory in Denver, Colorado. The studies were made under Contract No. 14-06-D-3399 between the California Department of Water Resources and the Bureau of Reclamation.

The designs were conceived and prepared by Department of Water Resources engineers. Model studies verified the general adequacy of the designs and also led to modifications needed to obtain more satisfactory performance. The high degree of cooperation that existed between the staffs of the two organizations helped materially in speeding final results.

During the course of the studies Messrs. H. G. Dewey, Jr., D. P. Thayer, G. W. Dukleth, J. J. Doody, and others of the California staff visited the laboratory to observe the tests and discuss model results. Mr. K. B. Bucher of the Hydraulics Unit of the Department was assigned to the Bureau laboratory for training and for assisting in the test program. Mr. Dukleth provided liaison between the Bureau and the Department.

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Denver, Colorado
April 26, 1963

Hydraulics Branch Report
No. Hyd. 507
Compiled by: W. P. Simmons
Reviewed by: W. E. Wagner
Submitted by: H. M. Martin

Subject: Model studies of the draft tube connections and surge characteristics of the tailrace tunnels for Oroville Powerplant--California Department of Water Resources--State of California

PURPOSE

Studies were made to determine the optimum design for connecting the draft tubes to the 35-foot-diameter tunnels, and to determine the adequacy of the tailrace system when surge conditions are imposed on it.

CONCLUSIONS

1. Best flow conditions and lowest head losses were obtained at the junction of the 3-barrelled draft tubes with the 35-foot-diameter tunnel when the draft tubes curved downstream and guide vanes were provided in the tunnel, Design 2 (Figures 8, 15, and 16).

2. When four 3-barrelled draft tubes enter the tunnel, straight 90° connections are nearly as good as the curved ones, and are much less expensive to build, Design 1 (Figures 8, 15, and 16).

3. Flow introduced into the tunnel upstream from a set of draft tube barrels with 90° connections tends to interfere with the discharge from the barrels. Thus, a higher pressure is required in the first barrel to displace the tunnel flow so the barrel can discharge. Progressively lower pressures are required in the succeeding barrels of the set because the modified tunnel flow pattern has become more nearly established, (Figure 16A).

4. The large deflectors or turning vanes of Design 2 extend inside the tunnel and guide the flow past the exits of the draft tubes so that, with Design 2, nearly equal pressures occur in the 3 barrels of each set, (Figure 16B).

5. The obstructions created in the tunnel by four sets of the large Design 2 turning vanes for four sets of draft tubes, cause head losses that essentially negate the otherwise beneficial aspects of the vanes, (Figure 16B).

6. The performance of the tailrace system under severe load rejection or load acceptance cycles is relatively insensitive to moderate changes in tailwater.

7. About 35 minutes (prototype) are required to obtain essentially surge-free conditions after a severe rejection cycle.

8. About 5.5 minutes (prototype) are required to obtain essentially steady conditions after a severe load acceptance.

9. Tunnel 1 will not completely fill at the upstream end, even under the most severe load rejection possible, unless the tailwater is at least 13 feet above normal.

10. Tunnel 1 will not completely fill during severe acceptance cycles, with normal tailwater elevation, when full load acceptances are made consecutively at 1 minute or longer intervals.

11. Under all normal acceptance rates and tailwater elevations no surging troubles will be experienced.

12. The tailrace tunnel system, as designed by the California engineers, performs well and is satisfactory for prototype use.

INTRODUCTION

Oroville Dam and its related appurtenances are part of the large water development program being undertaken by the State of California through its agency, The Department of Water Resources. The dam and reservoir are key features of the multipurpose Oroville Division of the Feather River Project, which is an important part of the California Water Plan.

The 735-foot-high earth and rock fill dam is being built across the Feather River about 5-1/2 miles upstream from Oroville, California, (Figures 1 and 2). A gate-controlled spillway will pass floodwaters through a natural saddle near the right end of the dam and power will be developed from normal water releases by a 600,000-kilowatt underground powerhouse under the left abutment. An outlet works will discharge waters needed for downstream commitments after the diversion tunnels are closed and before the powerhouse releases begin, and during emergencies at subsequent times.

A more detailed description of the dam and facilities is presented in a previous report.1/ Discussions of model studies on other features of the dam are also individually presented.2/3/4/

The underground powerplant will contain six units and will discharge into the downstream portions of the tunnels orginally used for river diversion, (Figure 3). Units 1, 3, and 5 will be conventional Francis-type turbines and Units 2, 4, and 6 will be reversible pump turbines. The draft tubes of Units 1 and 2 discharge directly into Tunnel 2, and the draft tubes of Units 3, 4, 5, and 6 pass under Tunnel 2 to connect to Tunnel 1.

Tailrace Tunnel 1 begins at the tunnel plug with the invert at elevation 205.33 and slopes downward 3 percent to Station 32+30.76, (Figures 3 and 4). It then slopes upward to elevation 182.00 at the submerged outlet portal. Thus, most of this tunnel is below the tailwater elevation and it operates as a pressure tunnel. At the upstream end, near the plug, the top of the tunnel is above the tailwater and a free water surface exists.

Tunnel 2 is constructed with the invert horizontal and at elevation 207.50, (Figures 3 and 4). It flows about half full at the normal tailwater elevation of 225.0 and remains partly full at all other operating conditions. Large open ports connect Tunnel 2 with the draft tubes of Units 3, 4, 5, and 6 that pass beneath it, (Figure 4). Thus, Tunnel 2 acts as a surge chamber to receive water from, or supply water to the draft tubes and Tunnel 1 during load changes on the system. The area of the port in each draft tube equals the cross-sectional area of the tube.

To provide atmospheric pressure on the free water surface of Tunnel 1 at all times, a vent interconnects the upstream ends of the tunnels, (Figure 4).

When all powerplant units are generating at their installed capacity at the design reservoir head of 620 feet, the discharge into the tailrace is about 13,250 cubic feet per second. However, a maximum discharge of 16,500 cubic feet per second will be obtained when all units are generating at full load under a 500-foot head. The latter discharge produces a flow velocity of 11 feet per second in each tunnel.

1/Numbers refer to Bibliography.

If the load on one or more generators is suddenly cut off, the wicket gates on the affected units will automatically close and stop the flow into the tailrace tunnels. However, the mass of water already in motion in the tunnels will continue to move due to its momentum, and will lower the upstream water surfaces in both tunnels. This continued water movement will create a retreating wave front in Tunnel 2 with the water surface behind the front lower than the surface ahead. This front will move downstream through the tunnel and out the portal into the river channel. In Tunnel 1, the result of the continued outflow of water is a lowering of pressures throughout the tunnel, except at the free water surface which is vented to the atmosphere through Tunnel 2.

Excessive drawdown of the water surfaces in the tunnels is prevented by drawing upon water stored between the plug and upstream unit in each tunnel, and by an interchange of water from one tunnel to another through the surge ports into Draft Tubes 3, 4, 5, and 6.

By the time the retreating wave front in Tunnel 2 passes through the outlet portal into the river channel, the flow in both tunnels has slowed to a stop. An unbalanced energy condition then exists between the lowered water surface in Tunnel 2 and the higher water surface in the river. This unbalance produces an advancing wave front with the water surface behind the wave higher than the water in front of it. The wave moves rapidly upstream in the tunnel.

A similar energy unbalance occurs in Tunnel 1 due to the lowered water surface in the upstream end of the tunnel, and to the generally lowered hydraulic gradient. At about the time the advancing wave front starts in Tunnel 2, flow also starts upstream in Tunnel 1. Because Tunnel 1 is full throughout most of its length, the water surface in the upstream end rises as soon as upstream flow starts. A momentarily higher water surface soon results in Tunnel 1 and creates an energy unbalance relative to the still lowered water surface in the upstream end of Tunnel 2. Therefore, water will flow through the surge ports from Tunnel 1 into Tunnel 2, (Figure 5A).

The flow entering Tunnel 2 through the surge ports causes the water surface to rise and creates advancing wave fronts. One of these fronts moves upstream toward the outlet works bulkhead, while the other moves downstream toward the river. Thus, in the section of Tunnel 2 between the powerplant and the outlet portal an advancing wave is traveling upstream from the portal and another is traveling downstream from the surge ports. These waves collide in the horizontal bend, (Figure 5B). Reflected wave fronts are produced and one travels downstream, increasing in amplitude, and passes out into the river, (Figures 5C and 5D).

The momentum of the water which has been flowing back into the tunnels tends to overfill the tunnels and again creates an energy unbalance in the downstream direction. This causes the water to stop and then flow downstream to start another surge cycle. The oscillations continue until the friction in the conduits damps them out.

During load acceptances, the wicket gates open and flows start through the turbines. These flows move through the draft tubes and into the tunnels to produce advancing wave fronts that travel toward the plugs and the downstream portals. The upstream wave front can, under extremely severe conditions, fill the upper end of Tunnel 1 and "top out" into the air vent before sufficient downstream flow is established to lower the water surface, (Figure 18A). In Tunnel 2, no difficulty occurs upstream from the units, but a large wave advances downstream and into the river channel, (Figure 6). The surges die down rapidly thereafter, and steady conditions are achieved.

The tailrace system was developed by California Department of Water Resources engineers after careful analytical studies of the problems. The following description is quoted from their informal report entitled "Surge Studies, History and Description."

> "The system acts as an open channel combined with a simple surge tank. The resulting interaction of flow greatly increased the complexity of the overall analysis; however, relatively simple computations proved the downsurge following load rejection would be well within allowable limits. The designers were concerned with the possibility of an in-phase return of the mass surge and the surface waves of the open channel. Superposition of these phenomena could cause 'topping out' in the tunnel because very little freeboard is available in the surge chamber. Several techniques were considered for the solution of the mass surge problem, including the digital computer; but it was finally decided to use a graphical procedure developed by Professor A. K. Schoklitsch. This graphical approach allows the designer to follow and even anticipate the development of the overall problem. The Schoklitsch method has the added advantage of requiring no major assumptions for this phase of the problem; the method allows for both friction and wicket gate closure time. The designers were confident the wicket gate closure time could be neglected because of the long period of the surges, but it was felt the closure time, as well as any other variable that might be adapted to a method of solution, should be included. The open channel phase required much more research, for none of

the existing methods of solution for translatory waves proved entirely applicable. It was necessary to combine the numerical computation methods of R. D. Johnson with a graphical approach by Lois Bergeron to contend with the overtaking surges and keep track of the continually changing wave patterns. It was necessary in this portion of the analysis to assume the water level is the same in the two tunnels near the interconnections, that in the free surface tunnel friction, and also the velocity head at the portal, can be neglected. All of the assumptions err on the side of safety. The step-by-step results were checked for continuity of mass and momentum. The analysis was tedious and time-consuming, but the designers were confident of the results. Thus it was concluded that for all normal operations the design was acceptable.

"All of the aforementioned computations were concerned with load rejection under normal conditions of operation. There was no assurance of safety of operation under abnormal conditions, such as high flood stages or rapid load acceptance. Also the limiting factors were not known. How rapid could a load be accepted with safety? At what flood stage would the tailwater condition be critical? These problems are better suited to model study than to direct computation. A model study would also provide an excellent opportunity to determine the accuracy of the assumptions. The Bureau of Reclamation was already performing tests on a 1:55 scale model of the Oroville diversion tunnels. It was decided to contract with the USBR to adapt this model and perform the tailrace surge tests for the Department of Water Resources."

The additions and alterations that were made to the 1:55 hydraulic model to adapt it to the surge studies, the tests made, and the results that were obtained are discussed in this report.

Studies were also made to determine the effect on energy losses and flow stability of three different designs for connecting the draft tubes to the 35-foot-diameter tunnels, (Figures 7 and 8). In one of the designs the connections were made at 90°, whereas in the others, the tubes were curved downstream so that intersection angles were 60°. The test facilities and the results obtained in these studies are also discussed in this report.

THE MODELS

Draft Tube Connections--Air Model

For reasons of economy, speed, and ease of operation, the studies of the draft tube connections were made using air as the testing fluid. Previous investigations show this practice to be feasible and accurate when the system flows completely full and when the air velocities do not exceed about 200 feet per second. 5/

The model consisted of a centrifugal air blower, an orifice station for determining rate of airflow, and the test section, (Figure 8). In the first tests, each type of connection was tested separately. Air from the blower passed through a transition and a partitioned wooden conduit that represented the three passages of the proposed 3-barrelled draft tubes. It then entered the connection section, which was attached to a 9-inch-diameter sheet metal pipeline that represented the 35-foot-diameter tailrace tunnel. The upstream end of the tunnel was blocked off a short distance upstream from the draft tube connection, and air discharged freely into the atmosphere from the other end.

In the final tests four connecting sections of Design 1, and subsequently, four sections of Design 2, were assembled to represent the tunnel where Units 3, 4, 5, and 6 are attached, (Figure 9). A rectangular wooden manifold was attached to the discharge side of the air blower to receive and distribute the air evenly among the four 3-barrelled draft tubes. The velocities in the draft tube legs were balanced by placing suitable resistances (screens) across the entrances of the draft tube sections. Piezometers were placed at a number of places in the system to facilitate energy loss and pressure head measurements.

Tailrace Surge Studies--Hydraulic Model

The downstream portions of the 7.69-inch-inside-diameter plastic tunnels used in the diversion tests were re-used for the surge studies, (Figure 10). The tunnels were alined to represent the 80-foot spacing in the powerhouse region, and were set at the design elevations and slopes, (Figures 3 and 4). Bulkheads were provided at the appropriate stations to represent the tunnel plug face in Tunnel 1 and the outlet works bulkhead in Tunnel 2.

The straight sections of the tunnels had previously been shortened for the diversion tunnel studies to compensate for the greater equivalent friction of the model. The shortened tunnels were used without change in the tailrace studies.

The existing tailbox containing the tunnel outlet portals and downstream river channel was also used. The topography of the river channel had been built up with horizontal wooden templates cut to the contour shape of specific elevations and appropriately placed in the model, (Figure 11A). These templates were covered with expanded metal lath that was stretched to conform to the ridges and valleys of the hillsides. A 3/4-inch-thick layer of concrete was placed over the lath to produce the finished surfaces, (Figure 11B).

Additions to the model included a new water supply system to produce powerplant flows, a gate system for controlling flows through the draft tubes, the draft tubes, their connections to the tunnels, and the surge ports, (Figures 10, 11, and 12).

The water supply system consisted of a 6-inch portable pump, a standard laboratory orifice-venturi meter for measuring rate of flow, a control valve for regulating the discharge, and a baffled head box for receiving and quieting the flows, (Figure 12). Water flowed by gravity from this box to the manifold tank.

The manifold tank provided flows to the draft tube at a nearly constant head during load acceptances or rejections. It was constructed with an adjustable overflow weir for controlling head and slide gates for controlling flows into the draft tubes. The weir height was adjusted until the required discharge passed through the open draft tubes and the water surface in the manifold tank was at the level of the weir crest. Then in load rejection cycles when flow to one or more draft tubes was shut off, the excess water in the manifold tank spilled over the long weir. The slight rise in head on the 8-1/2-foot-long weir was insufficient to appreciably affect the flows continuing through the open draft tubes, and no shock loads were imposed on the system. In load acceptances, the weir was set so that the water surface was at the weir crest when the units were fully opened. The gates were then closed in preparation for the tests, and the excess water spilled over the weir until the gates were opened.

The gate control system consisted of a reversible motor, a speed selector, a reciprocating cam plate, and actuating arms, (Figures 11C and 12). The two slots on the cam plate were designed to give the turbines and pump turbines closing and opening times of 7 and 20 seconds, respectively. Three microswitches were positioned on the plate to signal the beginning and end of the effective slide gate movement over the draft tube opening, (Figure 11C). The first switch (lowest) signaled the start of the rejection cycle or the finish of the acceptance cycle of all units. The second switch signaled the completion of gate closure for the rejection cycle or the start of opening for the acceptance cycle for the turbines. The third switch (top) provided similar signals for the pump turbines.

The slide gates were operated by arms extending from two longitudinal shafts mounted in brackets on the manifold tank. The shafts were rotated by levers which held pins that extended into the cam plate slots. The "wicket gates" to be operated for a particular test were set by installing tapered pins through collars on the actuating rods, thereby fastening the gate arms to the shafts, (Figure 11C). Pins were removed from the arms of gates not used in the test, and the shafts rotated freely inside the collars.

Detailed model draft tubes were made of transparent plastic. These were fastened to the bottom of the manifold tank beneath the slide gates, and curved upward to receive straight sections that extended to the two tailrace tunnels, (Figures 4, 11C, and 11D). Straight, 90° connections without deflectors were used to join the draft tubes to the tunnels. Surge ports were provided through the bottom of Tunnel 2 into the draft tubes passing underneath. The air vent at the upstream end of Tunnel 1 was also provided.

Six piezometers were used to measure pressure conditions in the tunnels, (Figure 13). The piezometers were located at the plugs, immediately downstream from Draft Tube 6 in Tunnel 2, downstream from the horizontal bends in each tunnel, and immediately upstream from the outlet portal of Tunnel 2. Pressure cells were connected directly to these piezometers. Velocities and direction of flow were measured in both tunnels by calibrated, two-directional, cylindrical velocity tubes. These tubes, located a short distance downstream from the horizontal tunnel bends, were coupled to sensitive differential pressure cells to obtain the instantaneous velocity changes. A six-channel and a two-channel recorder were used to simultaneously record pressures from the cells on the six piezometers and the two velocity tubes. The data traces showed the transient pressures and water surfaces in the tunnels, the transient velocities and directions of flow, the start and finish of gate movements, and a repeating 1-second time pip. A complete data chart for a load rejection cycle is shown in Figure 14.

INVESTIGATION

Draft Tube Connection Studies

Design 1 of the draft tube connections entered the tunnel at a 90° angle. No turning occurred in the draft tube barrels and no deflectors were provided in the tunnel, (Figures 7A and 8). Designs 2 and 3 provided downstream curvature in the draft tube barrels and turning vanes that extended into the tunnel, (Figures 7 and 8). The intersection angles averaged 52° for Design 2 and were 60° for Design 3.

Tests showed that the average energy losses for Designs 1 and 3, measured between a station in the draft tube barrels 1.13 times the barrel height upstream from the tunnel to a station in the tunnel 17.0 diameters downstream from the draft tube centerline, were about 0.95 times the velocity head in the barrels, (Figure 15). Design 2 produced a smaller loss factor of 0.70 and more stable flow conditions than the other designs.

The tests were made over a range of Reynolds number values, $R = \frac{Vd}{\nu}$, from 0.54×10^5 to 3.12×10^5. No significant effect on losses was noted.

More extensive tests were made to determine the losses and pressure distributions that occurred with several draft tubes discharging into the tunnel. Four connection sections of Design 1 were assembled and tested in the model tunnel, (Figures 9A and 16). Similarly, four sections of the Design 2 connections were assembled and tested.

Results showed that for the four section installation, the average overall losses were 1.57 and 1.47 times the draft tube velocity head for Designs 1 and 2, respectively, (Figure 16A and 16B). Thus, there was only a minor advantage in favor of the more complex 60° design with the large turning vanes.

A difference in the pressure conditions was noted within the individual barrels of the two designs, (Figure 16). In Design 1, essentially equal pressures occurred in each of the three barrels of the upstream draft tube. But as the flow moved downstream through the tunnel, it tended to block the flow issuing from the first barrel of the subsequent draft tube. As a result, a higher piezometric pressure was required in this first barrel to move its flow into the tunnel and to provide a regime suitable for the discharge of the other two barrels. Similarly, when the flows from the first two draft tubes combined and approached the third draft tube, and then again when they approached the fourth draft tube, the interference was repeated on progressively larger scales.

In Design 2, the action was different. The large guide vanes preceding the first barrels of the draft tubes deflected the tunnel flows so all draft tube barrels could easily discharge their flows into the tunnel. No large pressure differentials were created in the separate barrels of the tubes and a more uniform pressure pattern existed. Unfortunately, the large guide vanes of the 60° connections restricted the available flow area through the tunnels and, in the four abreast installations, produced losses which largely negate other advantages. The high construction costs of the curved 60° connections were not believed justified on the basis of the small reduction in losses. Therefore, the simpler and less expensive 90° connections were recommended for prototype use.

Pressure distributions and head loss factors for Design 1 connections in assemblies of 1, 2, 3, and 4 draft tubes discharging into a single tunnel are presented in Figure 17.

During pumping operations with the pump turbine units, flow will move from the tunnels into the draft tubes. Energy losses in this direction will affect the pumping operations, but the flow velocities will be so low that the losses are negligible. At the request of the California Department of Water Resources, no tests were made to represent these pumping conditions.

Tailrace Surge Studies

A summary of the test runs made in the tailrace surge studies is presented in Tables 1 and 2. Test variables consisted of the number of operating units, length of time of the load acceptance or rejection cycles, discharge, and tailwater elevation.

Tests were made by setting the desired rate of flow, adjusting the manifold tank weir to the proper height, adjusting the tailwater to the proper elevation, and setting the number and operating time of the gates. After sufficient time had elapsed to obtain stabilized flow, the rejection or acceptance cycle was started by operating the gate control system. Transient pressure and velocity conditions in the tunnels were recorded by the electronic recording equipment and photographs were taken. After a test had been satisfactorily completed, new conditions were set and another test started.

Difficulty was experienced in duplicating prototype tailwater conditions because the model tailbox was much smaller, relatively, than the afterbay of the prototype. Thus, it tended to respond to changes of inflow much more rapidly than the prototype will. To obtain acceptable test conditions it was necessary to adjust the tailgate of the model as the discharge changed to maintain the desired water surface elevations. In the case of rejection tests, it was also necessary to supply water to the tailbox through a hose to replace water that leaked past the tailgate assembly. Reasonably accurate results were obtained after the technique was developed, and all tests reported herein were made in this manner.

Rejection Tests

The most significant load rejection tests were run at the maximum initial discharge of 16,500 cubic feet per second, Table 1, (Figure 5). The normal tailwater elevation for this flow was 226.5. Tailwater elevations between 215.0 and 239.0 were also tested. In Tunnel 2 the maximum water surface drawdown from the initial steady running condition occurred in Tests 17 and 18 when the tailwater was lowered 7 and 12 feet below normal, respectively. The drawdown at the outlet works bulkhead was 15 feet, but the water surface did not fall low enough to allow entry of air at the surge ports. The surges damped out in about 35 minutes, prototype.

As the tailwater was increased, the velocity of the surges increased slightly, and, because the effective friction became less, the time required for damping the surges also increased. At the maximum tested tailwater elevation of 239.0, slight surging was still evident 42 minutes after the rejection.

"Topping out" occurred in Tunnel 1 when the tailwater was raised 13 feet above normal, (Test 15). The "topping out" was accompanied by severe shock waves that exceeded the sensitivity capacity of the instruments used for recording transient conditions. The above action was similar to that shown in Figure 18.

At all lower tailwater elevations the surges and waves created by even the severest rejection cycles were within acceptable design limits. Similarly, the surges and waves created by less severe rejection cycles were within acceptable limits. Thus, the overtaking surges and continually changing wave patterns mentioned by the designers and quoted in the introduction, and the simplifying assumptions, were satisfactorily solved in the analytical phases of the design study.

Acceptance Tests

Heavy load acceptances accomplished in time periods measured in seconds rather than minutes are unusual, or even unlikely, in large hydroelectric plants. Nevertheless, to determine the behavior of the tailrace system under such adverse conditions, tests were made with the model, (Table 2).

When full load at critical head was accepted by all units at the very high rates of 7 seconds for the turbines and 20 seconds for the pump turbines (Test 1), the initial upsurge filled the upstream end of Tunnel 1 and "topped out" into the air vent, (Figure 18). Tunnel 1 also topped out when all the units were brought onto the line in 1 minute, (Test 6). The normal tailwater elevations of 226.5 were used in the tests.

A heavy shock occurred in the model when the tunnel filled. This action was sensed by the pressure cell at the bulkhead and was recorded by the chart recorder, (Figure 18B). The full magnitude of the shock is not shown on the chart because it exceeded the physical limits of the pen travel at the recorder sensitivity used.

"Topping out" did not occur during a consecutive loading on all units with a rate of 1 unit per minute (Test 5), or when the three pump turbines were in steady flow and the turbines were put on in 7 seconds, (Tests 3, 4, and 7). Normal tailwater elevations were used in these tests.

The initial surge moved downstream in Tunnel 2 with a pronounced front when loads were accepted rapidly by all units, (Figure 6). This action created a large wave in the river channel downstream from the portal. Steady flow was established in the tunnels in about 5.5 minutes (prototype) after the "wicket" gates were opened.

Comparison of Model and Analytical Data

An analysis of the model data was made by the California engineers and checked by the Bureau of Reclamation. The essential parts of the analysis are quoted from the Department of Water Resouces' informal report entitled "Comparison of Analytical and Model Data." The computations are contained in the Appendix and the original model data is generally similar to that presented in Figure 14.

> "Similitude of both Froude and Reynold's numbers could not each (both) be attained in the model since water was used in both model and prototype, nor could the model be distorted without affecting the magnitude and period of the surges in the submerged tunnel. * * * However, a prediction factor for roughness, developed from the steady state conditions in the model, has been applied to the model data. As may be seen in Figure 19A, the model curve shows excellent correlation with the analytical curve during the first half cycle; but the model indicates considerably less upsurge in the following half cycle. This was to be expected for the analytical approach did not account for velocity head at the portal nor friction in the upper tailrace. The effects of these assumptions would not appear until the second half of the first cycle. Also, and most important, the tailwater in the model dropped from elevation 226.5 at the start of

the test to elevation 225.0 very rapidly, while in the computations the tailwater was assumed to remain constant. * * * As may be seen in Figure 19B, representing the velocity versus time in the submerged tunnel, the model and analytical curves show very close agreement. The velocity time curves for the open channel (Figure 19C) show some agreement in the first half cycle, but thereafter the agreement is in shape only. This again reflects the effects of the assumptions which were necessary for the solution of the wave action in this tunnel and shows they are indeed conservative. The velocity tap 1,000 feet from the portal was used for the model curve, for there is no velocity tap representing the other curve shown on Figure 3. As an additional check it would be desirable to have a velocity tap located at Station 1+55.01 in the open channel tailrace for the rerun of Test No. 9 with constant tailwater. * * *"

General Conclusion

The tests showed that satisfactory conditions would prevail in the powerplant tailrace system under even the most extreme load rejections or acceptances theoretically possible. This conclusion substantiates the one reached by the design engineers through their analytical studies.

APPENDIX

Determination of Model-prototype Time Relationship:6/

For models where the Froude relation prevails,

$$\frac{T_p}{T_m} = \left(\frac{L_p}{L_m}\right)^{\frac{1}{2}}$$

On this basis, $T_p = T_m\ (54.63)^{\frac{1}{2}}$
$T_p = T_m\ (7.40)$ for the Oroville tests;

where T equals time, L equals length, and the subscripts p and m refer to prototype and model.

However, considerable disparity exists between the expected prototype conduit friction and the friction represented by the model. In the model, even though extremely smooth and well alined conduit surfaces were used, the friction was higher than it should be to represent prototype conditions.

Using an "n" value of 0.014 for the prototype, and the relation

$$n_p = n_m\left(\frac{1}{L}\right)^{\frac{1}{6}}$$

the model friction value required for accurate representation should be $n_m' = 0.014\left(\frac{1}{1.95}\right)$

$n_m' = 0.007.$

The actual model friction, determined from steady state flow conditions was

$$n_m = 0.011 \text{ (including bend and exit losses)}$$

Based on the observed model roughness and the relation

$$T' = T_m\left(\frac{n_m}{n_m'}\right) = 7.40\left(\frac{0.007}{0.011}\right)$$

$$T_1 = 4.7$$

that is, 1 second on the model equals 4.7 seconds, prototype.

Refinements can be made to these computations, but they are believed sufficiently accurate for their purpose. Thus, the time scale of 4.7 was used for the data presented in Figure 19. Standard Froude scaling was used for the water surface elevations, pressures, etc., because the model, in all major aspects except roughness, was a true Froude model for Tunnel 1.

Table 1

LOAD REJECTION TESTS

Test No.	Initial condition		Final condition		Remarks
	Draft (cfs)	Tailwater elevation (feet)	Draft (cfs)	Tailwater elevation (feet)	
9	16, 500	226.5	0	225.0	3 turbines off in 7 seconds, 3 pump turbines off in 20 seconds
9A	16, 500	226.5	0	226.5	Same as Test No. 9
10	16, 500	229.6	0	227.5	Same as Test No. 9
11	16, 500	226.5	0	225.0	All units off in 7 seconds
12	16, 500	229.6	0	226.5	Same as Test No. 11
13	13, 200	226.0	10, 700	225.7	1 turbine unit off in 1.0 minute gate time--Determine period of tailrace instability
14	12, 000	239.0	0	237.0	Determine maximum at which "topping out" will occur on return surge, normal timing
15	16, 500	239.0	0	237.0	Same as Test No. 14
17	16, 500	220	0	218.5	All units off--7 seconds for turbines, 20 seconds for P-T
18	16, 500	215	0	213.5	Same as Test No. 17
19	16, 500	214	0	232.5	Same as Test No. 17

Table 2

LOAD ACCEPTANCE TESTS

Test No.	Initial condition: Draft (cfs)	Initial condition: Tailwater elevation (feet)	Final condition: Draft (cfs)	Final condition: Tailwater elevation (feet)	Remarks
1	0	225.0	16,500	226.5	3 turbines on in 7 seconds, 3 pump turbines on in 20 seconds
2	0	226.5	16,500	229.6	Same as Test No. 1
3	7,500	225.3	16,500	226.5	3 pump turbines in steady state flow of 7,500--3 turbines on in 7 seconds
4	7,500	227.9	16,500	229.6	Same as Test No. 3
5	0	226.5	16,500	229.6	Consecutive loading (1.0 minute prototype gate time) of units in order 2-4-6-1-3-5
6	0	226.5	16,500	229.6	All units full on in 1.0 minute
7	7,500	229.5	16,500	230.8	Determine maximum initial and final tailwater elevations that will not cause "topping out" for loading required in Test No. 3
8	5,250	232.5	12,000	233.5	Same as Test No. 7
16	5,250	238.0	12,000	238.8	3 turbines on in 7 seconds, 3 pump turbines on initially steady

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2. "Hydraulic Model Studies of the Spillway for Oroville Dam," Laboratory Report Hyd. 510, 1963, by T. J. Rhone.

3. "Hydraulic Model Studies of the Outlet Works for Oroville Dam," Laboratory Report Hyd. 508, 1963, by Donald Colgate.

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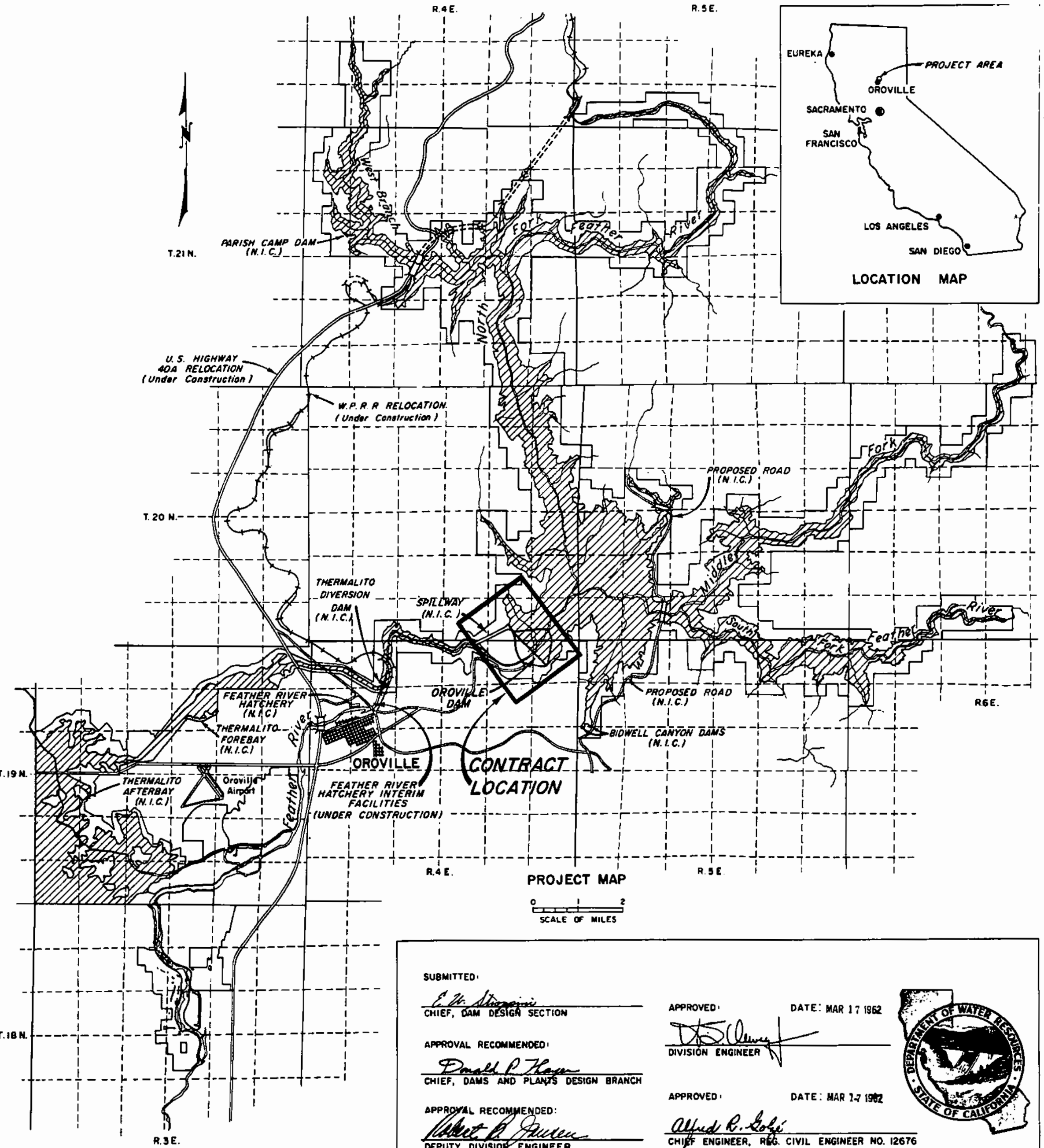
5. "Model Tests Using Low Velocity Air," by J. W. Ball. Paper No. 2517, Transactions, ASCE, Volume 117, 1952.

6. "Similitude in Engineering" by Glenn Murphy, The Ronald Press Company, 1960.



SUBMITTED:
CHIEF, DAM DESIGN SECTION

APPROVAL RECOMMENDED:
CHIEF, DAMS AND PLANTS DESIGN BRANCH

APPROVAL RECOMMENDED:
DEPUTY DIVISION ENGINEER

APPROVED: DATE: MAR 17 1962
DIVISION ENGINEER

APPROVED: DATE: MAR 17 1962
CHIEF ENGINEER, REG. CIVIL ENGINEER NO. 12676

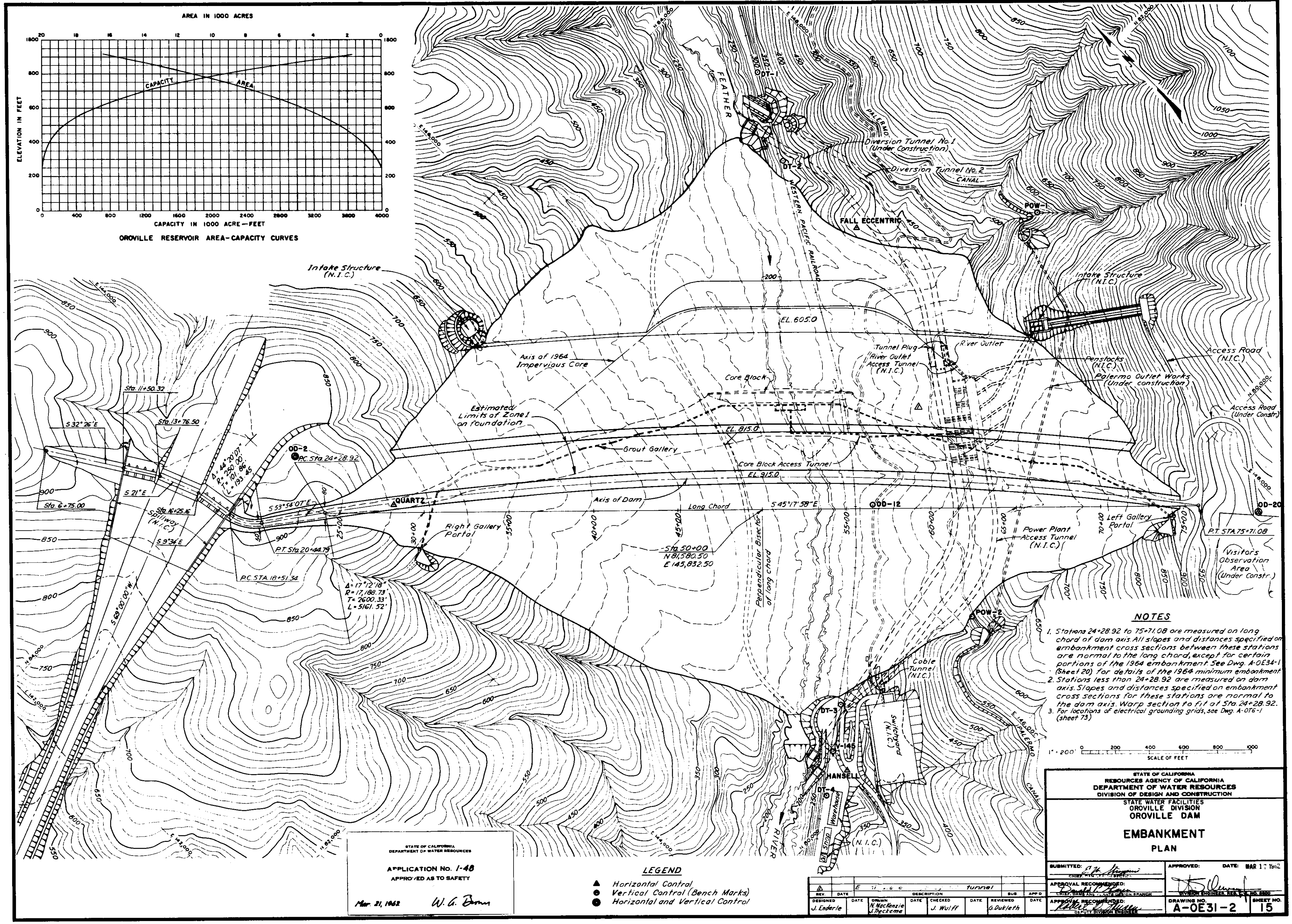
DEPARTMENT OF WATER RESOURCES STATE OF CALIFORNIA

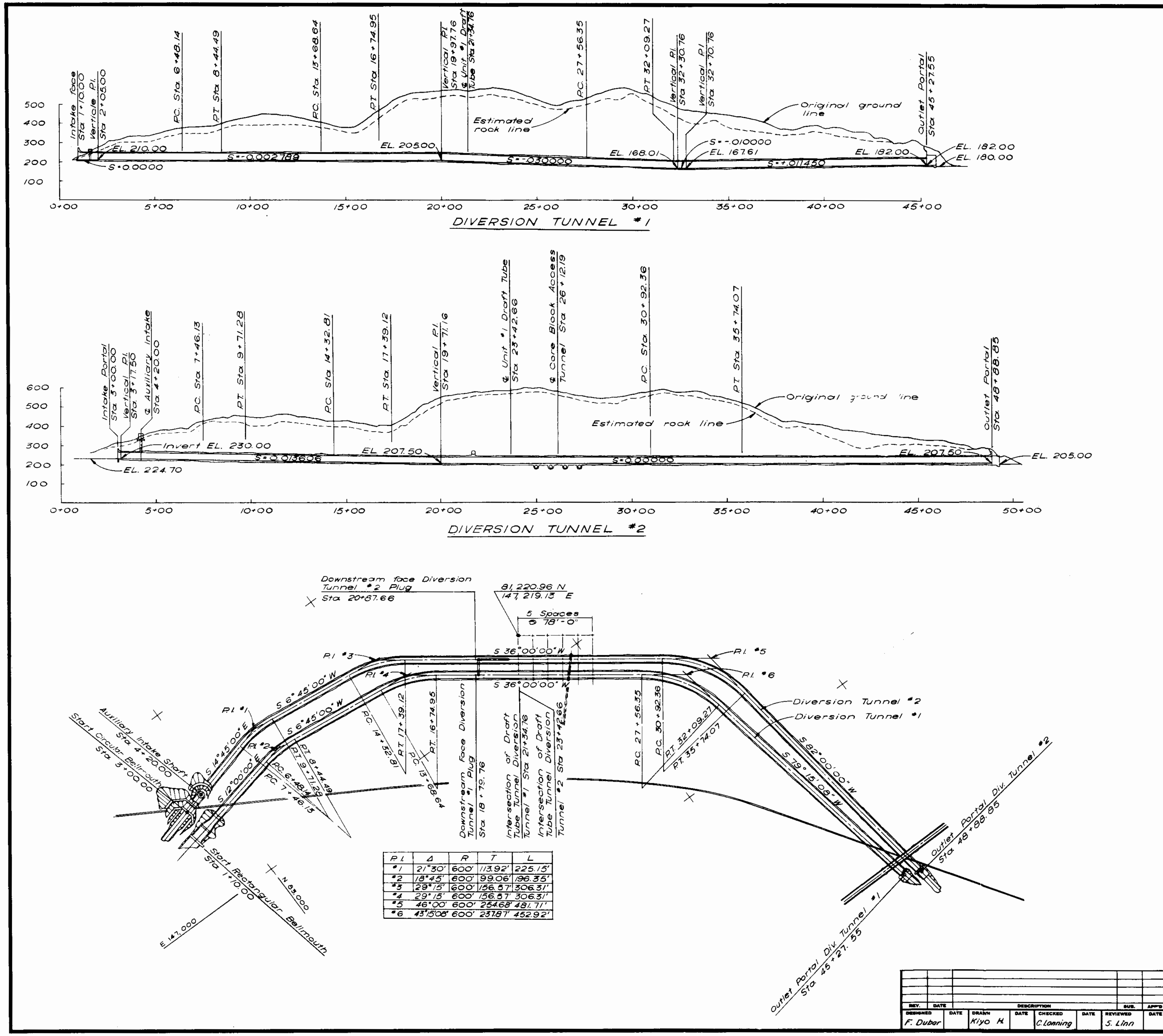
OROVILLE DAM

DRAFT TUBE AND TAILRACE STUDIES

LOCATION MAP

FIGURE 2
REPORT HYD. 507





P.I.	Δ	R	T	L
#1	21°30'	600'	113.92'	225.15'
#2	18°45'	600'	99.06'	196.35'
#3	29°15'	600'	156.57'	306.31'
#4	29°15'	600'	156.57'	306.31'
#5	46°00'	600'	254.68'	481.71'
#6	43°15'08"	600'	237.87'	452.92'

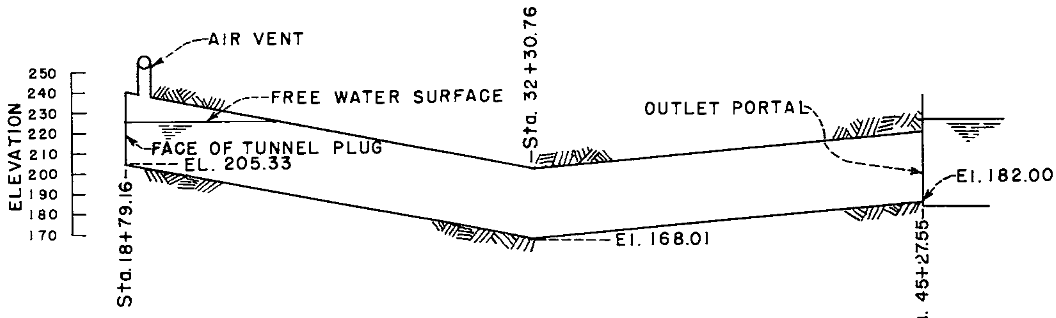
STATE OF CALIFORNIA
RESOURCES AGENCY OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF DESIGN AND CONSTRUCTION

STATE WATER FACILITIES
OROVILLE DIVISION
OROVILLE DAM

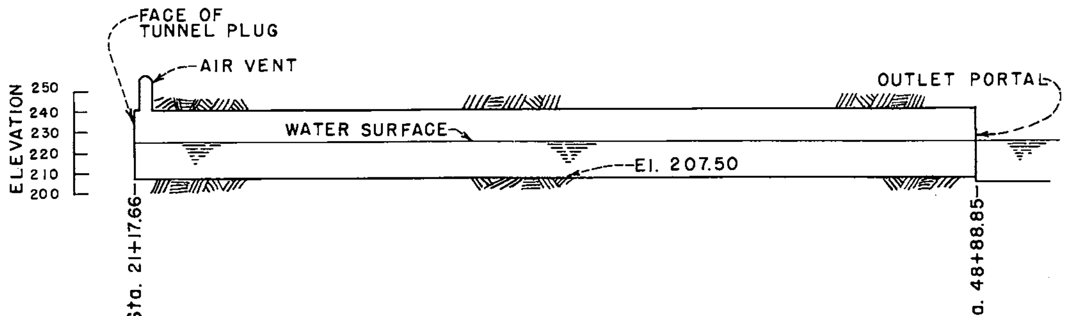
DIVERSION TUNNEL MODEL STUDIES
PLAN AND PROFILE

DESIGNED	DATE	DRAWN	DATE	CHECKED	DATE	REVIEWED	DATE
F. Dubor		Kiyo H.		C. Lonning		S. Linn	

SUBMITTED: CHIEF, DAM DESIGN SECTION
APPROVAL RECOMMENDED:
APPROVED: DATE: JAN 18 1963
DRAWING NO. A-OD16-1
SHEET NO.



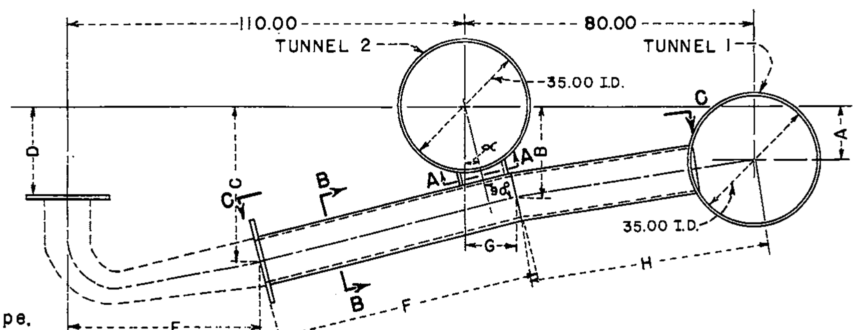
A. PROFILE OF TUNNEL 1



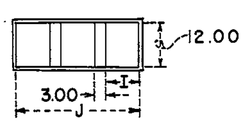
B. PROFILE OF TUNNEL 2

	UNIT 3	UNIT 4	UNIT 5	UNIT 6
A	12.10	14.50	16.90	19.30
B	24.86	24.26	24.86	24.26
C	42.66	38.86	42.66	38.86
D	24.00	23.39	24.00	23.39
E	53.54	63.96	63.54	63.96
F	72.98	63.28	72.98	63.28
G	14.34	15.52	14.34	15.52
H	66.51	64.92	65.97	64.81
I	9.50	7.50	9.50	7.50
J	34.42	28.50	34.42	28.50
α	14°7'	13°19'	14°7'	13°19'
R_f	1.20	1.00	1.20	1.00

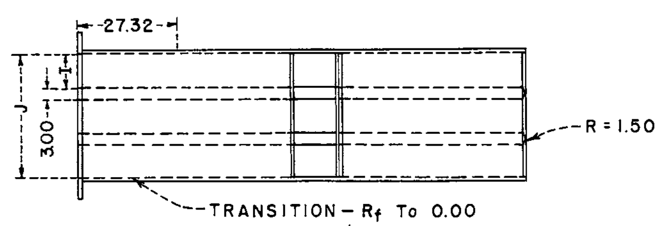
NOTE:
All dimensions in feet, prototype.



ELEVATION



SECTION A-A AND B-B
(Surge ports and draft tubes)



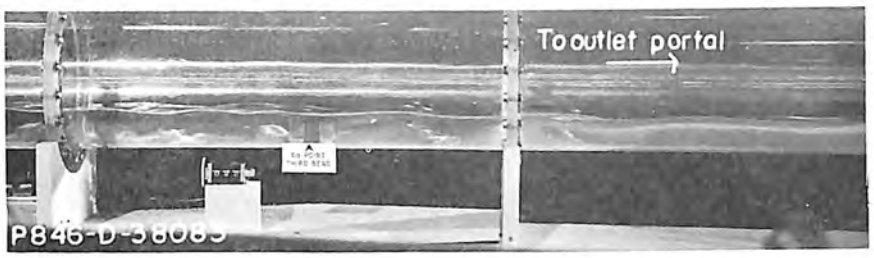
SECTION C-C

C. DRAFT TUBE EXTENSIONS AND SURGE PORTS
UNITS 3, 4, 5, AND 6

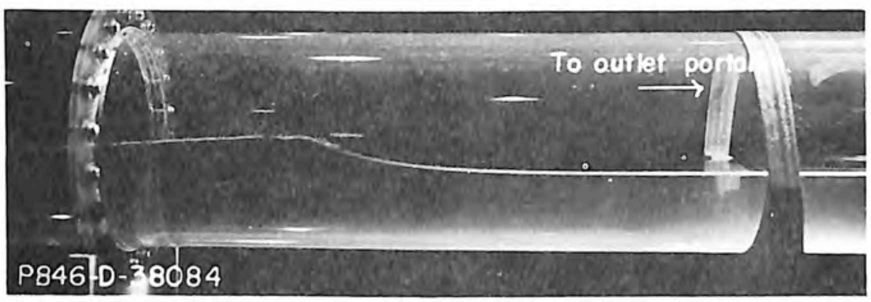
OROVILLE DAM
DRAFT TUBE AND TAILRACE STUDIES
TUNNEL AND DRAFT TUBE PROFILES
1:54.63 SCALE MODEL

642

A. Dye shows flow of water from Tunnel 1 into Tunnel 2 through the draft tubes and surge ports 2.46 minutes after rejection.



B. Wave fronts advancing from surge ports and outlet portals collided in horizontal bend after 2.71 minutes.



C. Reflected wave from collision moved downstream past Station 44+50, 4.07 minutes after rejection.

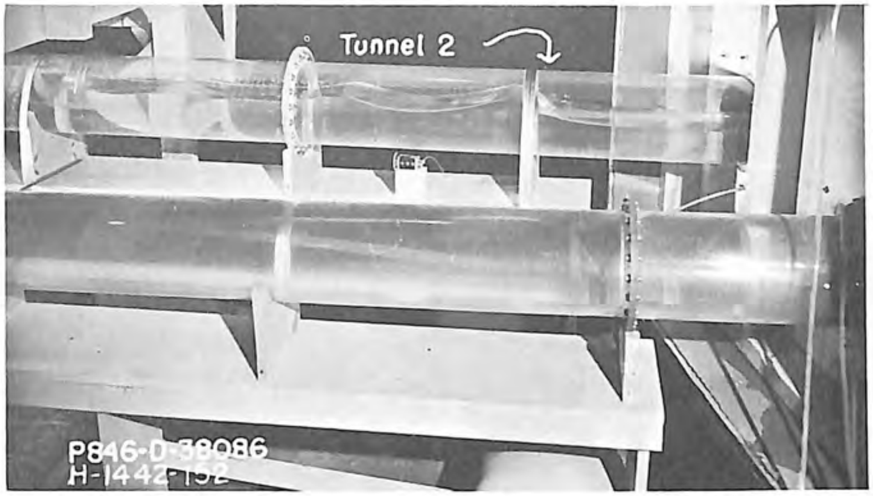
D. Reflected wave from collision passed through outlet portal 4.55 minutes after rejection.

Q_1 = 16, 500 TW_1 = 226.5 Q_2 = 0 TW_2 = 225.0

Turbines off in 7 seconds--pump turbines off in 20 seconds

OROVILLE DAM
DRAFT TUBE AND TAILRACE STUDY

Surges in Tunnel 2--Rejection Cycle
1:54.63 Scale Model



A. Advancing wave front moved past Station 40+87, 1.60 minutes after acceptance.

B. Advancing wave front emerged from portal 1.85 minutes after acceptance.

$Q_1 = 0$ $TW_1 = 225.0$ $Q_2 = 16,500$ $TW_2 = 226.5$
Turbines on in 7 seconds--pump turbines on in 20 seconds

OROVILLE DAM
DRAFT TUBE AND TAILRACE STUDIES

Surges in Tunnel 2--Load Acceptance
1:54.63 Scale Model

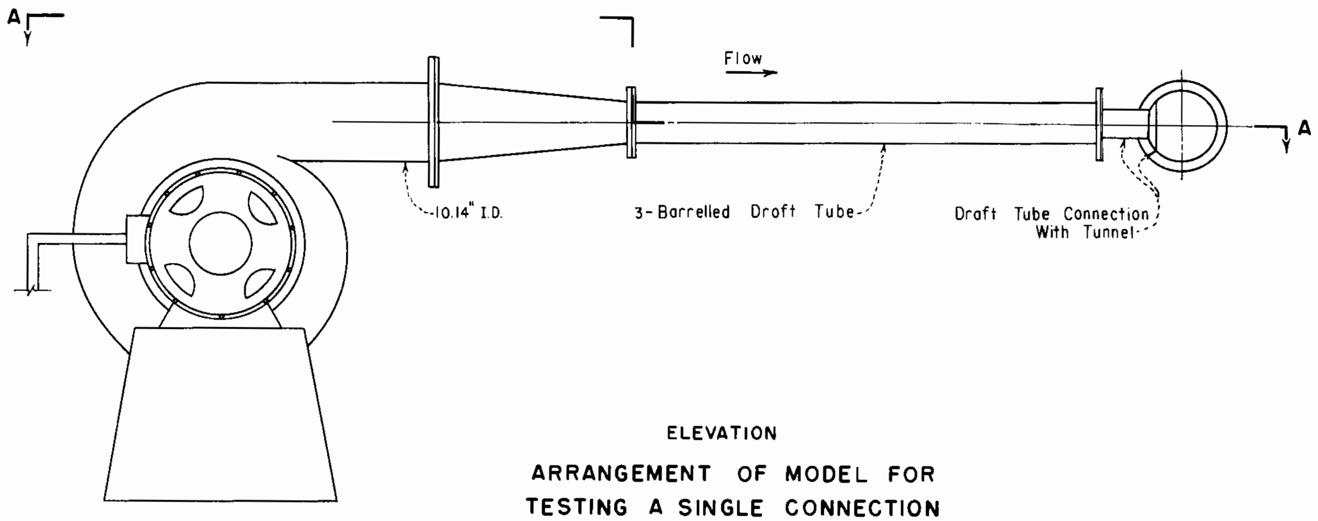
A. Design 1.--No turning in draft tube barrels.

B. Design 2.--48°, 38°, and 28° turning in barrels.

C. Design 3.--30° turning in barrels.

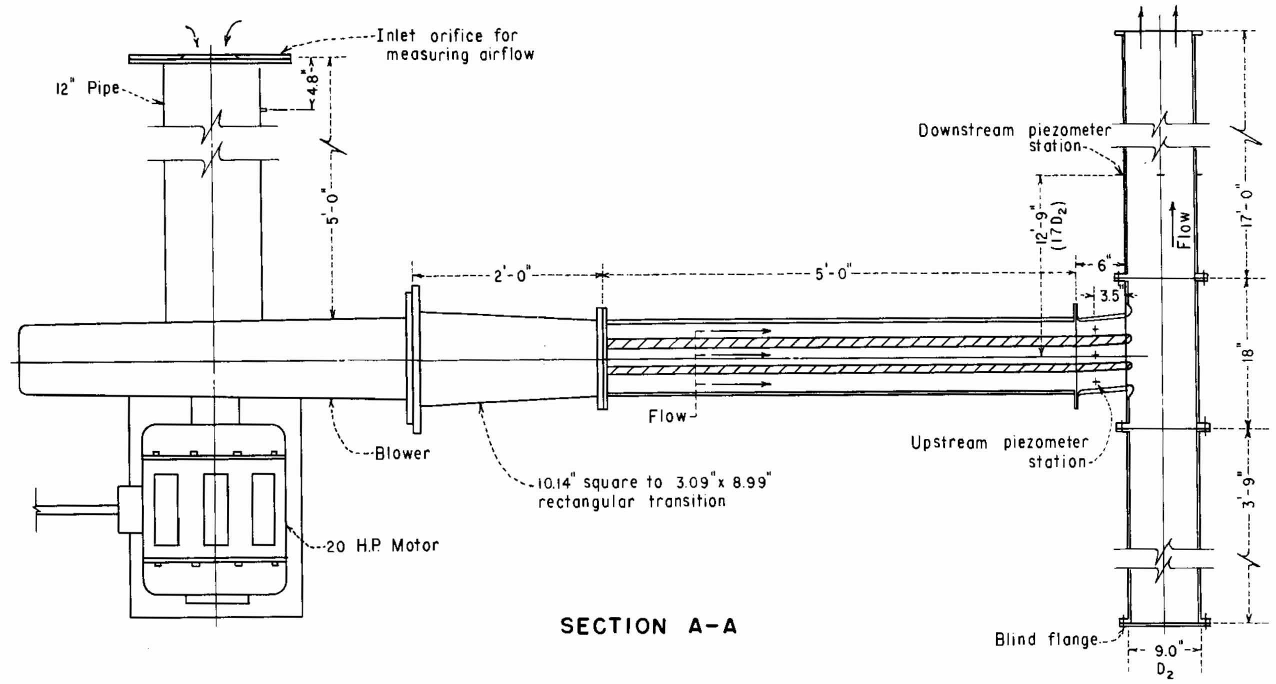
OROVILLE DAM
DRAFT TUBE AND TAILRACE STUDIES

Draft Tube Connections to Tunnels
1:46.67 Air Model

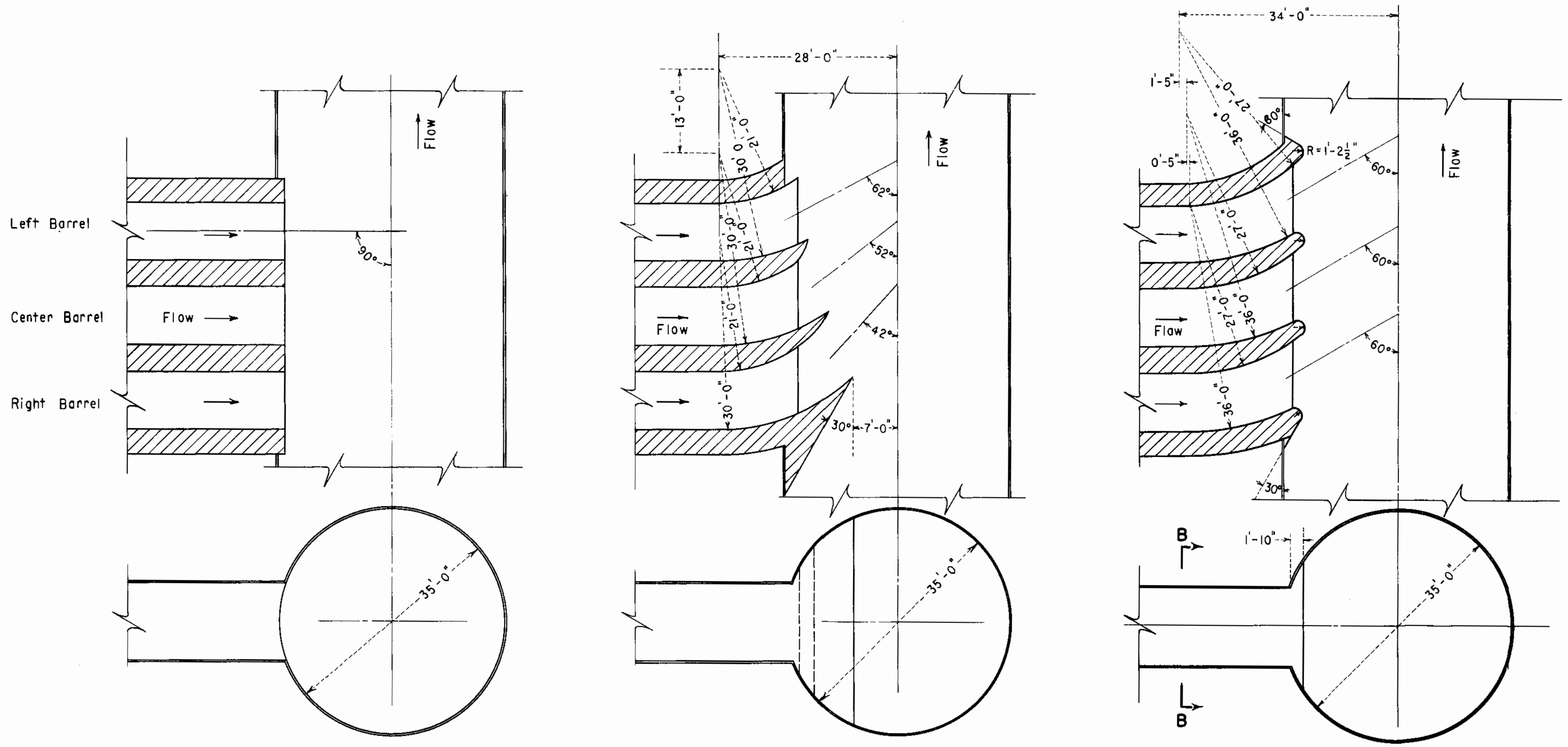


ELEVATION

ARRANGEMENT OF MODEL FOR TESTING A SINGLE CONNECTION
MODEL DIMENSIONS

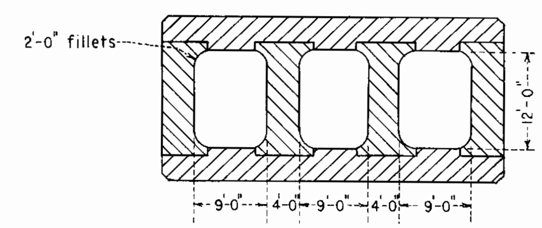


SECTION A-A



DESIGN 1 DESIGN 2 DESIGN 3

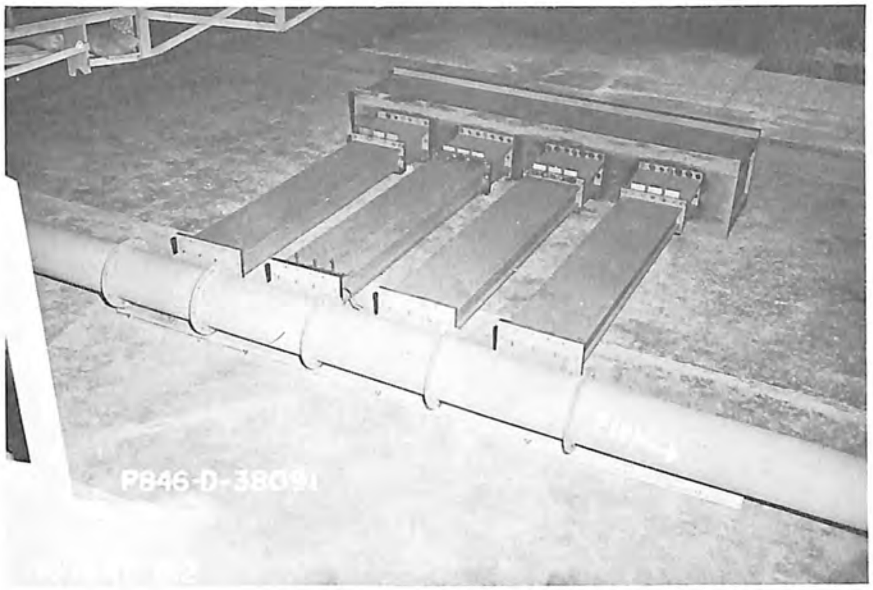
DRAFT TUBE CONNECTIONS
PROTOTYPE DIMENSIONS



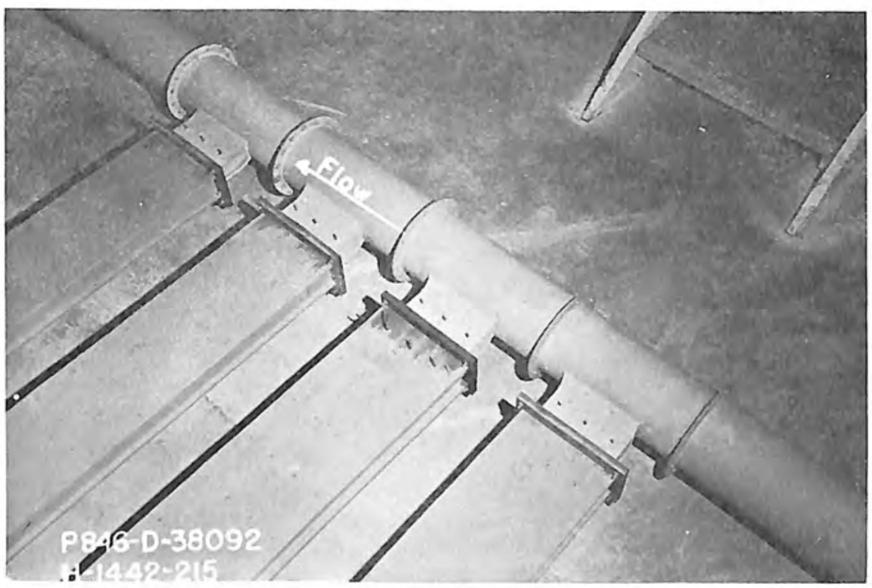
SECTION B-B
TYPICAL

OROVILLE DAM
DRAFT TUBE AND TAILRACE STUDIES
AIR MODEL FOR DRAFT TUBE CONNECTION STUDIES AND CONNECTION GEOMETRIES
1:46.67 SCALE MODEL

642



A. Air from pump entered manifold distribution box, then passed through transitions into the 3-barreled draft tubes to the tunnel connection sections.



B. Flow passed through the connection sections into the tunnel.

OROVILLE DAM
DRAFT TUBE AND TAILRACE STUDIES

Four Draft Tube Connection Assembly--Design 2
1:46.67 Air Model

Figure 10
Report Hyd. 507

A. Overall view looking downstream to river channel.

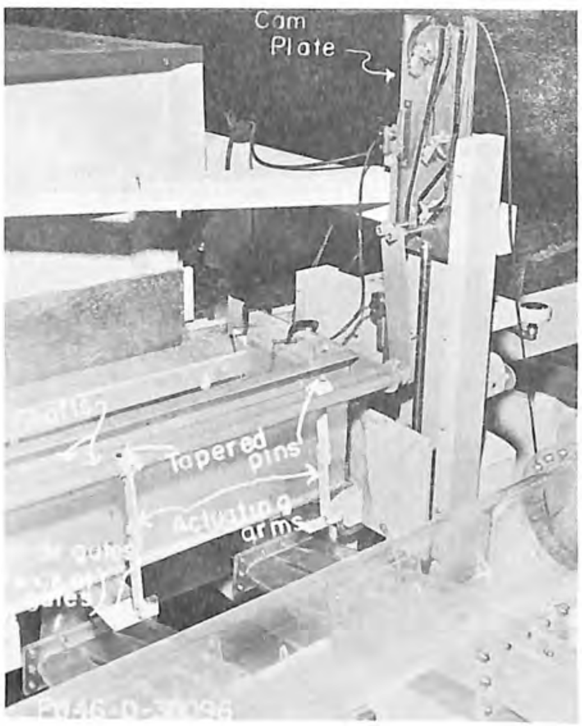
B. Headbox, manifold tank, gate control, weirbox and tailrace tunnels.

OROVILLE DAM
DRAFT TUBE AND TAILRACE STUDIES

Overall Views of the Hydraulic Model
1:54.63 Scale Model

A. River channel during construction.

B. Completed river channel and tunnel outlet portals

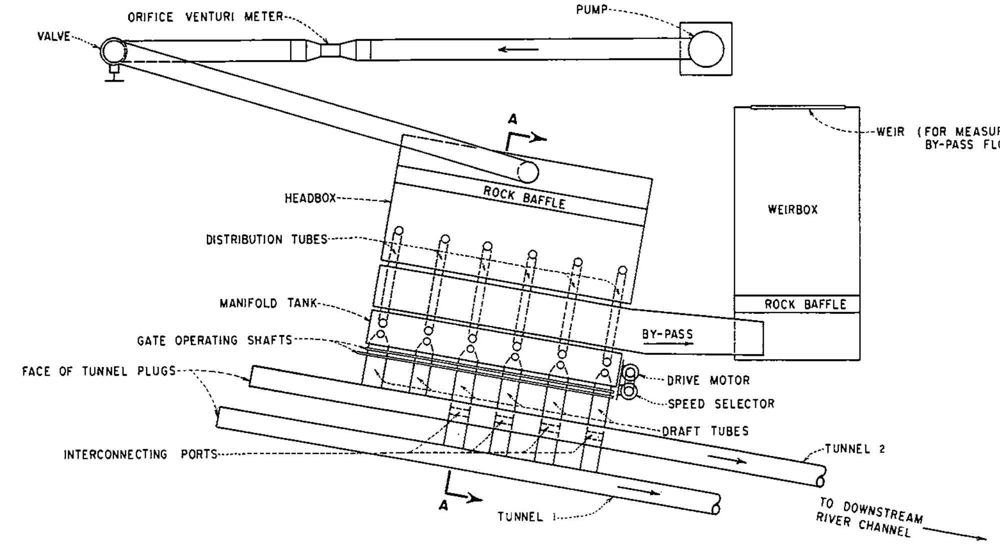


C. Motor-operated cam, with actuating arms, slide gates and draft tubes.

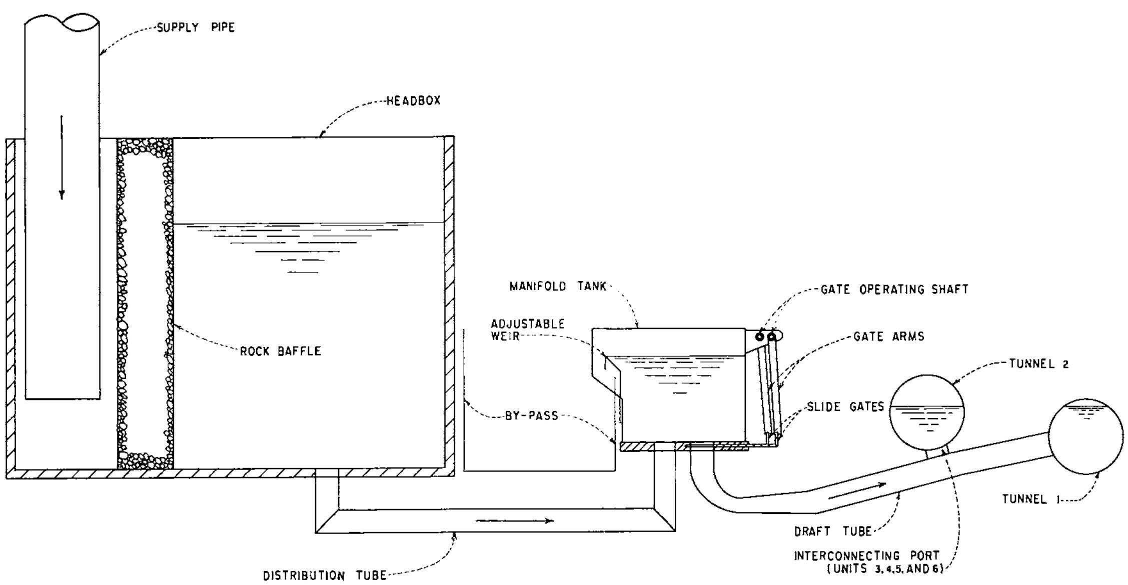
D. Manifold tank, draft tubes and tailrace tunnels. Note surge ports in invert of Tunnel 2.

OROVILLE DAM
DRAFT TUBE AND TAILRACE STUDIES

Detailed Views of the Hydraulic Model
1:54.63 Scale Model



PLAN

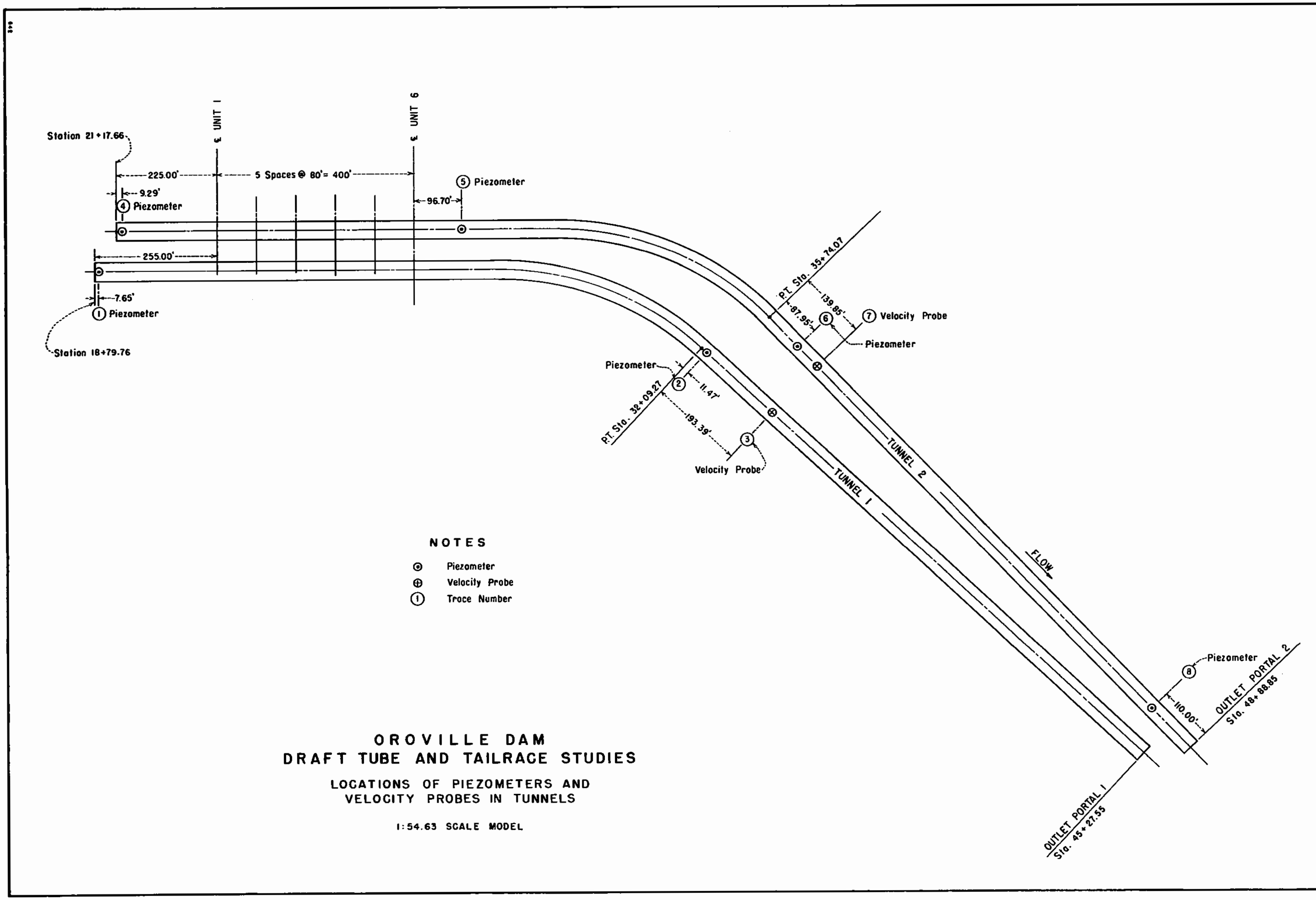


SECTION A-A

OROVILLE DAM
DRAFT TUBE AND TAILRACE STUDIES
SCHEMATIC VIEWS OF LABORATORY TEST COMPLEX

1:54.63 SCALE MODEL

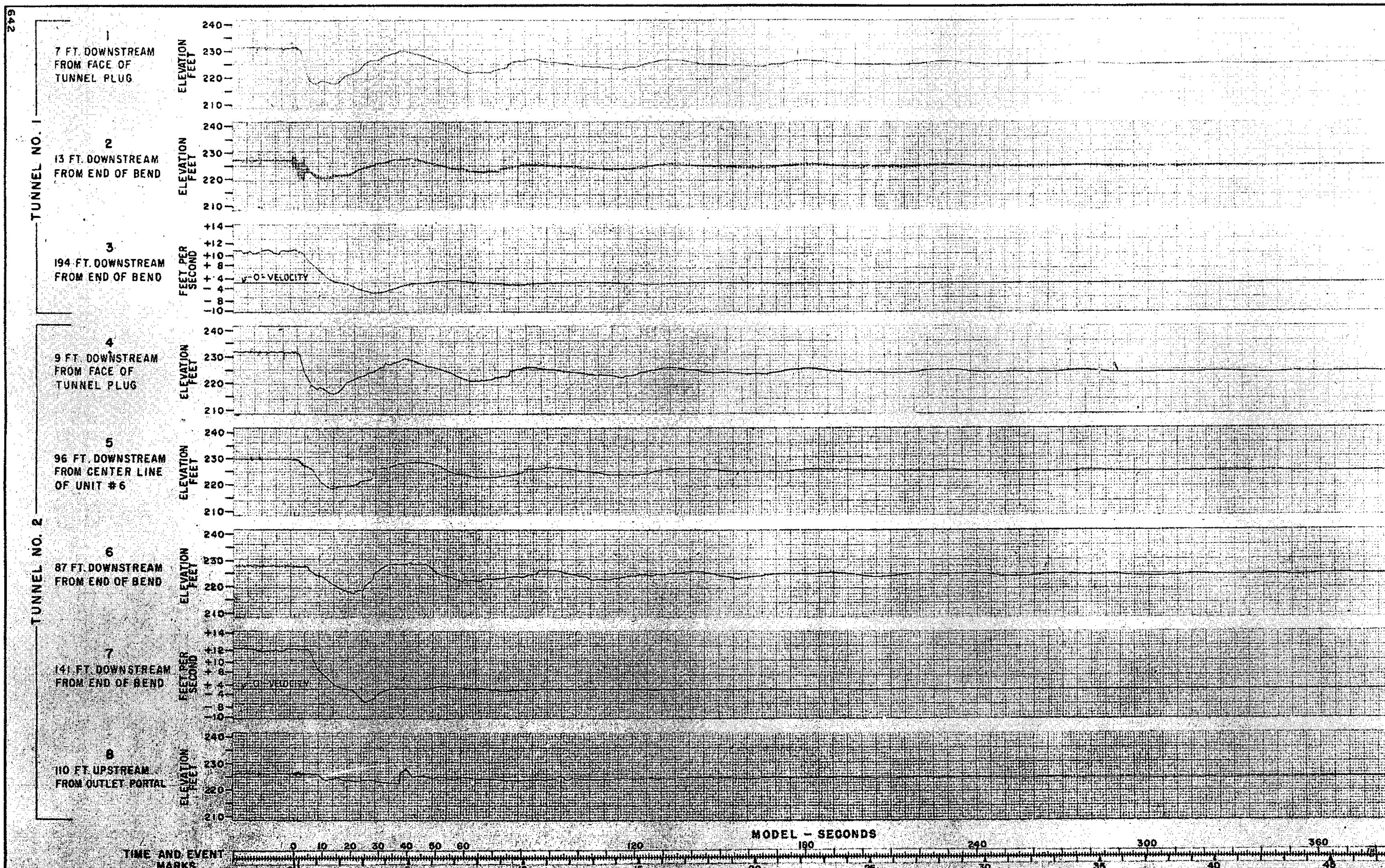
642



OROVILLE DAM
DRAFT TUBE AND TAILRACE STUDIES

LOCATIONS OF PIEZOMETERS AND
VELOCITY PROBES IN TUNNELS

1:54.63 SCALE MODEL

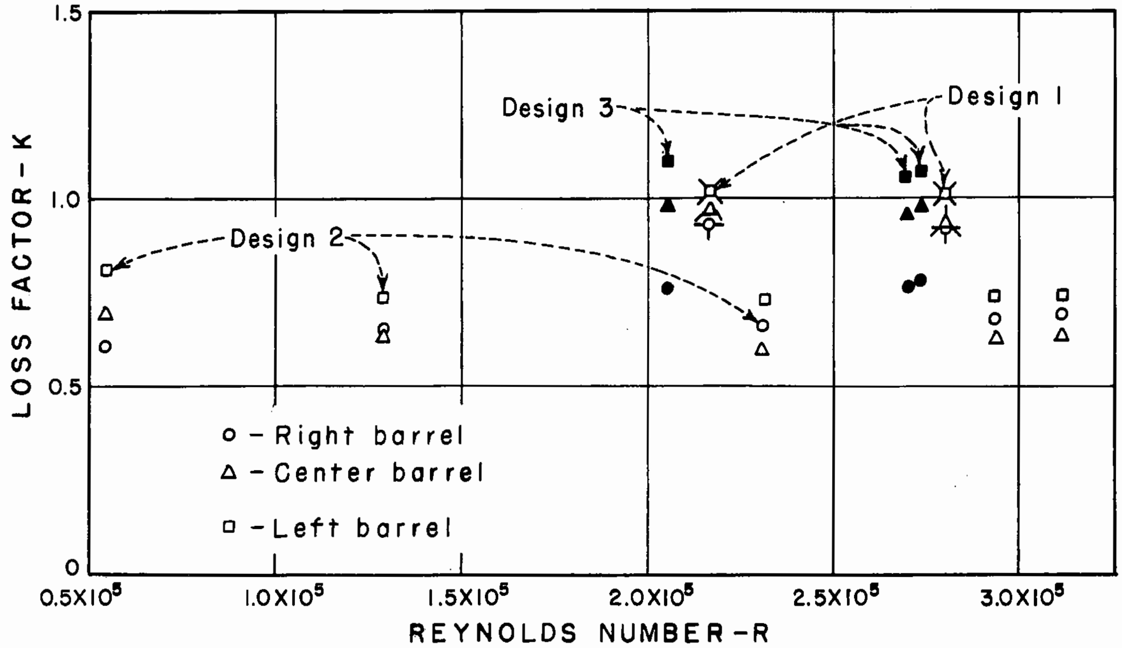


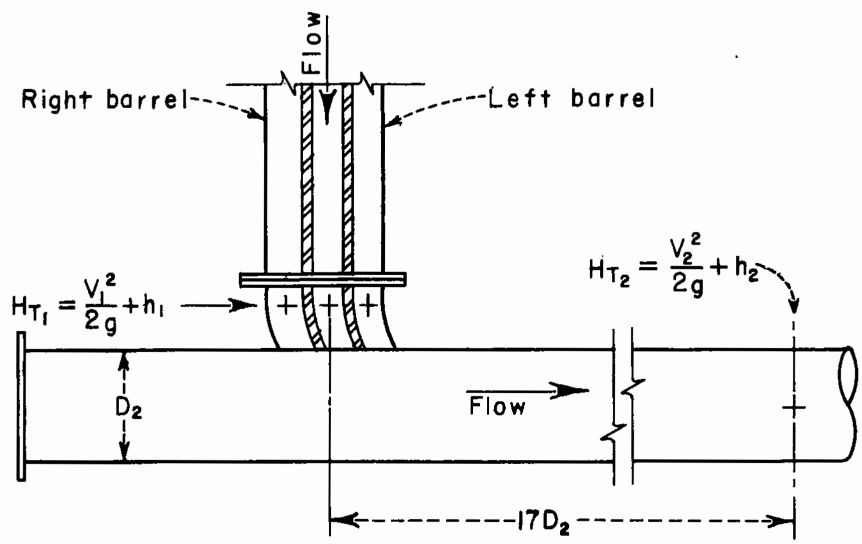
① START OF CLOSURE OF ALL UNITS
② CLOSURE COMPLETED FOR ALL UNITS

OROVILLE DAM - DRAFT TUBE AND TAILRACE STUDIES
DATA TRACES FROM LOAD REJECTION TEST NO. 11

Q INITIAL = 16,500 CFS   Q FINAL = 0 CFS   T.W. EL. INITIAL = 226.5   T.W. EL. FINAL = 225.0   ALL UNITS OFF IN 7 SECONDS

DATA FROM 1:54.63 SCALE MODEL





$$K = \frac{H_{T_1} - H_{T_2}}{\frac{V_1^2}{2g}}$$

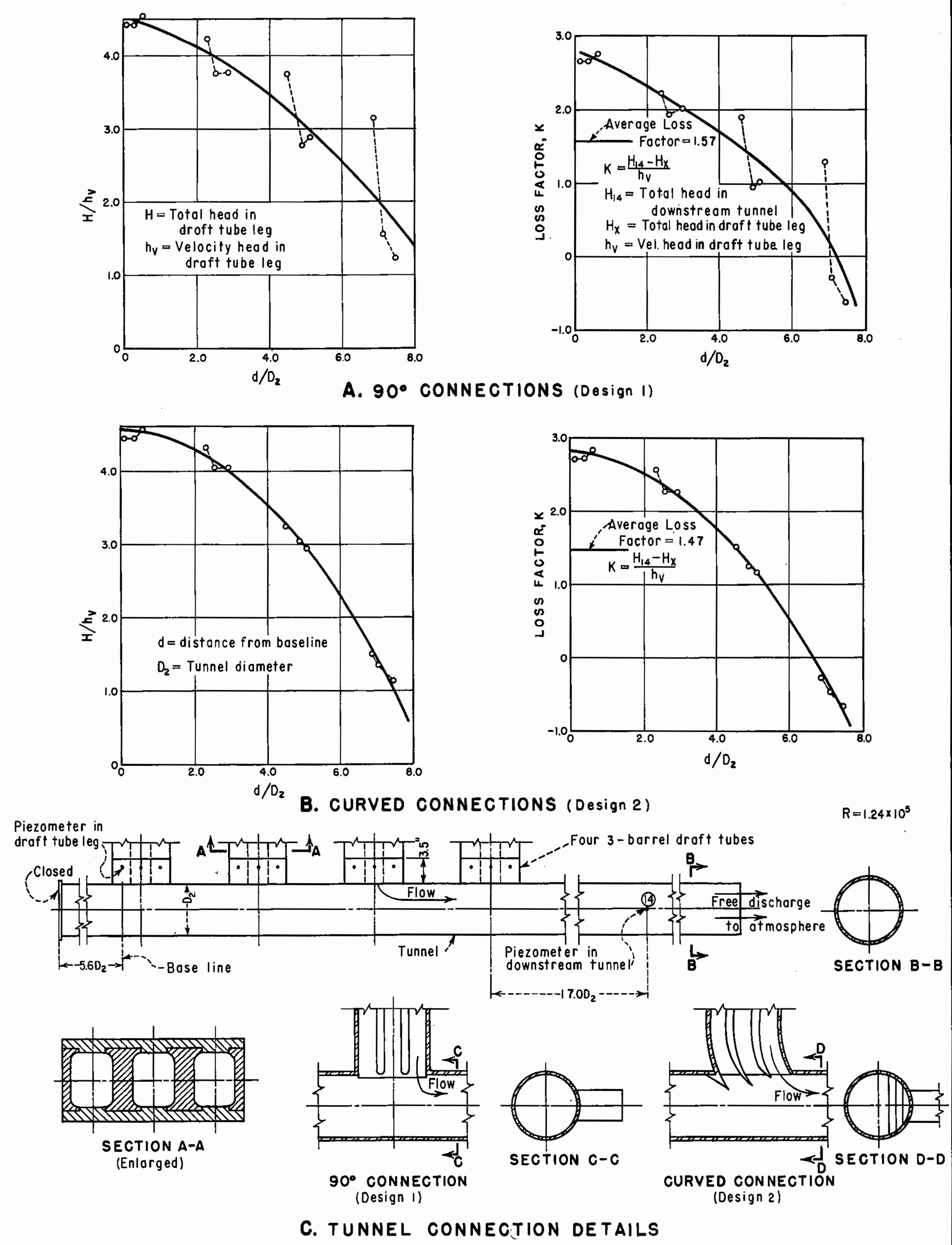
$$R = \frac{V_1 d}{\nu}$$

where
V_1 = Velocity in draft tube barrels
d = Height of barrels
ν = Kinematic viscosity of fluid

OROVILLE DAM
DRAFT TUBE AND TAILRACE STUDIES

HEAD LOSS FACTORS—vs—REYNOLDS NUMBER FOR SINGLE DRAFT TUBE CONNECTION

DATA FROM 1:46.67 AIR MODEL

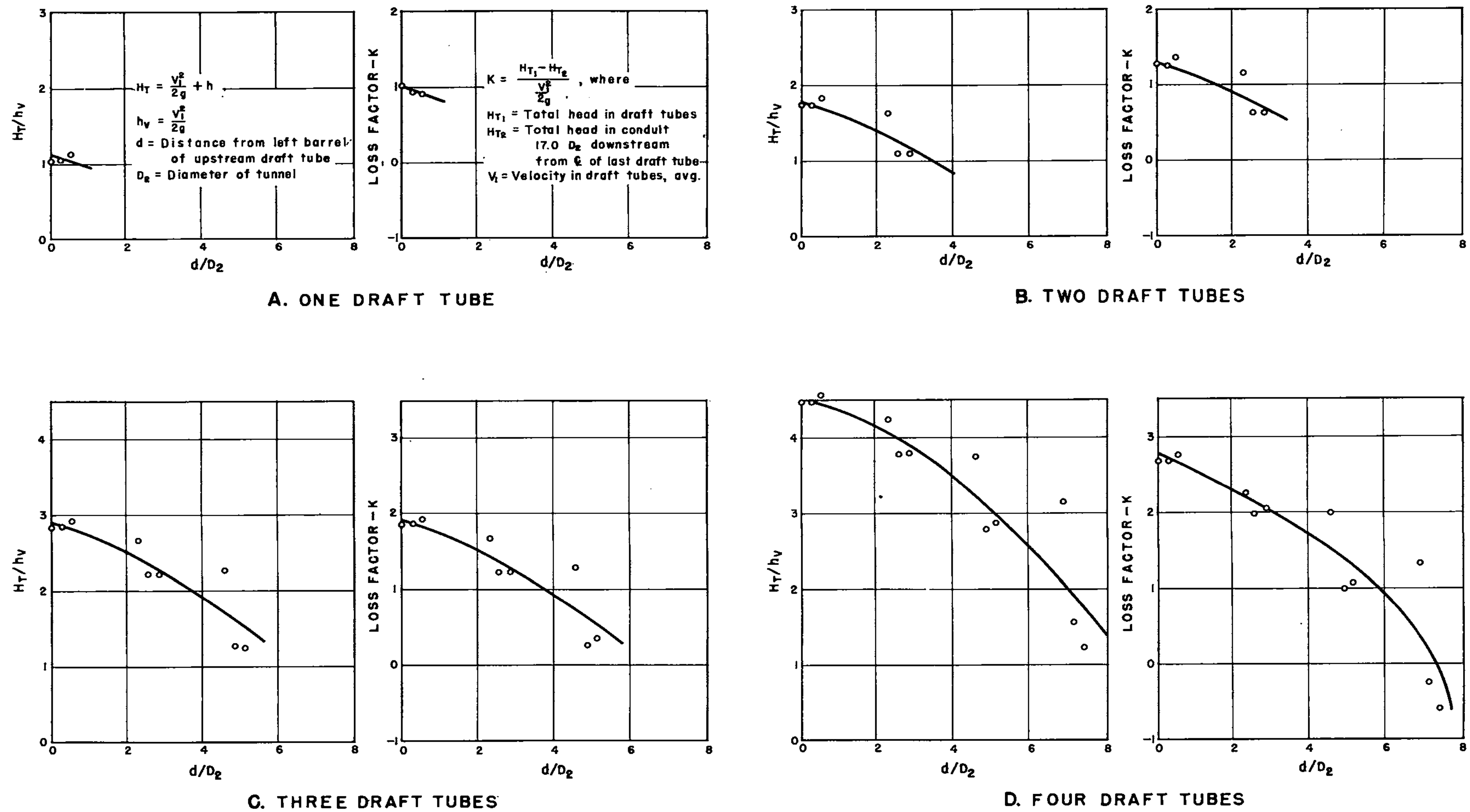


OROVILLE DAM
DRAFT TUBE AND TAILRACE STUDIES
PRESSURE CONDITIONS AND LOSS FACTORS WITH FOUR DRAFT TUBES DISCHARGING INTO TAILRACE TUNNEL

DATA FROM 1:46.7 AIR MODEL

642

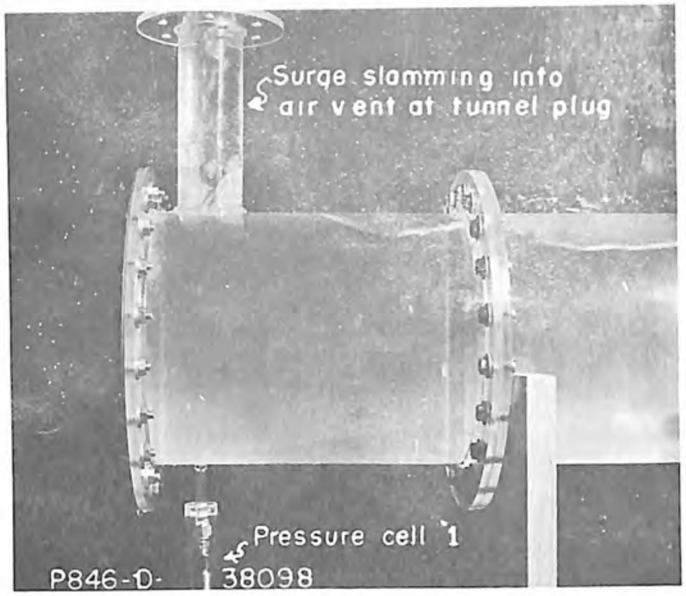
FIGURE 17
REPORT HYD. 507



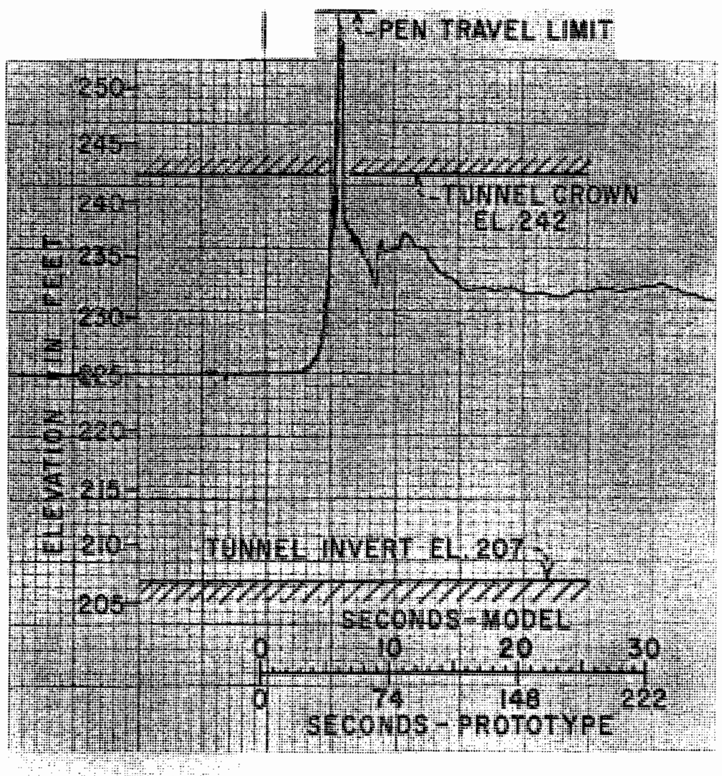
OROVILLE DAM
DRAFT TUBE AND TAILRACE STUDIES

PRESSURE CONDITIONS AND LOSS FACTORS WITH 1,2,3, AND 4 DRAFT TUBE CONNECTIONS – DESIGN 1

DATA FROM 1:46.67 AIR MODEL



A. A shock occurs when the tunnel fills at the closed upstream end due to a return surge.



240.33

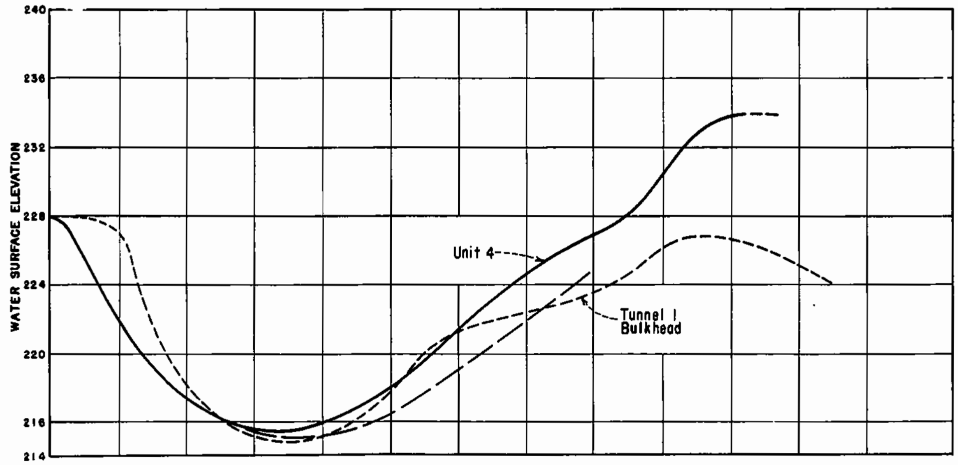
205.33

B. Shock of surge recorded on oscillograph chart.

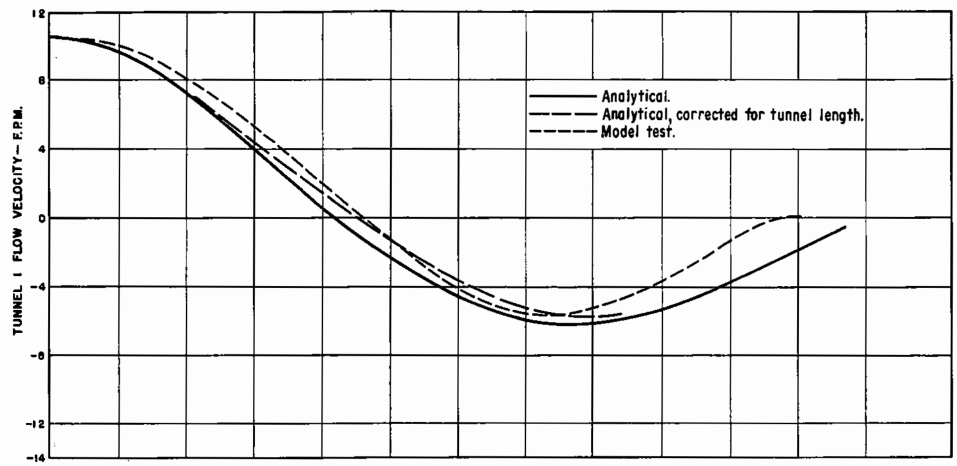
$Q_1 = 0$ $TW_1 = 225.0$
$Q_2 = 16,500$ $TW_2 = 226.5$
Turbines on in 7 seconds--pump turbines on in 20 seconds

OROVILLE DAM
DRAFT TUBE AND TAILRACE STUDIES

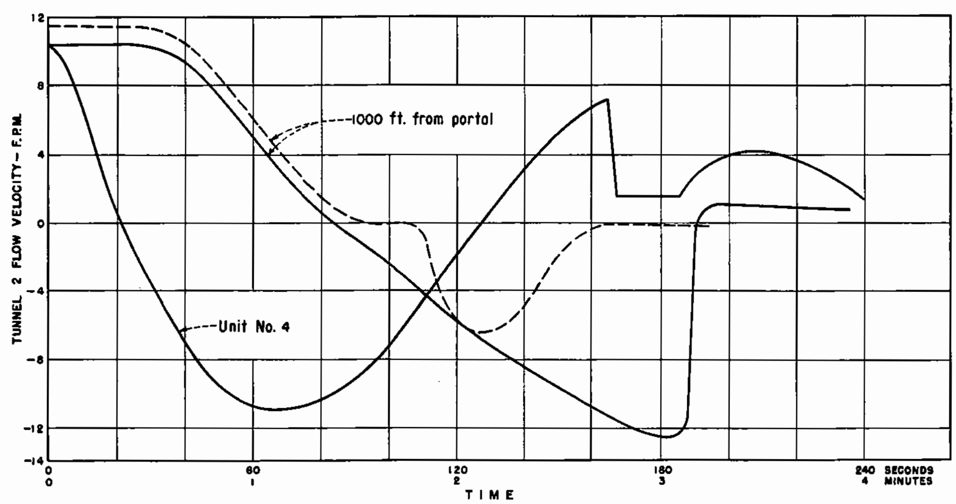
Shock When Surge Wave Fills Tunnel at Plug--Load Acceptance--Tunnel 1
1:54.63 Scale Model



A. WATER SURFACE ELEVATIONS - TUNNEL 1



B. FLOW VELOCITIES - TUNNEL 1



C. FLOW VELOCITIES - TUNNEL 2

OROVILLE DAM
DRAFT TUBE AND TAILRACE STUDIES

CORRELATION OF ANALYTICAL AND
EXPERIMENTAL SURGE DETERMINATIONS