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HYDRAULIC MODEL STUDIES FOR GRAND COULEE THIRD POWERPLANT FOREBAY AND TAILRACE CHANNELS

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Engineering and Research Center
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16. ABSTRACT
The water treaty with Canada, making possible additional water storage upstream from Grand Coulee Dam, and the historic large releases wasted over the spillway, contributed to the conception of a Third Powerplant at Grand Coulee. This powerplant will ultimately house twelve 600-Mw units. Six units have been authorized and construction has started, with three units to be installed in the initial phase. Because each unit has a discharge capacity of approximately 30,000 cfs, unusual problems of design in the forebay and tailrace of the new powerplant could be foreseen. A 1:120 scale model study showed the need for extensive revisions in the design of the forebay channel, and minor revisions in the tailrace configuration. A vortex formation noted above the penstock entrances prompted an additional study which will be reported separately. Observations and measurements were made in the forebay channel and tailrace for both 6- and 12-unit plant operation. Results of these studies are presented.

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HYDRAULIC MODEL STUDIES FOR GRAND COULEE THIRD POWERPLANT FOREBAY AND TAILRACE CHANNELS

by

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February 1973

Hydraulics Branch
Division of General Research
Engineering and Research Center
Denver, Colorado

UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION
Rogers C. B. Morton
Secretary

ACKNOWLEDGMENT

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PURPOSE

The purpose of this study was to assist in developing the designs of the forebay channel and tailrace for both 6- and 12-unit plant configurations. In addition, effects of simultaneous operation of the new and existing features were determined.

CONCLUSIONS

1. The design of the forebay channel required modifications to improve the velocity distribution. The forebay channel floor was excavated to elevation 1110 and a dike at elevation 1150 was left at the upstream end of the channel, resulting in considerably improved velocity distribution. The right wall of the channel was moved inward as far as possible to minimize excavation. Excavation of the rock formation at the juncture between Grand Coulee Dam and Forebay Dam improved velocity distribution.

2. Guide walls in the upstream portion of the forebay channel improved the velocity distribution but created excessive head loss (up to 7 feet).

3. A low sill in the forebay channel between Units 24 and 25 created excessive surface disturbances and head loss. This sill was proposed to reduce excavation when the 6-unit forebay channel is extended for 12 units.

4. Vortices formed above some of the penstock entrances for water surfaces below elevation 1240. The occurrence and severity of the vortices increased with decreasing reservoir elevation and with an increase in the number of units operating. Additional studies were required for development of appurtenances to alleviate vortex formation in the event that prototype operation discloses a problem, and are described in a separate report.

5. Only minor modifications were required for the tailrace configurations of the 6- and 12-unit plants. The desired shape of the right bank was determined in each case, and velocities and wave heights were measured. The model study suggested that the concrete cofferdam pad near the anchor block between the Right Powerplant and the Third Powerplant should be retained as a permanent feature to block the movement of bed material into the draft tube discharge region of the Third Powerplant.

6. The effect of 6-unit tailrace configuration and downstream channel improvement on water surface elevations in the tailrace was determined. The measured water surface elevations were slightly higher (maximum of 1.6 feet) than those determined theoretically.

7. Measurement of transient velocity and water surface in the 6-unit tailrace during a plant startup procedure showed no sudden increases in velocity or turbulent fluctuations, or waves which could damage the bank material. Similar results would be expected for the 12-unit plant.

8. 700-megawatt (Mw) units are presently being discussed for installation at the remaining three authorized units (three 600-Mw units are under construction). Discharges corresponding to the larger units were not tested during this study; however, some increase in the severity of problems such as vortex formation and bed scour would be expected. Therefore, a change to 700-Mw units should not be made unless additional studies are made to evaluate these effects.

APPLICATIONS

The results of this study apply specifically to the Grand Coulee Third Powerplant, which is essentially unique.

INTRODUCTION

The existing Grand Coulee Dam, Figure 1, includes as its primary features a spillway, multiple outlets, and a powerplant on each bank. The spillway is designed for a maximum discharge of 1 million cubic feet per second (cfs) at maximum reservoir elevation 1290. Each powerplant has a capacity of approximately 1,000 Mw.

The Columbia River Treaty with Canada has made possible additional storage capacity upstream from Grand Coulee Dam. Previously, water has been wasted over the spillway. Therefore, the Third Powerplant was conceived as a very attractive addition to the Grand Coulee complex.

Figure 1. Grand Coulee Dam - Existing features. Photo TP222-D-9106

The Third Powerplant, Figure 2, will have an ultimate capacity of 7,200 Mw in the form of twelve 600-Mw units. Six units are presently authorized. This will be the most inexpensive hydroelectric power in the United States from a plant which is expected to be the world's largest for many years. Installation of the 12 units will occur in stages according to the growth in need for peaking power. Estimated completion for full capacity is 1992.

Three 600-Mw units are now under construction. Increasing the size of the remaining three authorized units to 700-Mw is being discussed. Though the exact effects are unknown, an increase in the severity of potential problems such as vortex formation and bed scour would be expected.

THE MODEL

The 1:120 scale model was constructed and tested in stages, according to the need for design information. The preliminary forebay channel for the 12-unit plant was installed and tested first. Later, the penstocks and powerhouse structure were attached and the tailrace topography was installed. The model included the spillway and both existing powerplants from the start.

Water was supplied to the model through two risers which could be adjusted to modify the pattern of flow entering the model. Discharge was measured with permanent volumetrically calibrated venturi meters. Reservoir elevations were set by staff gages; head loss was measured with point gages. Tailwater elevations were also set with a staff gage. Water surface profiles in the tailrace were determined with piezometers mounted flush with the riverbed. The piezometers were connected to a pressure transducer. The output from the transducer was displayed on a digital voltmeter, with voltage corresponding to head on the transducer. Velocities in the forebay and tailrace were measured with a miniature propeller meter connected to an electronic counter and paper tape printer or with a pitot tube connected to a differential pressure transducer. Waves were recorded with capacitance-type probes connected to a direct-writing oscillograph recorder.

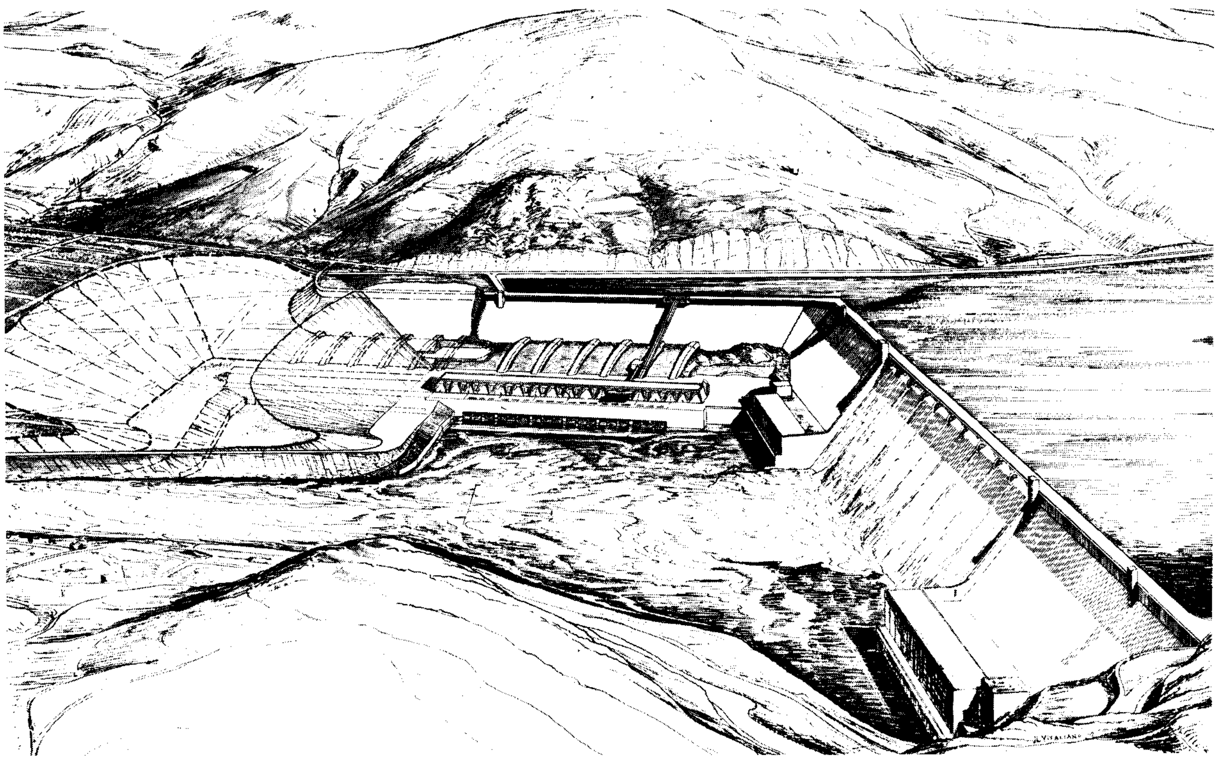


Figure 2. Third Powerplant - Artist's conception. Photo P1222-D-63800

TEST CONDITIONS

The following conditions were used in planning the model tests.

At minimum reservoir elevation 1208:

One unit operating - 29,200 cfs
Twelve units operating - 330,000 cfs (27,-500 cfs per unit)

At maximum reservoir elevation 1290:

One unit operating - 31,000 cfs
Twelve units operating - 372,000 cfs (31,-000 cfs per unit)

Right and Left Powerplants - 45,000 cfs each

Spillway - 1,000,000 cfs maximum

	Tailwater at bridge gage	
Channel discharge cfs	Unimproved channel	With fill channel "D"[1]
60,000	950.1	950.6
80,000	951.9	952.2
160,000	959.4	960.8
240,000	966.4	968.6
300,000	971.1	973.9
500,000	984.8	988.7
750,000	999.4	1005.8
1,000,000	1012.5	1018.4

[1] Fill channel "D" is one of several downstream channel configurations and was chosen for prototype construction. The theoretical tailwater corresponding to this configuration was used in the model study.

Information concerning these conditions became available at different times during the study. Therefore, this report may at times refer to somewhat different conditions.

INVESTIGATION

Forebay Channel

Preliminary design. –Figure 3 shows the initial configuration of the forebay channel. The upstream portions of the penstocks and the penstock entrances were simulated with 4-inch-diameter plastic tubes (40 feet, prototype) with slide gates on the downstream ends of the tubes. A portion of the topography at the upstream end of the forebay channel was included. Velocities were measured across the forebay channel on a line representing an extension of the upstream face of Grand Coulee Dam, and on lines perpendicular to the Forebay Dam approximately 300 and 600 feet downstream. Surface flow patterns in the forebay channel are represented by the confetti streaks in Figure 4. The total discharge through 12 units was 330,000 cfs, reservoir elevation 1208 (minimum). The confetti streaks indicate that the flow is directed toward the right side of the channel, with accompanying high velocities in that area. The eddy formed downstream from the corner at the juncture of the dams is apparent, as well as surface swirls along the face of the Forebay Dam. Figure 5 is a closer view of the eddy formed at the corner, for a discharge of 392, 400 cfs, reservoir elevation 1290 (maximum). Nearly dead water occurs at the downstream end of the channel.

Velocity distributions for these conditions are shown in Figure 6. At reservoir elevation 1208, Figure 6A, upstream velocities to 3 feet per second (fps)

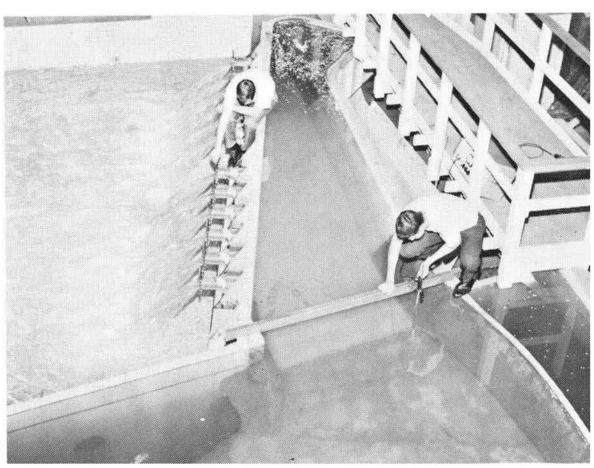


Figure 3. Preliminary forebay channel. Photo P1222-D-72991

Figure 4. Flow pattern in preliminary forebay channel. Photo P1222-D-72992

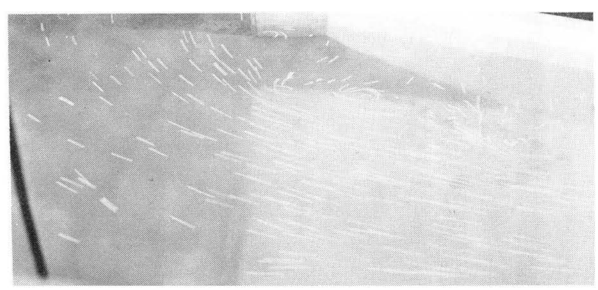
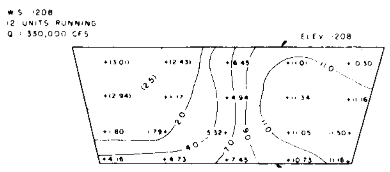
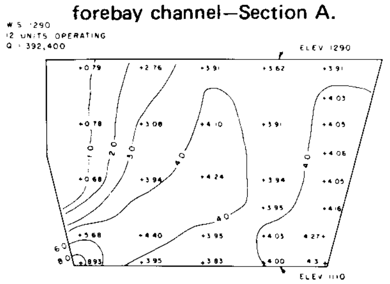


Figure 5. Flow pattern at juncture between dams. Photo P1222-D-72993

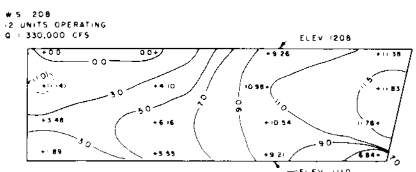
were observed near the Forebay Dam (left side of channel). Velocities over 11 fps occurred near the right side. These were average velocities; therefore, higher instantaneous velocities would be expected. Attempts were made to limit the velocity along the right side to less than 10 fps. At reservoir elevation 1290, the highest velocities occurred in a limited region near the lower left corner of the channel, Figure 6B. Both Figures 6A and 6B show that the corner eddy is primarily a surface phenomenon. Vortices formed above several of the penstock entrances at the minimum reservoir elevation. The change in water surface elevation from the main



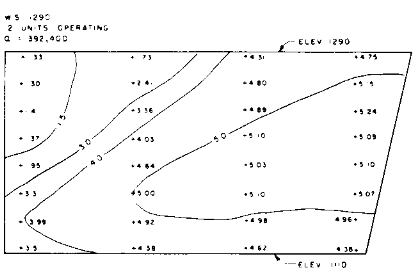
A. Velocity distribution in preliminary forebay channel—Section A.



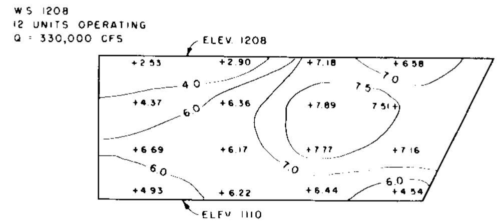
B. Velocity distribution in preliminary forebay channel—Section A.



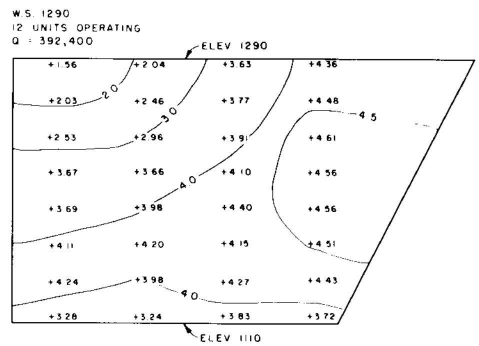
C. Velocity distribution in preliminary forebay channel—Section B.



D. Velocity distribution in preliminary forebay channel—Section B.



E. Velocity distribution in preliminary forebay channel—Section C.



F. Velocity distribution in preliminary forebay channel—Section C.

KEY

+	**Point Velocity fps**
+( )	**Reverse Velocity**
- - -	**Reverse Velocity Contour**

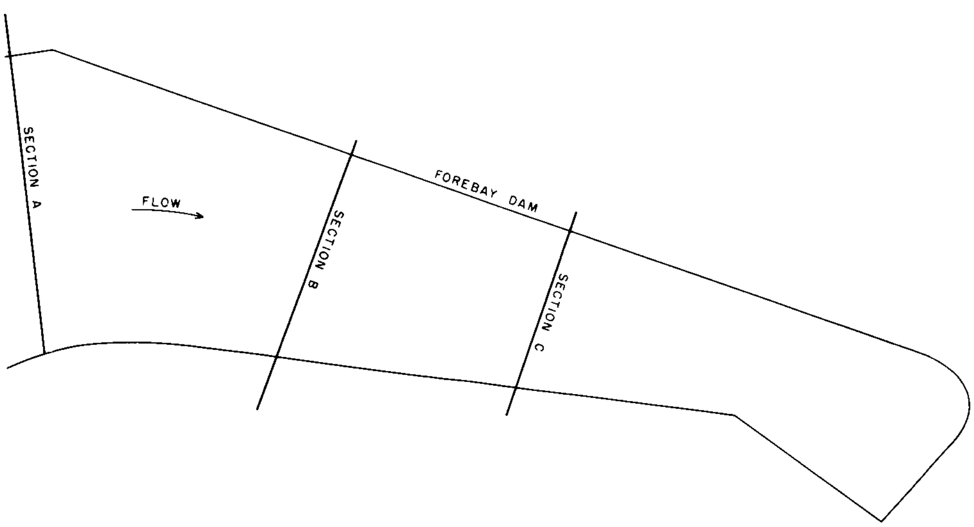


Figure 6. Velocity distribution in preliminary forebay channel.

body of the reservoir to the first unit was approximately 2 feet at minimum reservoir. The change was negligible at maximum reservoir.

Several modifications and appurtenances were tried in attempts to improve velocity distribution in the forebay channel. Rounding of the corner at the juncture of the dams had no effect. The remaining topography between the channel and the reservoir was installed for this test.

Guide walls placed in the channel, such as that shown in Figure 7A, were successful in improving the velocity distribution. Such structures would consist of unexcavated rock. Improving the velocity distribution allowed the right wall to be moved inward, as shown in Figure 7B. This arrangement improved the velocity distribution, but resulted in excessive head loss. Water surface drop from the reservoir was as much as 7 feet. Operation without the guide wall in the middle part of the channel suggested that some revision of the right wall configuration would be advantageous.

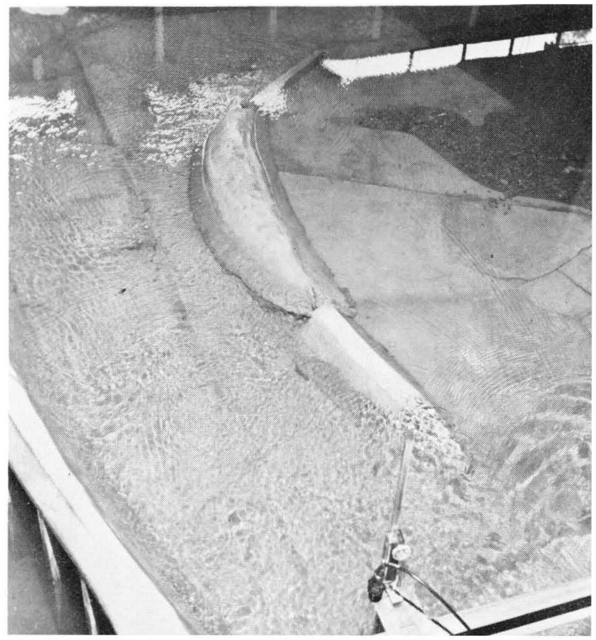
After several more trials, the configuration shown in Figure 8 was determined to be a necessary improvement. The channel floor was lowered to elevation 1110 and a curved rock dike, with its crest at elevation 1150, was placed across the channel entrance. The resulting velocity distribution is shown in Figure 9.

Lowering the topography at the corner from elevation 1250, Figure 10A, to elevation 1190, Figure 10C, further improved the velocity distribution, Figure 11. It was later determined that the topography could be lowered to elevation 1200 without an unreasonably large amount of excavation.

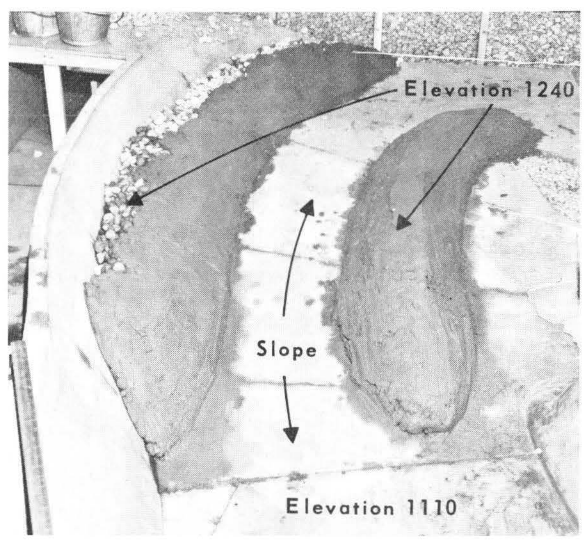
Moving the right wall inward 20 feet resulted in the velocity distribution of Figure 12. This change had no apparent affect on the velocity distribution.

Recommended design.—After several additional minor modifications, the forebay channel configuration shown in Figure 13 was recommended.

Velocity distributions for the 12-unit configuration are given in Figure 14 (the corner topography was at elevation 1225 during these measurements). Velocities of nearly 11 fps were measured along the right wall; however, these velocities were determined to be acceptable. Velocities of more than 13 fps are required to move 20-inch riprap. Since the blocks of rock in the wall of the forebay channel are equivalent to sizes much larger than 20 inches, the expected velocities should cause no problem.



A. Photo P1222-D-72995.



B. Photo P1222-D-72994.

Figure 7. Trial curved guide walls.

Figure 15 shows streaks caused by submerged pieces of confetti, with 12 units operating. The photograph shows that, at several points in the channel, the subsurface movement is nearly parallel

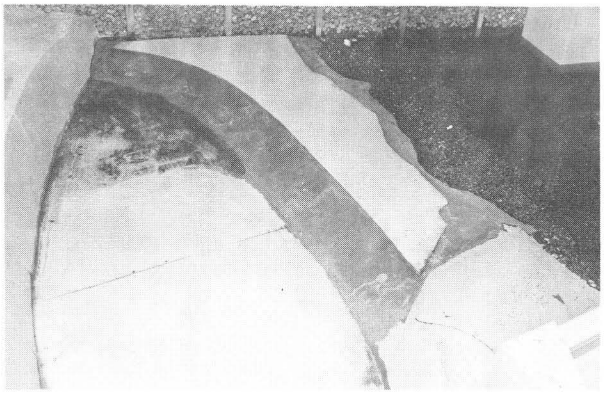


Figure 8. Recommended dike. Photo P1222-D-73005

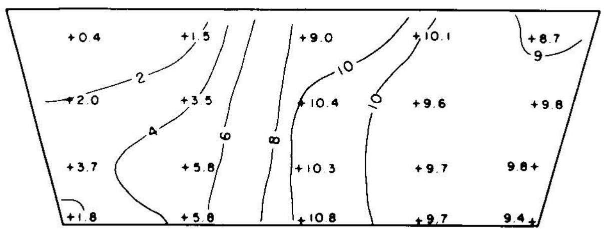


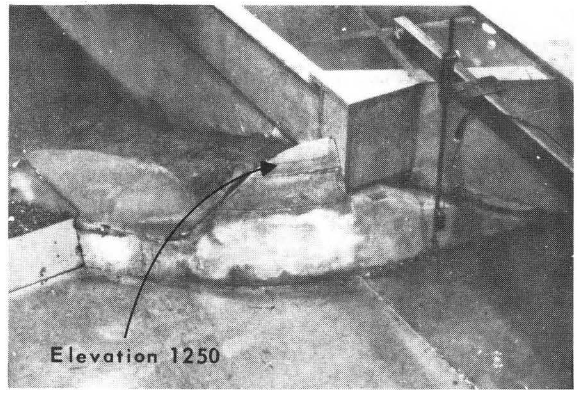
Figure 9. Velocity distribution at Section A with recommended dike.

to the face of the Forebay Dam. By measuring the exact camera shutter speed, the velocities could be determined by measuring the length of the streaks. These data were useful in designing the trashracks for the penstock intakes. Figure 16 shows surface flow patterns near the upstream units (19, 20, and 21) and near the downstream units (28, 29, and 30). Figure 16A shows a standing wave which causes rapid deceleration of the surface velocity. The shadow of this wave can be seen on the channel bottom. The surface eddy above Units 19, 20, and 21 is also apparent in this photograph.

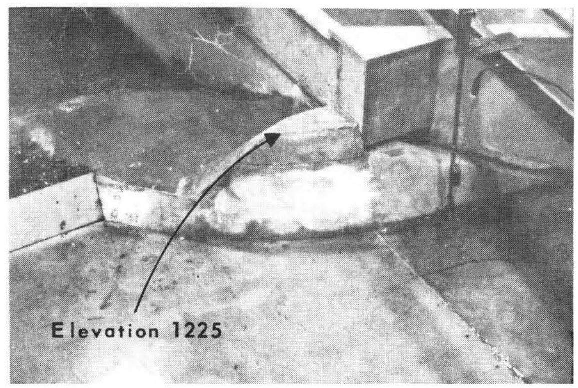
The following observations on vortex formation were made for the 6-unit plant configuration:

Unit 19 operating alone at a discharge of 31,000 cfs:

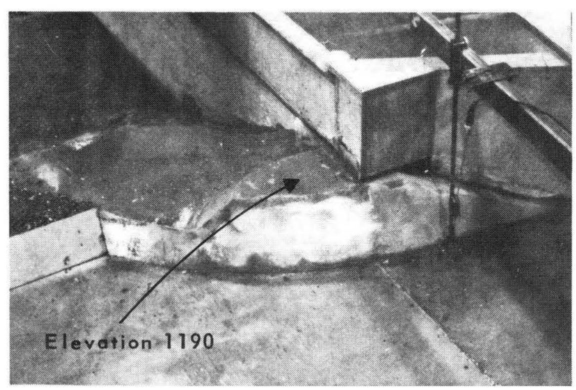
Dimpling of the water surface immediately after submergence of the entrance. Decreasing strength as the water surface rose to the minimum reservoir elevation 1208. Dimpling again noted at elevation 1213. Weak circulation with no surface dimpling at elevation 1250.



A. Photo P1222-D-73018.



B. Photo P1222-D-73016.



C. Photo P1222-D-73017.

Figure 10. Variable topography at juncture between dams.

Units 19, 20, and 21 operating, each at a discharge of 31,000 cfs:

Below elevation 1208, short duration, weak to strong vortices formed at times. Some air taken

Figure 8. Recommended dike. Photo P1222-D-73005

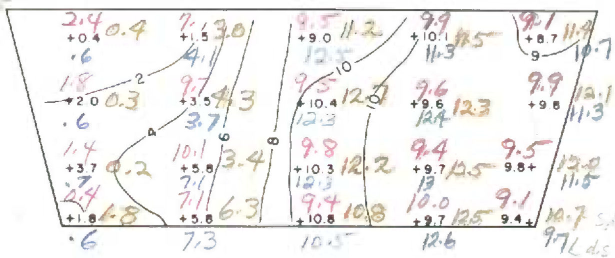


Figure 9. Velocity distribution at Section A with recommended dike.

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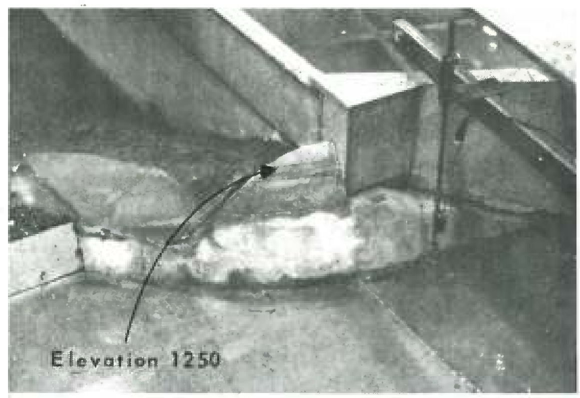
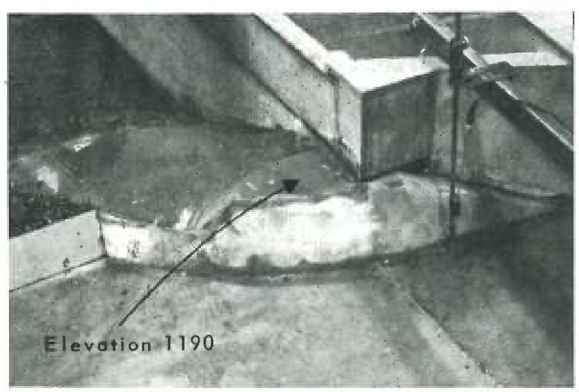


A. Photo P1222-D-73018.

B. Photo P1222-D-73016.



C. Photo P1222-D-73017.

Figure 10. Variable topography at juncture between dams.

Units 19, 20, and 21 operating, each at a discharge of 31,000 cfs:

Below elevation 1208, short duration, weak to strong vortices formed at times. Some air taken

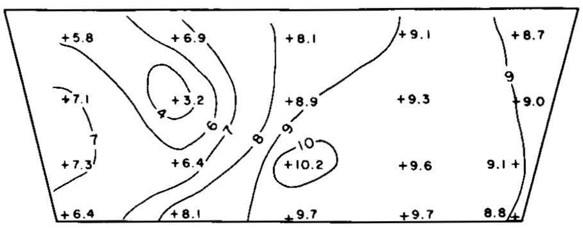


Figure 11. Effect of juncture changes on velocity distribution at Section A.

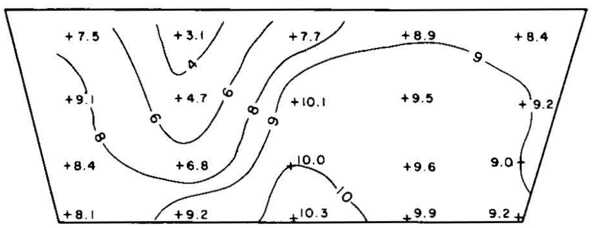


Figure 12. Velocity distribution at Section A with modified right wall in forebay channel.

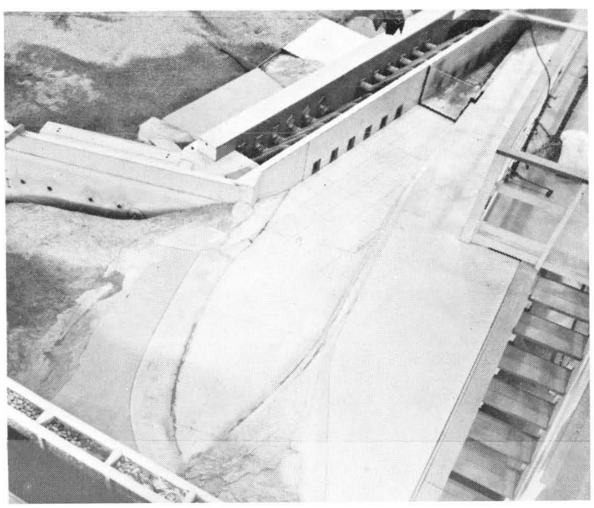


Figure 13. Recommended forebay channel. Barrier at mid-length represents end of channel for 6-unit plant. Photo P1222-D-73019.

into penstocks. At elevation 1208, a vortex formed above Unit 19 which took air and lasted for several seconds. At elevation 1223, surface dimpling was noted and most of the circulation was above Unit 19. A weak intermittent vortex formed above Unit 19 at elevation 1238. At elevation 1266, intermittent surface dimples formed above all three units.

Units 19, 20, 21, 22, 23, and 24 operating, each at a discharge of 31,000 cfs:

Occasional strong vortices formed below elevation 1208, primarily at Units 19, 20, 21, and 22. Surface dimpling at elevation 1213.

Strong, concentrated swirls at elevation 1220, no air taken. Short duration, strong vortex above Unit 19 at elevation 1226, took air. Observed again at elevations 1228, 1229, 1230, and 1234. Represents prototype vortex with a diameter of about 10 feet. Intermittent vortices above Unit 20 took air at elevation 1250, and again at elevation 1253. Deep, intermittent dimples above Unit 20 at elevation 1260, with strong counterclockwise circulation.

Observations were also made with all 12 units operating at reservoir elevation 1208, with varying discharge, as described below:

Q = 330,000 cfs:

Strong, unstable vortices above Units 19-24 took air for short periods through any of these six units. Moving dimples observed above Units 25-30, no air taken.

Q = 284,000 cfs:

Short duration, large vortex, took air into penstock of Unit 20. Incipient vortex formation above Units 21 and 22. Dimpled surface throughout the length of the channel.

Q = 266,000 cfs:

Short duration, large vortices above Units 20, 21, and 22 took air. Calm water surface above Unit 19. Dimpled surface throughout the length of the channel.

Q = 252,000 cfs:

Short duration, moderate vortices formed above Units 20 and 21, but much less frequently than for higher discharges. Small amounts of air taken. Dimpled surface throughout the length of the channel.

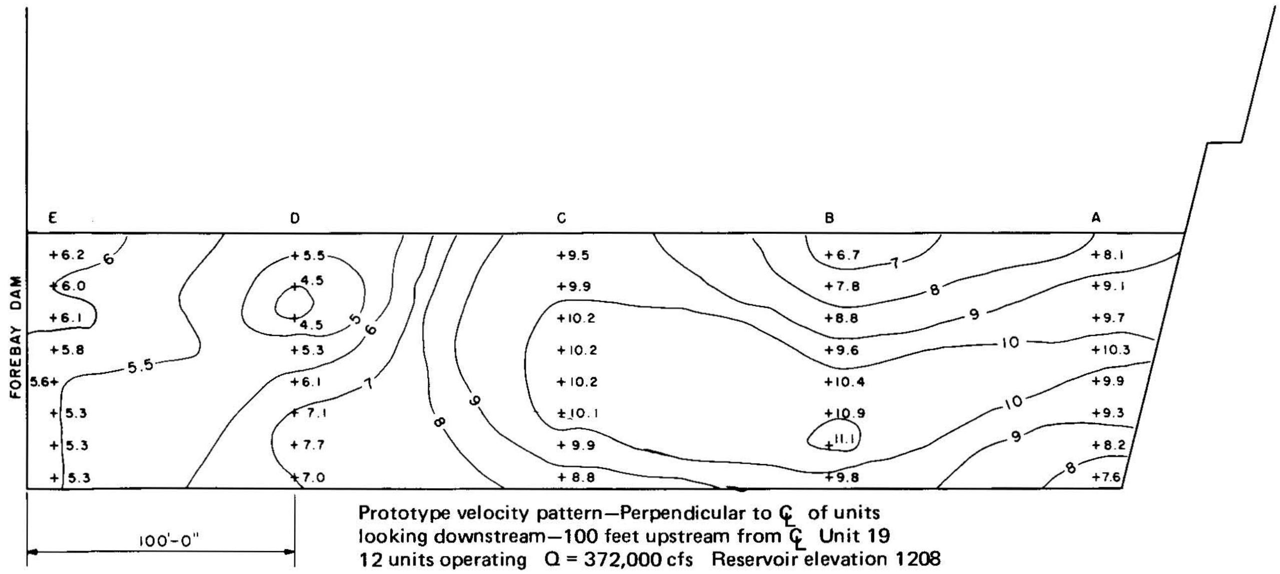


Figure 14. Velocity distribution in recommended forebay channel.

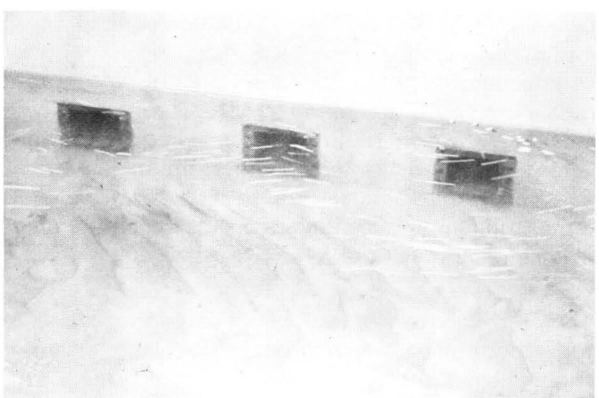


Figure 15. Flow pattern within forebay channel flow. Photo P1222-D-72999

> Q = 237,000 cfs (representing 72 percent of full load):
>
> Short duration, moderate vortices formed above Units 20, 21, 22; did not take air. However, vortices had deep cores. Small amount of air taken into penstock of Unit 20. Dimpled surface throughout the length of the channel.

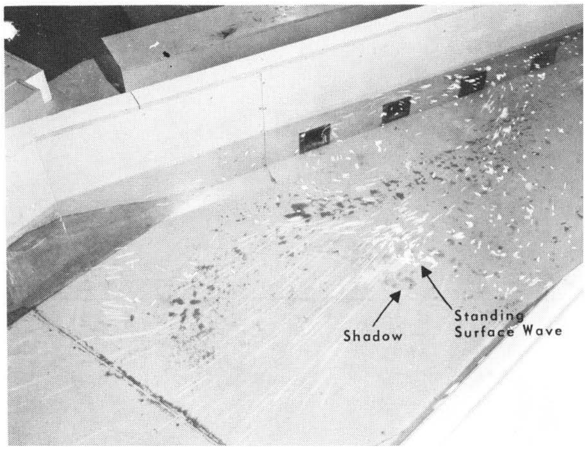
The effects of these vortices on operation of the turbines could not be determined in this study. Also, the exact performance of the prototype forebay channel could not be determined because the laws of similitude for vortices are not yet well established. Additional studies on a larger model would be advisable for development of modifications and appurtenances to alleviate the vortex problem.

During the course of the forebay channel tests, the spacing between penstocks in each of the 6-unit groups was changed from 133.5 feet to 119 feet. This change had no effect on the test results.

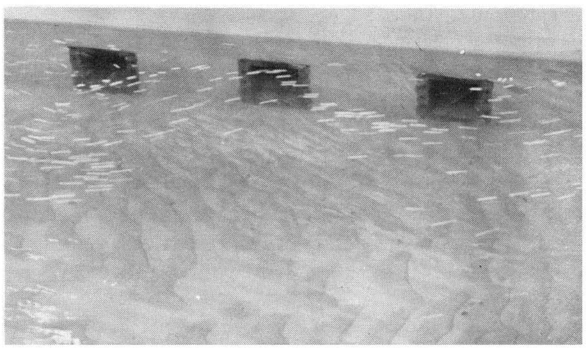
A proposal was made to leave a rock "weir" between Units 24 and 25, to reduce the required amount of underwater excavation. Such a structure was installed in the model, with the top of the structure at either elevation 1170 or 1200. For the lower structure, operation up to reservoir elevation 1250 resulted in very rough flow and large vortices in the channel adjacent to Units 25-30. Approximately 1 foot of head loss occurred across the structure at reservoir elevation 1262. For the higher structure, unsatisfactory flow conditions were observed up to reservoir elevation 1263.

Tailrace

Six-unit plant.—The model was modified to include the penstocks, powerhouse, and tailrace for the 6-unit plant, Figure 17.



A. Units 19-22. Photo P1222-D-72996



B. Units 19-21. Photo P1222-D-73900

C. Units 28-30. Photo P1222-D-73001

Figure 16. Surface flow pattern in forebay channel.

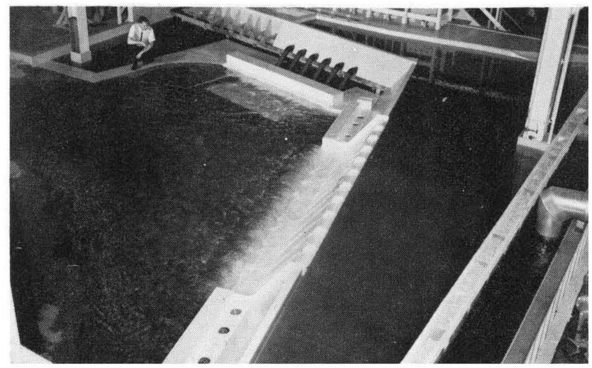


Figure 17. Preliminary 6-unit tailrace configuration. Photo P1222-D-72997

Two configurations of the right bank of the tailrace channel were tested. Figure 18 shows the preliminary configuration of the right bank of the tailrace channel, along with locations of velocity measurements. Table 1 shows the velocity data. Velocities exceeding 15 fps were measured at several points. The maximum recorded velocity of 17 fps would cause movement of riprap material less than 42 inches in diameter.[1] Concern over the possible movement of channel bed material resulted in a modification to the right bank. The recommended configuration and locations of velocity measurements are shown in Figure 19. The resulting velocities are shown in Table 2. The maximum recorded velocity of 13.5 fps would move riprap less than 27 inches in diameter. Figure 20 shows several representative flow conditions in the recommended tailrace channel for the 6-unit plant.

The question was raised concerning the possible movement of bed material between the existing Right Powerplant and the tailrace of the Third Powerplant. Velocities measured in this area for

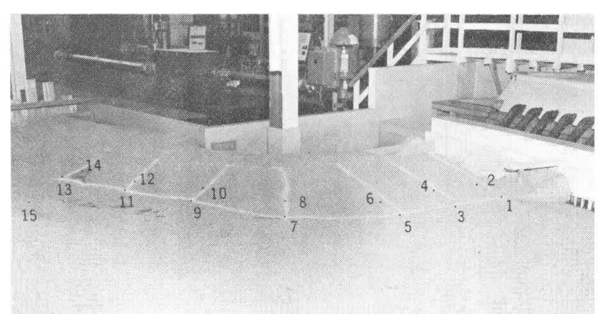


Figure 18. Velocity measurements in preliminary 6-unit tailrace. Photo P1222-D-73006

[1]Figure 165, "Hydraulic Design of Stilling Basins and Energy Dissipators", Bureau of Reclamation Engineering Monograph No. 25, July, 1963.

Table 1

VELOCITIES MEASURED AT POINTS IN FIGURE 18

Point No. / Run No.	Velocities – fps						
	1	2	3	4	5	6	7
1	5.8	5.3	4.5	4.4	3.7	3.6	2.3
2	2.8	0.2	0.6	0.5	1.4	2.2	1.6
3	3.5	1.7	2.8	3.0	2.5	1.7	0.8
4	2.7	1.8	1.6	1.7	0.8	1.1	1.4
5	3.7	3.5	3.5	3.5	3.6	1.6	0.8
6	4.1	2.9	3.6	3.8	3.3	1.9	1.0
7	2.8	3.2	4.4	5.3	6.4	5.4	4.8
8	0.9	3.5	6.4	6.3	6.4	6.9	4.4
9	1.8	3.2	4.3	4.8	6.4	7.5	10.4
10	0.8	0.6	0.7	0.9	3.6	9.8	8.7
11	2.8	4.0	5.6	7.8	9.1	12.2	13.3
12	1.8	2.4	3.3	3.7	6.3	10.4	12.5
13	4.1	4.8	6.9	7.3	10.4	15.1	17.0
14	0.8	1.8	0.6	1.2	0.8	8.0	10.6
15	4.2	–	9.2	12.1	10.7	15.4	16.5

Run No.	Existing plants	6-unit 3rd pp	Spillway	Total discharge	Bridge tailwater elevation	Backwater
1	0	* 93,000	0	93,000	953.8	1.2
2	0	186,000	0	186,000	963.5	1.8
3	90,000	150,000	0	240,000	968.6	2.4
4	90,000	186,000	24,000	300,000	973.9	3.0
5	90,000	186,000	224,000	500,000	988.7	4.2
6	90,000	186,000	474,000	750,000	1005.8	4.8
7	90,000	186,000	724,000	1,000,000	1018.4	3.6

*Units 22-24

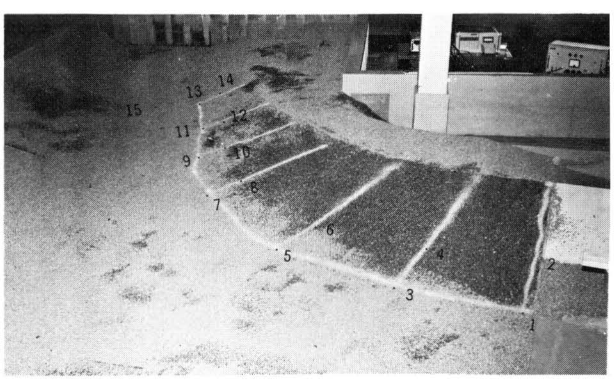


Figure 19. Velocity measurements in recommended 6-unit tailrace. Photo P1222-D-73007

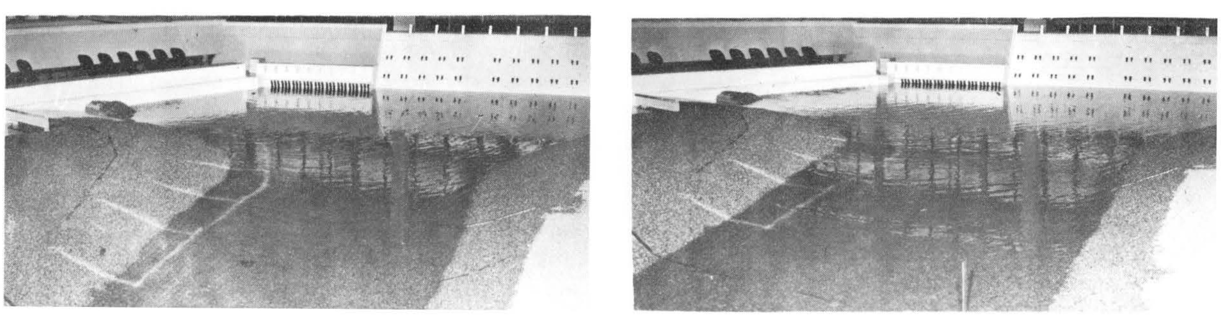
three representative flow conditions are shown in Figure 21. In cases where the model velocities were too low to measure with the miniature propeller meter, only flow patterns are shown. The magnitude of the velocities suggested that some of the material (less than about 4 inches in diameter) might tend to move into the Third Powerplant tailrace. Since a concrete pad was to be constructed for support of the cofferdam, it was suggested that this pad be left in place after completion of construction. The pad, shown in Figure 22, will tend to block the movement of material toward the Third Powerplant tailrace.

Table 2

VELOCITIES MEASURED AT POINTS IN FIGURE 19

Point No. / Run No.	Velocities – fps						
	1A	2A	3A	4A	5A	6A	7A
1	5.0	5.3	4.2	5.6	4.4	3.6	1.8
2	3.5	0.9	0.8	0.8	0.7	2.2	1.6
3	4.4	4.4	4.1	4.4	3.6	0.8	1.8
4	5.1	3.7	3.3	4.0	1.4	1.0	0.8
5	3.7	3.6	4.2	4.4	5.0	3.1	1.3
6	2.7	4.3	4.7	4.8	5.3	2.9	1.3
7	1.7	4.3	4.7	5.3	8.8	7.0	6.0
8	0.6	4.0	5.0	6.2	8.8	7.2	6.3
9	2.4	4.3	5.0	6.4	9.8	9.1	9.5
10	1.8	3.1	3.8	44.1	6.5	6.2	9.7
11	2.3	4.4	5.5	6.7	8.3	8.1	10.7
12	2.1	3.1	3.8	4.8	6.2	8.8	9.3
13	2.8	4.3	5.9	7.0	9.2	10.5	11.8
14	2.5	4.2	5.2	5.9	7.9	9.6	11.3
15	5.0	7.5	8.1	10.0	12.0	13.5	12.8

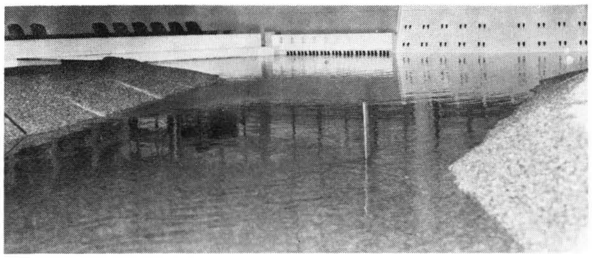
Run No.		Backwater
1A	Runs described on Table 1.	–
2A		–
3A		2.4
4A		2.4
5A		3.6
6A		3.0
7A		2.4



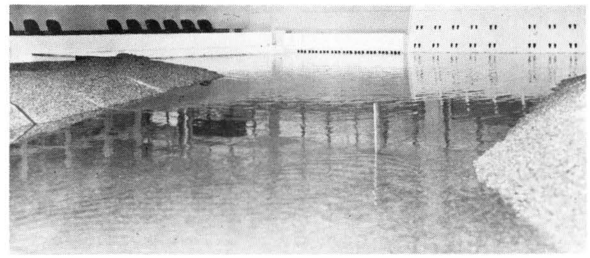
Units 22-24 of Third Powerplant, Q = 93,000 cfs, tailwater elevation 953.8. Photo P1222-D-73014

Units 19-24 of Third Powerplant, Q = 186,000 cfs, tailwater elevation 963.5. Photo P1222-D-73013

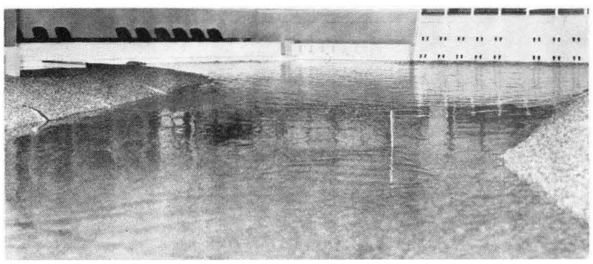
Figure 20. Flow conditions in the recommended 6-unit tailrace.



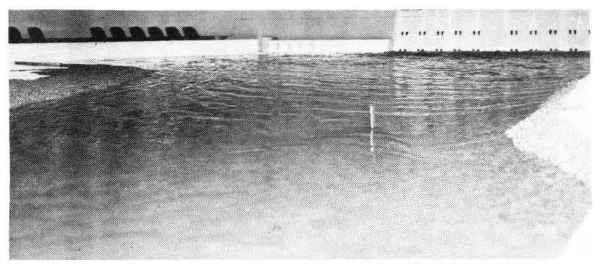
Units 19-24 at Q = 150,000 cfs plus existing plants at 90,000 cfs; tailwater elevation 968.6. Photo P1222-D-73012



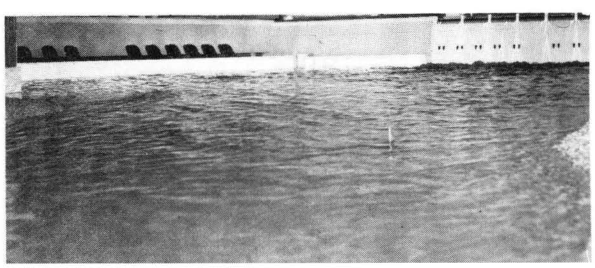
Units 19-24 at Q = 186,000 cfs plus existing plants at 90,000 cfs, spillway at 24,000 cfs; tailwater elevation 973.9. Photo P1222-D-73011



Units 19-24 at Q = 186,000 cfs plus existing plants at 90,000 cfs, spillway at 224,000 cfs; tailwater elevation 988.7. Photo P1222-D-73010



Units 19-24 at Q = 186,000 cfs plus existing plants at 90,000 cfs; spillway at 474,000 cfs; tailwater elevation 1005.8. Photo P1222-D-73009



Units 19-24 at Q = 186,000 cfs plus existing plants at 90,000 cfs, spillway at 724,000 cfs; tailwater elevation 1018.4. Photo P1222-D-73008

Figure 20. Flow conditions in the recommended 6-unit tailrace.—Continued

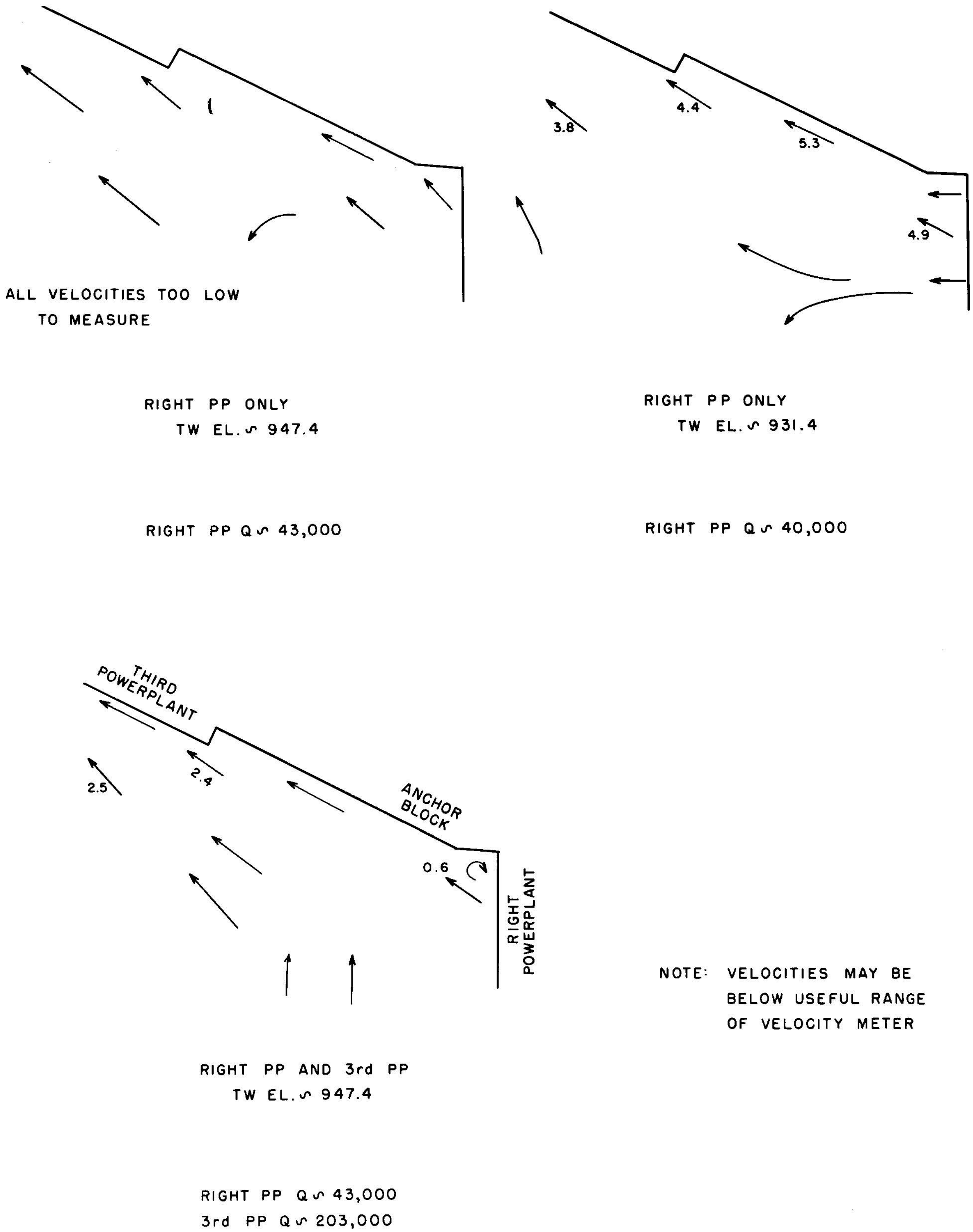


Figure 21. Velocities in vicinity of anchor block.

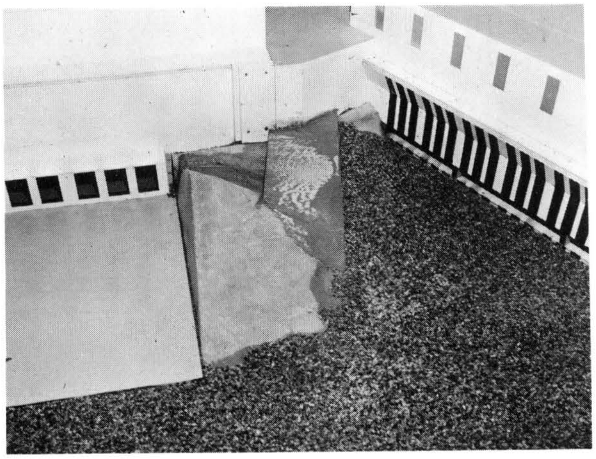


Figure 22. Cofferdam pad near anchor block. Photo P1222-D-72998

Twelve-unit plant.—Figure 23 shows the preliminary tailrace configuration for the 12-unit plant. The retaining wall at the base of the slope on the right bank was skewed 16.5° toward the channel. Figure 24 shows the location of velocity and wave-measuring instrumentation and surface flow patterns, as indicated by confetti, for three representative flow conditions. Figure 25 shows velocities and trough-to-crest wave heights in the preliminary tailrace. Velocities along the right bank approach 10 fps, suggesting the possible movement of bed material. The retaining wall was rotated so that its new location was perpendicular to the longitudinal axis of the powerplant. Velocities were again recorded, as shown in Figure 26. This configuration was recommended for the final design.

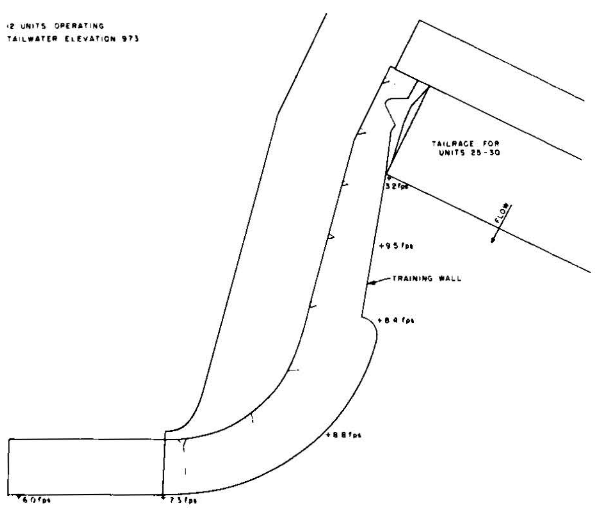
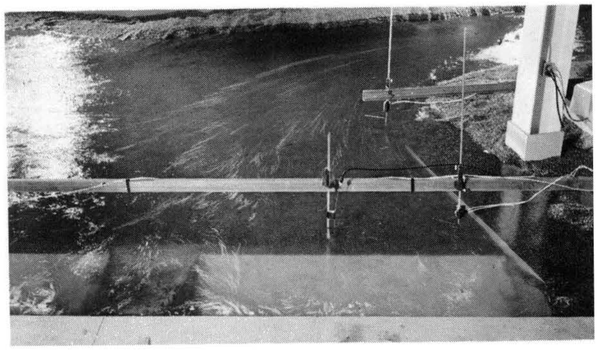
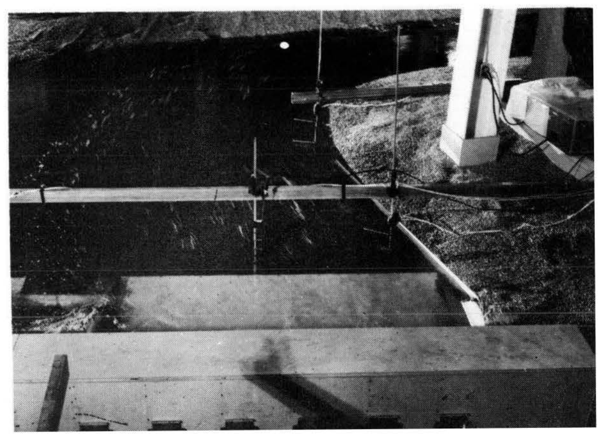


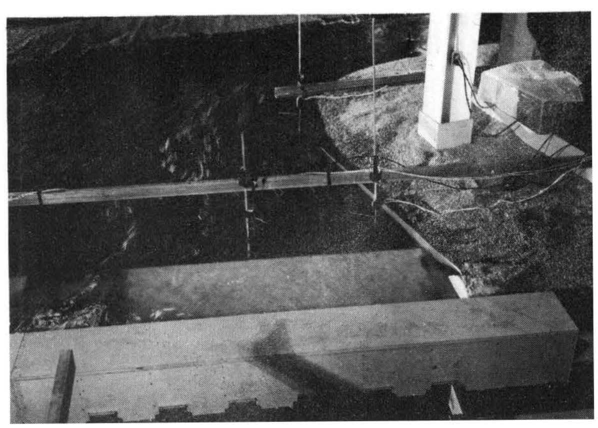
Figure 23. Preliminary 12-unit tailrace configuration.



All 12 units, existing powerplants, and spillway operating. Photo P1222-D-73004



Units 25-30 operating. Photo P1222-D-73002



All 12 units operating. Photo P1222-D-73003

Figure 24. Flow patterns and instrumentation in preliminary 12-unit tailrace.

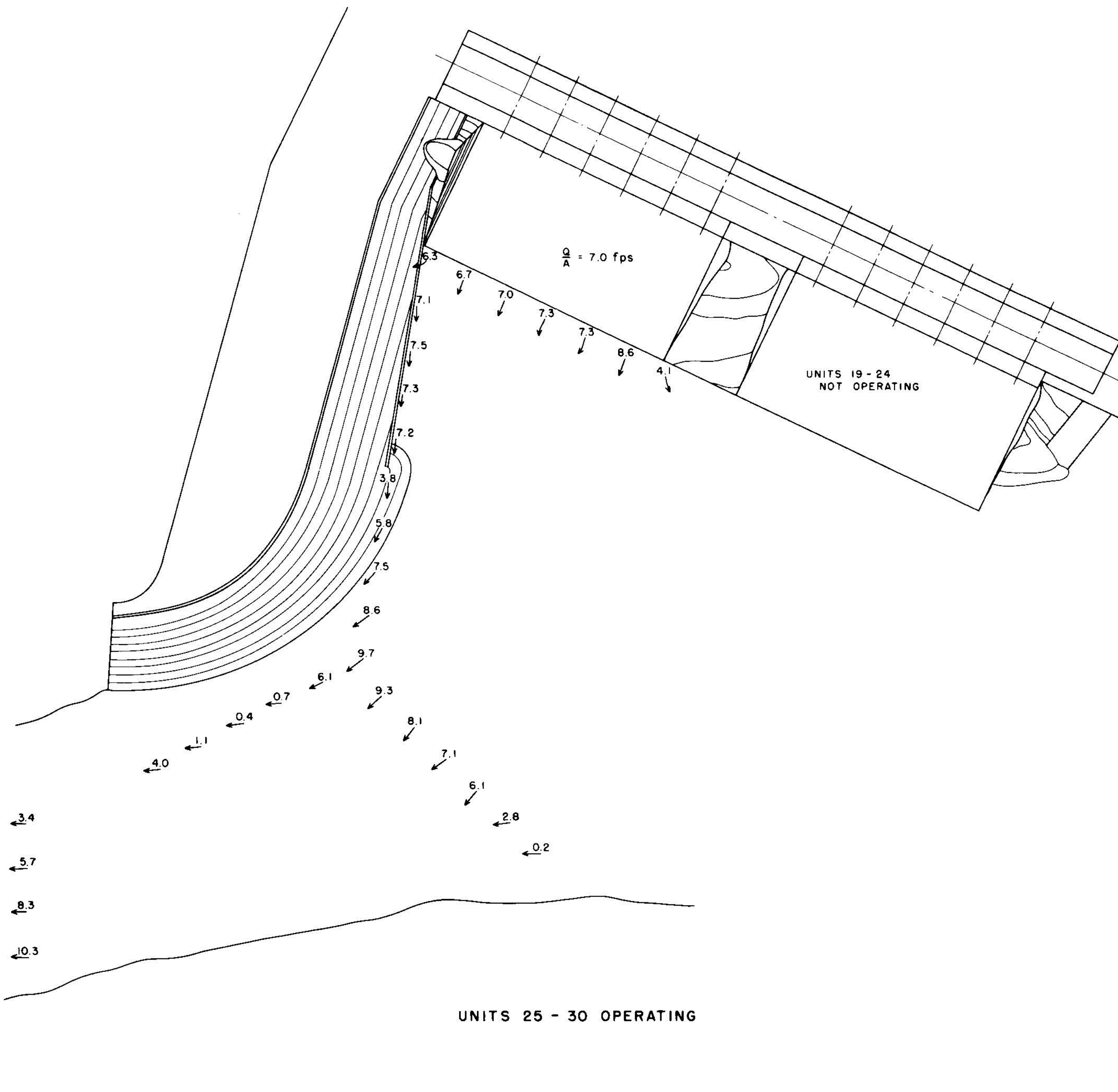


Figure 25. Velocities in preliminary 12-unit tailrace.

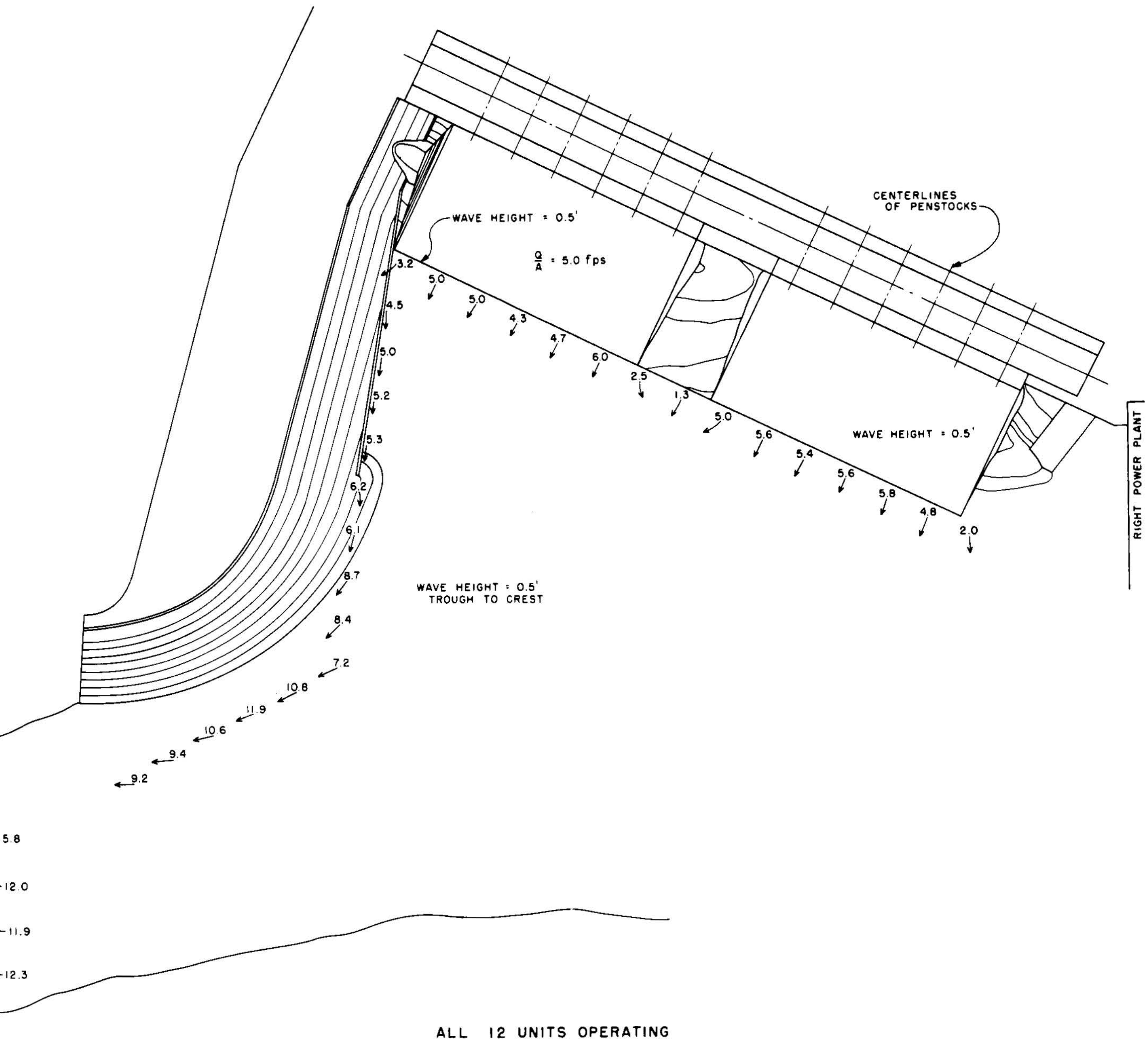
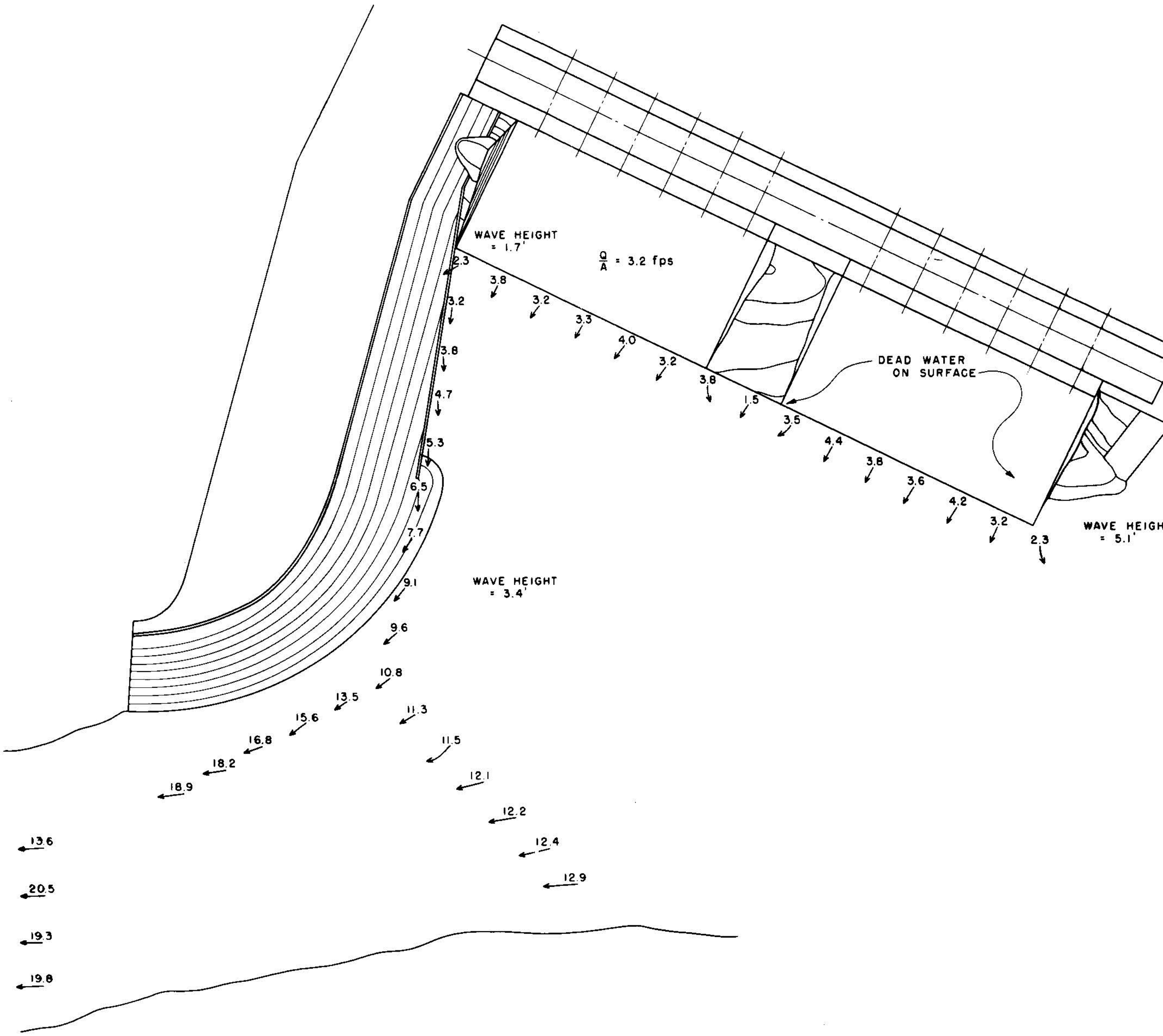


Figure 25. Velocities in preliminary 12-unit tailrace—Continued.



ALL 12 UNITS, EXISTING POWERPLANTS, AND SPILLWAY OPERATING

Figure 25. Velocities in preliminary 12-unit tailrace—Continued.

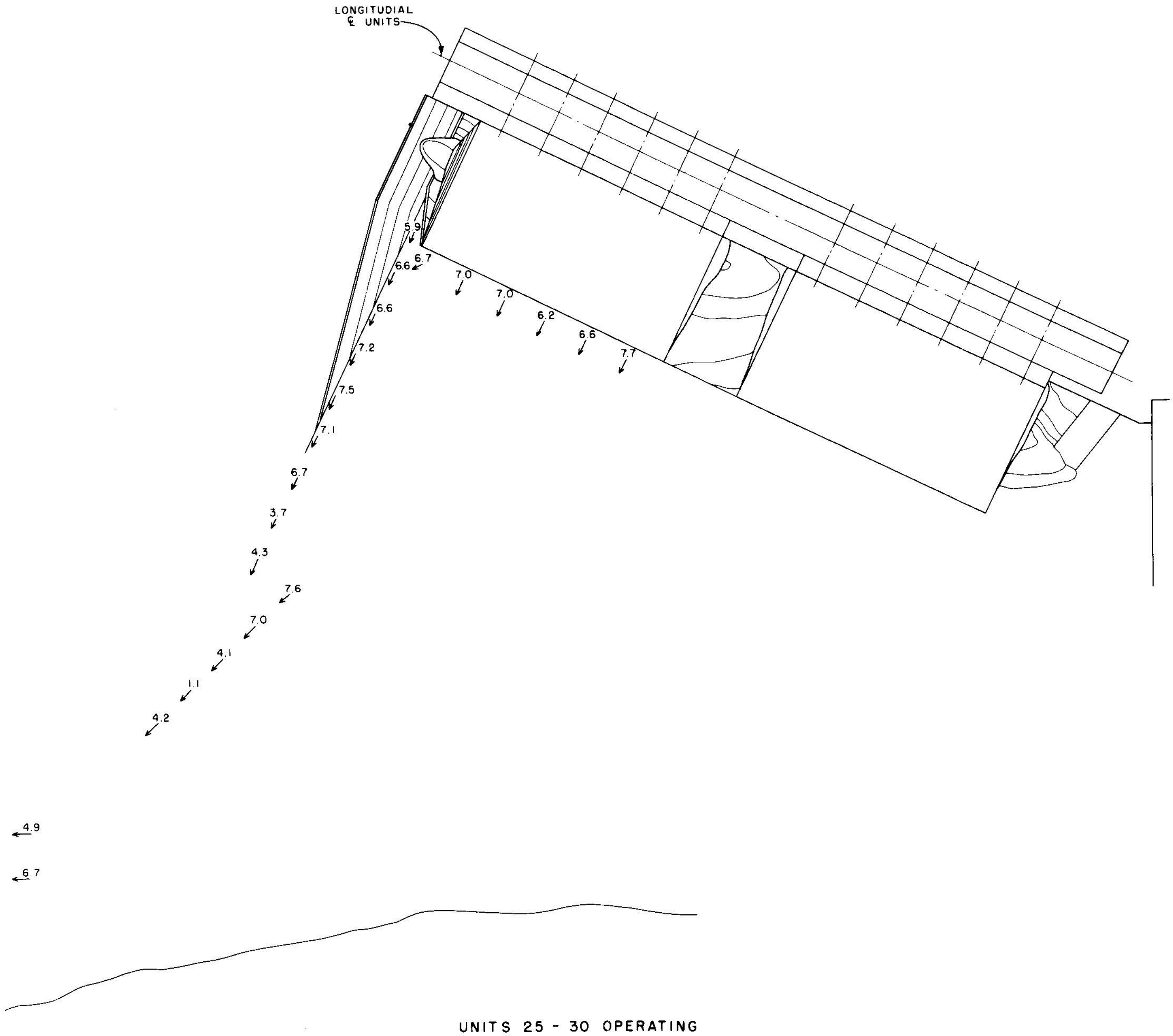
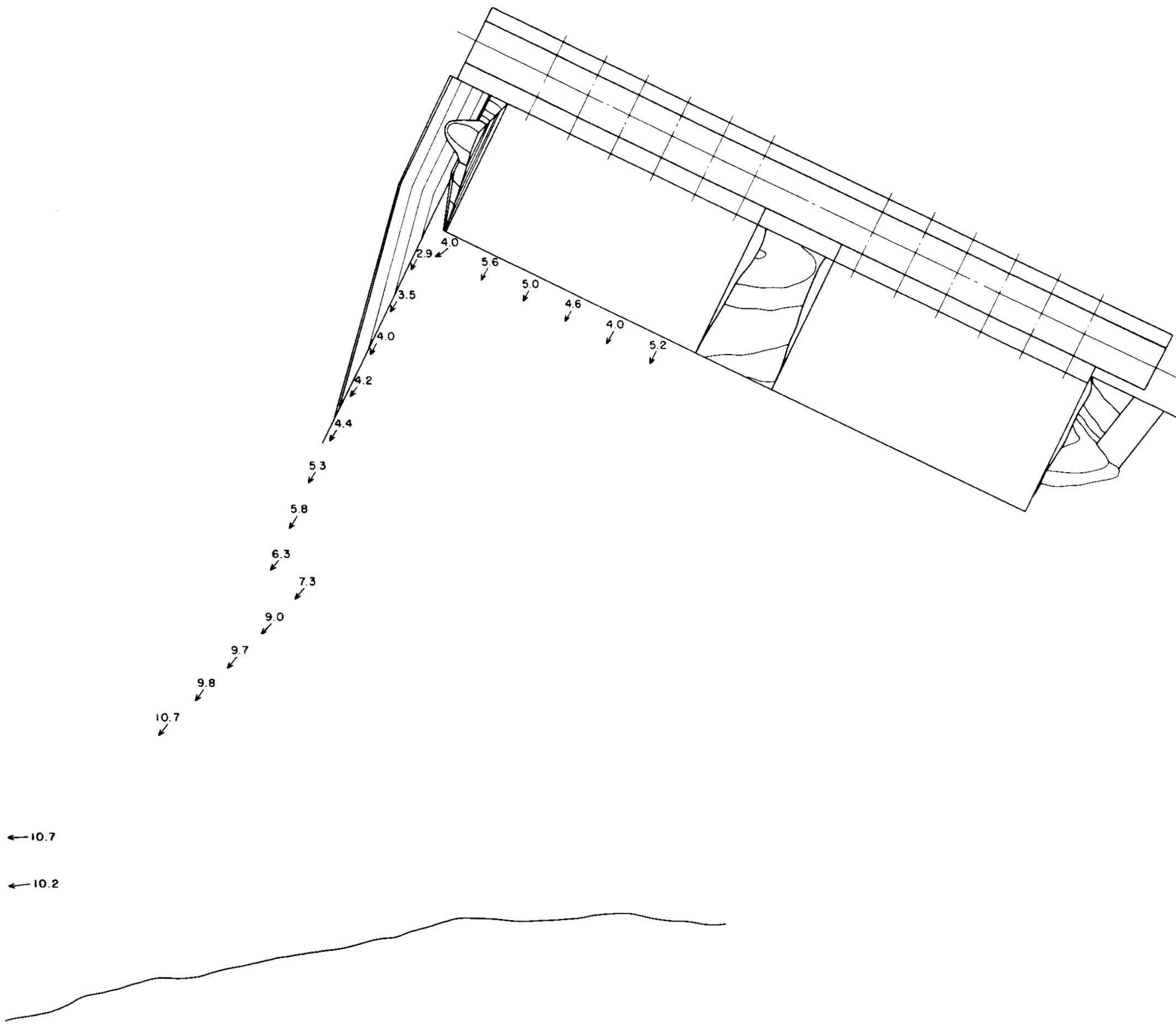
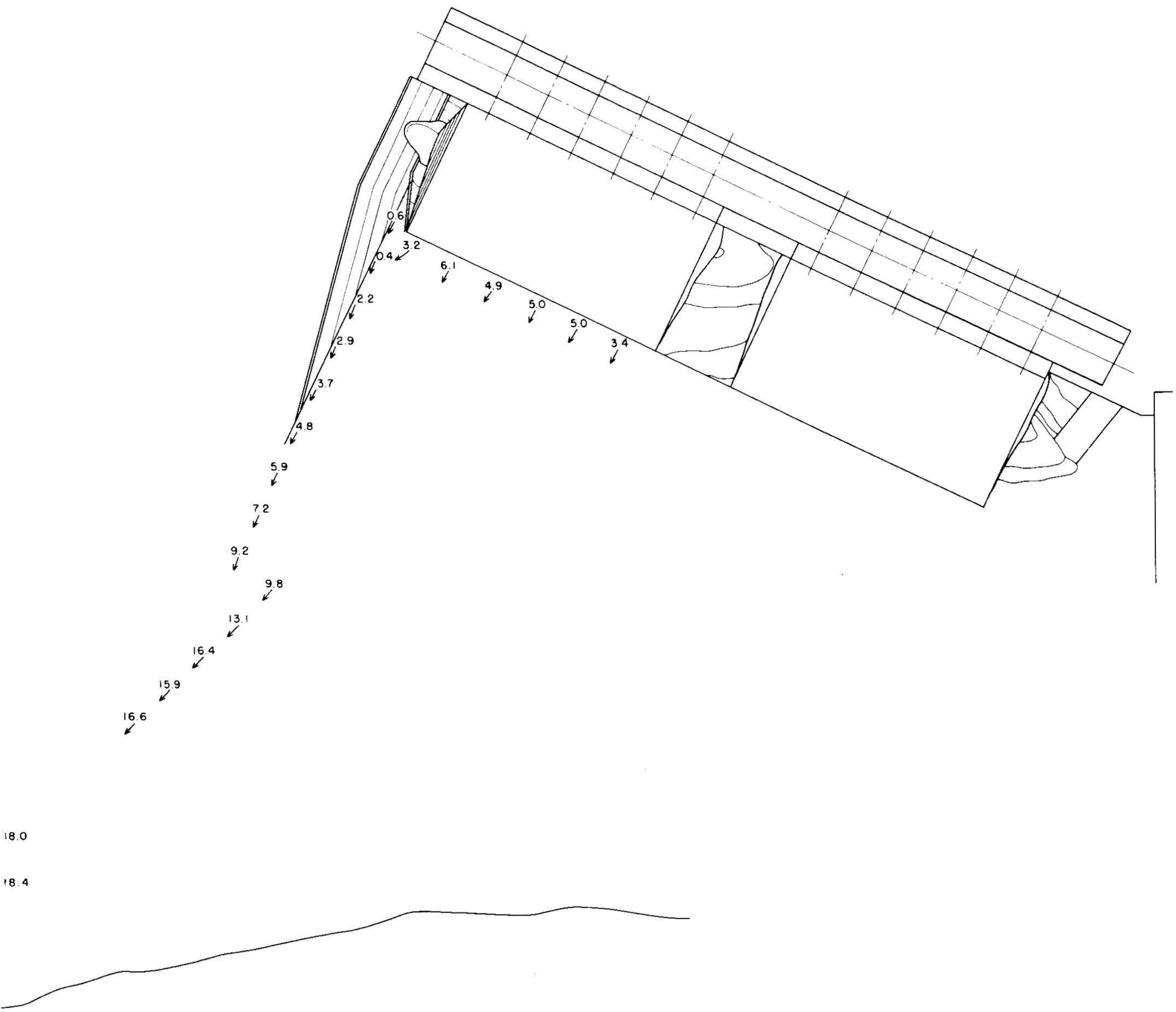


Figure 26. Velocities in recommended 12-unit tailrace.



ALL 12 UNITS OPERATING

Figure 26. Velocities in recommended 12-unit tailrace—Continued.



ALL 12 UNITS, EXISTING POWERPLANTS, AND SPILLWAY OPERATING

Figure 26. Velocities in recommended 12-unit tailrace—Continued.

During this phase of the testing, some movement of channel bed material was experienced in the prototype near the Left Powerplant. The model was used to evaluate the extent of this movement. Sand was placed in the model in the area adjacent to the Left Powerplant. After 1-1/2 hours of operation, with the Left Powerplant discharging alone at a capacity of 45,000 cfs, there was some indication of movement of sand toward the main channel. Also some beaching effect occurred at the water surface. However, no deposits were noted near the left training wall of the spillway. The model was then operated for about 1-1/2 hours with 45,000 cfs through the Left and Right Powerplants and about 750,000 cfs over the spillway. The tendency for the sand to move down the slope was noted. A sandbar was formed between the left tailrace channel and the main channel and a deposit existed on the downstream side of the roller bucket in the left one-third portion of the spillway. No deposit was noted near the left training wall.

Tailrace backwater tests.—Because of modifications to the channel banks downstream from the site, the need existed to evaluate the backwater effects of various bank configurations. If possible, attempts would be made to reduce the backwater to increase the power head. The channel was carefully shaped according to the latest cross section information; water surface elevation gages were located at positions corresponding to those in the prototype; and the model was operated at several required conditions. Water surface elevation gages in the model consisted of piezometer openings which were connected to a pressure transducer for very accurate measurement of the water surface.

The model was first operated with the existing tailrace configuration to determine model-prototype conformance. The data of Figure 27 show that this conformance was quite good. The correct water surface elevation was preset at the bridge gage.

The model was then operated with bridge gage water surface elevations set to correspond to computed elevations for operation with two different downstream channel configurations (A and B), and the tailrace configuration for the 6-unit Third Powerplant. The basic downstream channel configuration had been previously specified, and was denoted as fill channel "D". The water surface elevation data are shown in Figure 28. Figure 29 shows the total backwater existing between the Left Powerplant and the bridge gage, with downstream Channel A or B, for a full range of discharges from 0 to 1,000,000 cfs. These data show that Bank B is somewhat advantageous with respect to backwater effects. Comparison of the backwater effects of Banks A and B with the existing channel are shown in Figure 30.

Hydraulic transient tests.—The purpose of these tests was to determine the transient flow conditions occurring on the left bank of the tailrace channel during startup of the 6-unit Third Powerplant. The model was operated to simulate what was considered to be the most severe operating condition, with respect to startup of the units. The steady-state condition at the start of the test consisted of Unit 19 at full load with 31,500 cfs discharging. The existing plants were off. Units 20-24 were operated at a speed-no-load condition, 10 percent of the full-load discharge. The tailwater was set at elevation 949.2. Units 20-24 were then brought up to the full load in succession with each unit requiring 3 minutes (prototype). This operation would occur only under emergency conditions.

Instantaneous values of velocity, wave heights, and tailwater elevation were measured on the left bank near Station 27+77. This location was determined to be optimum for measurements by observing currents and by inspecting previous velocity data. The pitot tube and wave probe used for measuring velocity and waves are shown in Figure 31.

Two separate tests were performed. In the first test, an effort was made to simulate the tailwater change by operating the model tailgate. This proved to be unsatisfactory because (1) the exact relationship between time and tailwater elevation was not known, and (2) waves reflected from the moving tailgate affected results at the measuring point. A second test was performed in which the tailgate remained stationary. It was assumed that over the duration of the tests, waves did not have time to reach the downstream control point and travel back upstream to the model test section. If this assumption is incorrect, then the model represented a more severe condition than the prototype.

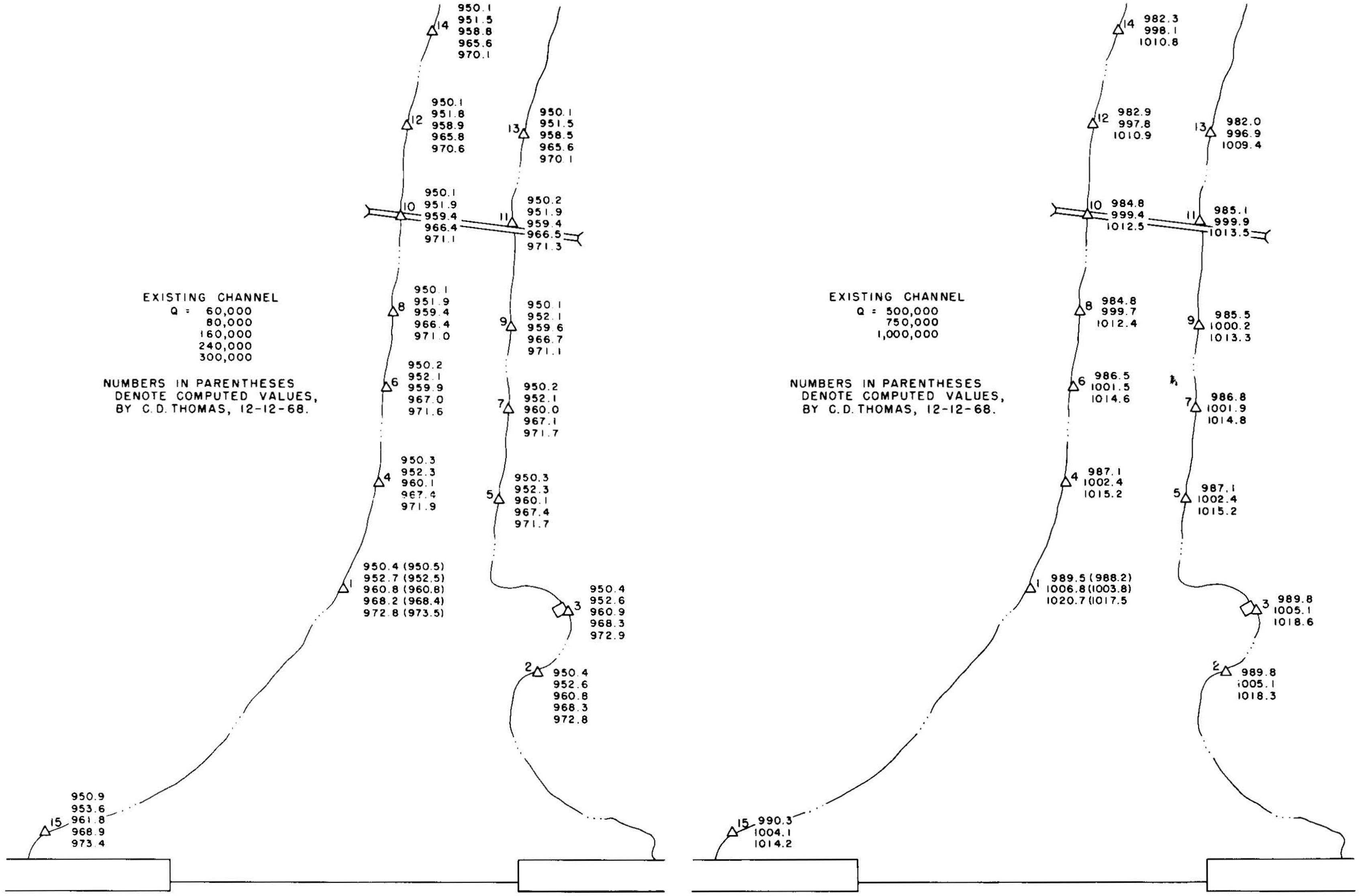


Figure 27. Water surface elevations in existing tailrace channel.

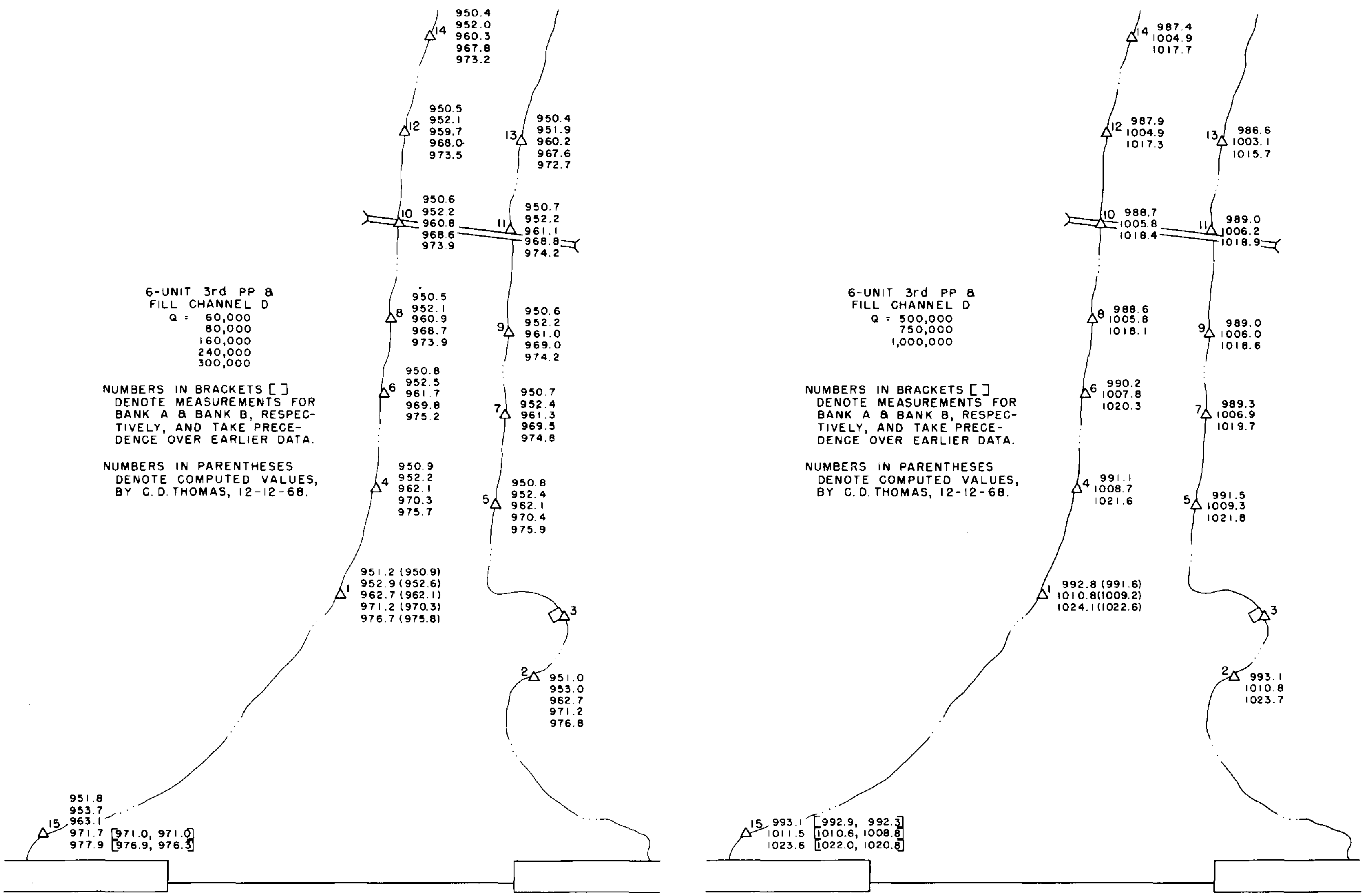


Figure 28. Water surface elevations with 6-unit Third Powerplant.

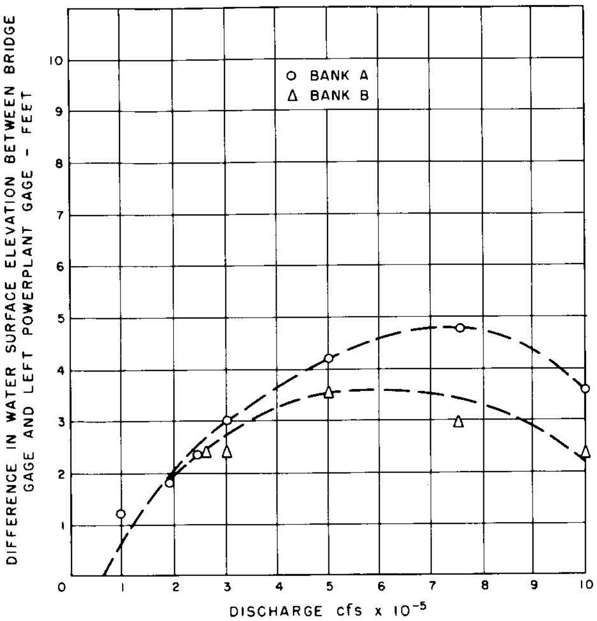


Figure 29. Total backwater between Left Powerplant and bridge gage, Banks A and B, steady flow.

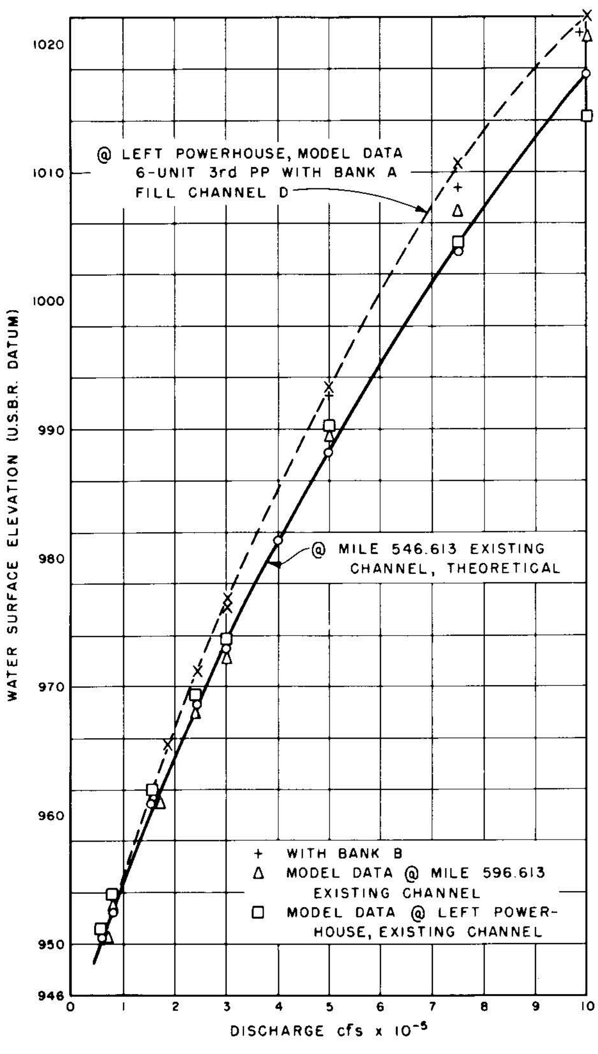


Figure 30. Backwater in existing and modified channels.

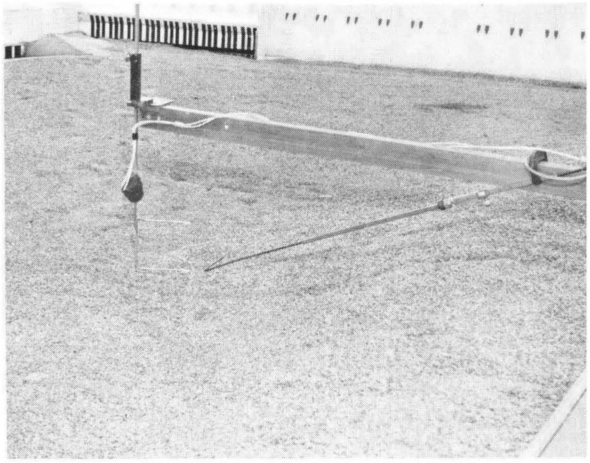


Figure 31. Pitot tube and wave probe used in hydraulic transient test. Photo P1222-D-73015

Wave and velocity data did not indicate the passage of a well-defined surge wave; instead, a gradual increase in the velocity and tailwater was indicated. Waves were too small to measure. The velocities were measured at about 20 feet and about 3 feet above the riverbed. These data are summarized in Figure 32. They do not indicate the presence of sudden increases in velocity or turbulent fluctuations which would cause damage to the bank material. Similar results would be expected for the 12-unit plant with gradual increase to the final velocities and tailwater level.

Figure 32 also shows that a near steady-state condition should occur about 30 minutes after the beginning of the operation. If the time required for the reflected wave to reach the tailrace is greater than 30 minutes, then the model results are valid. Otherwise, the measured velocities should be reduced to reflect the effect of the negative wave.

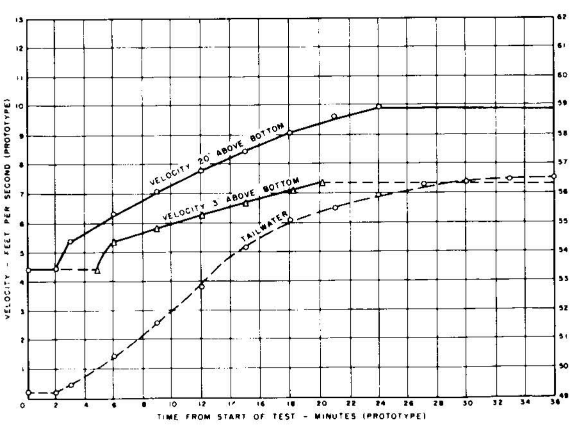


Figure 32. Results of hydraulic transient test.

7-1750 (3-71)
Bureau of Reclamation

CONVERSION FACTORS–BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, E 380-68) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given in the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg, that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Where approximate or nominal English units are used to express a value or range of values, the converted metric units in parentheses are also approximate or nominal. Where precise English units are used, the converted metric units are expressed as equally significant values.

Table I

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
	LENGTH	
Mil	25.4 (exactly)	Micron
Inches	25.4 (exactly)	Millimeters
Inches	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
Feet	0.3048 (exactly)*	Meters
Feet	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
Miles	1.609344 (exactly)	Kilometers
	AREA	
Square inches	6.4516 (exactly)	Square centimeters
Square feet	*929.03	Square centimeters
Square feet	0.092903	Square meters
Square yards	0.836127	Square meters
Acres	*0.40469	Hectares
Acres	*4,046.9	Square meters
Acres	*0.0040469	Square kilometers
Square miles	2.58999	Square kilometers
	VOLUME	
Cubic inches	16.3871	Cubic centimeters
Cubic feet	0.0283168	Cubic meters
Cubic yards	0.764555	Cubic meters
	CAPACITY	
Fluid ounces (U.S.)	29.5737	Cubic centimeters
Fluid ounces (U.S.)	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
Liquid pints (U.S.)	0.473166	Liters
Quarts (U.S.)	*946.358	Cubic centimeters
Quarts (U.S.)	*0.946331	Liters
Gallons (U.S.)	*3,785.43	Cubic centimeters
Gallons (U.S.)	3.78543	Cubic decimeters
Gallons (U.S.)	3.78533	Liters
Gallons (U.S.)	*0.00378543	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
Gallons (U.K.)	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	*764.55	Liters
Acre-feet	*1,233.5	Cubic meters
Acre-feet	*1,233,500	Liters

Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
MASS		
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams
Troy ounces (480 grains)	31.1035	Grams
Ounces (avdp)	28.3495	Grams
Pounds (avdp)	0.45359237 (exactly)	Kilograms
Short tons (2,000 lb)	907.185	Kilograms
Short tons (2,000 lb)	0.907185	Metric tons
Long tons (2,240 lb)	1,016.05	Kilograms
FORCE/AREA		
Pounds per square inch	0.070307	Kilograms per square centimeter
Pounds per square inch	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
Pounds per square foot	47.8803	Newtons per square meter
MASS/VOLUME (DENSITY)		
Ounces per cubic inch	1.72999	Grams per cubic centimeter
Pounds per cubic foot	16.0185	Kilograms per cubic meter
Pounds per cubic foot	0.0160185	Grams per cubic centimeter
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
MASS/CAPACITY		
Ounces per gallon (U.S.)	7.4893	Grams per liter
Ounces per gallon (U.K.)	6.2362	Grams per liter
Pounds per gallon (U.S.)	119.829	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
BENDING MOMENT OR TORQUE		
Inch-pounds	0.011521	Meter-kilograms
Inch-pounds	1.12985×10^6	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
Foot-pounds	1.35582×10^7	Centimeter-dynes
Foot-pounds per inch	5.4431	Centimeter-kilograms per centimeter
Ounce-inches	72.008	Gram-centimeters
VELOCITY		
Feet per second	30.48 (exactly)	Centimeters per second
Feet per second	0.3048 (exactly)*	Meters per second
Feet per year	$*0.965873 \times 10^{-6}$	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
Miles per hour	0.44704 (exactly)	Meters per second
ACCELERATION*		
Feet per second^2	*0.3048	Meters per second^2
FLOW		
Cubic feet per second (second-feet)	*0.028317	Cubic meters per second
Cubic feet per minute	0.4719	Liters per second
Gallons (U.S.) per minute	0.06309	Liters per second
FORCE*		
Pounds	*0.453592	Kilograms
Pounds	*4.4482	Newtons
Pounds	$*4.4482 \times 10^5$	Dynes

Table II—Continued

Multiply	By	To obtain
WORK AND ENERGY*		
British thermal units (Btu)	*0.252	Kilogram calories
British thermal units (Btu)	1,055.06	Joules
Btu per pound	2.326 (exactly)	Joules per gram
Foot-pounds	*1.35582	Joules
POWER		
Horsepower	745.700	Watts
Btu per hour	0.293071	Watts
Foot-pounds per second	1.35582	Watts
HEAT TRANSFER		
Btu in./hr ft^2 degree F (k, thermal conductivity)	1.442	Milliwatts/cm degree C
Btu in./hr ft^2 degree F (k, thermal conductivity)	0.1240	Kg cal/hr m degree C
Btu ft/hr ft^2 degree F	*1.4880	Kg cal m/hr m^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	0.568	Milliwatts/cm^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	4.882	Kg cal/hr m^2 degree C
Degree F hr ft^2/Btu (R, thermal resistance)	1.761	Degree C cm^2/milliwatt
Btu/lb degree F (c, heat capacity)	4.1868	J/g degree C
Btu/lb degree F	*1.000	Cal/gram degree C
Ft^2/hr (thermal diffusivity)	0.2581	Cm^2/sec
Ft^2/hr (thermal diffusivity)	*0.09290	M^2/hr
WATER VAPOR TRANSMISSION		
Grains/hr ft^2 (water vapor) transmission)	16.7	Grams/24 hr m^2
Perms (permeance)	0.659	Metric perms
Perm-inches (permeability)	1.67	Metric perm-centimeters

Table III

OTHER QUANTITIES AND UNITS

Multiply	By	To obtain
Cubic feet per square foot per day (seepage)	*304.8	Liters per square meter per day
Pound-seconds per square foot (viscosity)	*4.8824	Kilogram second per square meter
Square feet per second (viscosity)	*0.092903	Square meters per second
Fahrenheit degrees (change)*	5/9 exactly	Celsius or Kelvin degrees (change)*
Volts per mil	0.03937	Kilovolts per millimeter
Lumens per square foot (foot-candles)	10.764	Lumens per square meter
Ohm-circular mils per foot	0.001662	Ohm-square millimeters per meter
Millicuries per cubic foot	*35.3147	Millicuries per cubic meter
Milliamps per square foot	*10.7639	Milliamps per square meter
Gallons per square yard	*4.527219	Liters per square meter
Pounds per inch	*0.17858	Kilograms per centimeter

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ABSTRACT

The water treaty with Canada, making possible additional water storage upstream from Grand Coulee Dam, and the historic large releases wasted over the spillway, contributed to the conception of a Third Powerplant at Grand Coulee. This powerplant will ultimately house twelve 600-Mw units. Six units have been authorized and construction has started, with three units to be installed in the initial phase. Because each unit has a discharge capacity of approximately 30,000 cfs, unusual problems of design in the forebay and tailrace of the new powerplant could be foreseen. A 1:120 scale model study showed the need for extensive revisions in the design of the forebay channel, and minor revisions in the tailrace configuration. A vortex formation noted above the penstock entrances prompted an additional study which will be reported separately. Observations and measurements were made in the forebay channel and tailrace for both 6- and 12-unit plant operation. Results of these studies are presented.

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Bur Reclam Rep REC-ERC-73-2, Div Gen Res, Feb 1973. Bureau of Reclamation, Denver, 25 p, 32 fig, 2 tab

DESCRIPTORS--/ *forebays/ gravity dams/ hydraulic structures/ angle of approach/ backwater/ channels/ eddies/ head losses/ *model tests/ open channel flow/ permissible velocity/ *tailrace/ vortices/ current meters/ instrumentation/ erosion/ hydroelectric powerplants/ hydraulic design/ velocity distribution
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