REC-ERC-72-5

HYDRAULIC MODEL STUDIES OF THE FOREBAY RESERVOIR INLET-OUTLET STRUCTURE FOR MT. ELBERT PUMPED-STORAGE POWERPLANT, FRYINGPAN-ARKANSAS PROJECT, COLORADO

P. L. Johnson
Engineering and Research Center
Bureau of Reclamation

January 1972

MS-230 (8-70)
Bureau of Reclamation

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. REC-ERC-72-5	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE Hydraulic Model Studies of the Forebay Reservoir Inlet-Outlet Structure for Mt. Elbert Pumped-Storage Powerplant, Fryingpan-Arkansas Project, Colorado		5. REPORT DATE Jan 72
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) P. L. Johnson		8. PERFORMING ORGANIZATION REPORT NO. REC-ERC-72-5
9. PERFORMING ORGANIZATION NAME AND ADDRESS Engineering and Research Center, Bureau of Reclamation, Denver, Colorado 80225		10. WORK UNIT NO.
		11. CONTRACT OR GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Same		13. TYPE OF REPORT AND PERIOD COVERED
		14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Hydraulic model studies were performed to assure satisfactory flow conditions through the forebay reservoir inlet-outlet structure for Mt. Elbert Pumped-Storage Powerplant, Colorado. The main purpose for the studies was to develop a design to provide a uniform velocity distribution at the trashracks during the pumped cycle. Uniform velocity distribution would minimize the possibility of forming strong vortex shedding and reduce the forces causing trashrack fatigue failure. Flow conditions for the generating cycle were evaluated to ensure a uniform velocity distribution free of air entraining surface vortices. Head loss measurements were made for the inlet-outlet structure. A horizontal deflector with flip blocks was developed to improve the vertical velocity distribution at the trashrack position. A flat upward sloping floor was developed to replace the original concave floor in the structure. Two devices were developed to suppress generation of surface vortices.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS-- / *pumped storage/ hydraulic models/ *intake transitions/ *outlets/ flow characteristics/ flow distribution/ head losses/ trashracks/ model tests/ *velocity distribution/ vortices/ water surface/ design modifications/ disturbances/ *model studies

b. IDENTIFIERS-- / Fryingpan-Arkansas Proj, Colo/ Mount Elbert Pump-Storage Plt, Colo

c. COSATI Field/Group 13G

18. DISTRIBUTION STATEMENT *Available from the National Technical Information Service, Operations Division, Springfield, Virginia 22151.*	19. SECURITY CLASS (THIS REPORT) *UNCLASSIFIED*	21. NO. OF PAGES 16
	20. SECURITY CLASS (THIS PAGE) *UNCLASSIFIED*	22. PRICE

REC-ERC-72-5

HYDRAULIC MODEL STUDIES OF THE FOREBAY RESERVOIR INLET-OUTLET STRUCTURE FOR MT. ELBERT PUMPED-STORAGE POWERPLANT, FRYINGPAN-ARKANSAS PROJECT, COLORADO

by

P. L. Johnson

January 1972

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
Ellis L. Armstrong, Commissioner

ACKNOWLEDGMENT

The studies, conducted by the author, were reviewed and supervised by D. L. King, Applied Hydraulics Section Head. The final plans that evolved from these studies were developed through the cooperation of the Hydraulics Branch, Division of General Research, and the Hydraulic Structures Branch, Division of Design, at the Bureau of Reclamation Engineering and Research Center, during the period October 1970 through July 1971.

CONTENTS

LIST OF FIGURES

PURPOSE

These studies were made to assist in developing a satisfactory forebay inlet-outlet structure for the Mt. Elbert Pumped-Storage Powerplant, Colorado.

RESULTS

1. Flow concentrations were observed in the inlet-outlet structure during the pumping cycle. These flow concentrations were indicated by high- and low-velocity areas in sections where velocity distribution data were taken.

2. A deflector placed in the inlet-outlet structure significantly improved the velocity distribution in a vertical plane at the trashrack section for pumped flow.

3. A flat floor rising from an elevation of 9566.5 ft (2915.9 m) at the stoplog section to an elevation of 9580.5 ft (2920.1 m) at the base of the trashrack section was found to be satisfactory. This replaced the initial concave upward-shaped floor that connected the two points.

4. In the preliminary structure, a tendency for vortex formation was observed during the generating cycle for both one- and two-unit operation. The tendency was observed at all reservoir water-surface elevations between 9615 ft (2930.6 m) and 9640 ft (2938.3 m).

5. Two successful structures for vortex suppression were developed. The first consisted of a raft that was floated over the vortex. It supplied a simple, yet effective solution for all operating conditions. The raft did not eliminate the swirling flow, but it did eliminate air intake into the penstocks. The second successful vortex suppression structure consisted of a lattice-like wall extending from the top edge of the trashracks to an elevation of 9621 ft (2932.3 m). The wall extended upward on a 1:3 slope (perpendicular to trashrack face). Walls corresponding to both steel and reinforced concrete structures were tested and found satisfactory. As in the case of the raft, the walls did not eliminate the swirling flow, but they did eliminate air intake into the penstocks.

6. The observed head losses through approximately 124 ft (37.8 m) of penstock and the inlet-outlet structures for pumping flow were found to be 2.27 ft (0.692 m) for the initial unit and 2.46 ft (0.750 m) for the future unit. The corresponding pumping cycle resistance coefficient (head loss/velocity head in penstock) values are 0.48 and 0.52, respectively. The observed head losses for generating flow were found to be 2.18 ft (0.664 m) for the initial unit and 2.45 ft (0.747 m) for the future unit. The corresponding generating cycle resistance coefficient values are 0.34 and 0.38, respectively.

APPLICATION

The results of these studies are generally applicable only to structures with similar geometrical configurations. These studies may be useful in initial evaluation of similar problems.

INTRODUCTION

The Fryingpan-Arkansas Project is a multipurpose transmountain diversion development. It will make surplus water from the western slope of the Rocky Mountains available to inhabitants of the eastern slope (Figure 1). The water will be used for municipal, industrial, and irrigation purposes. Mt. Elbert Pumped-Storage Powerplant (Figure 2) is one of two powerplants to be constructed on this project. These powerplants will produce power from the water as it descends to the eastern plains. The prime contract for construction of Mt. Elbert is described in Specifications No. DC-6915.

Mt. Elbert Pumped-Storage Powerplant will eventually produce 200,000 kw of power with two units. These units will be reversible pump-turbine facilities. Each unit will have a 15-ft (4.57-m) diameter penstock that will connect it to a 10,000-acre-ft (12,335,000-m^3) forebay reservoir (Figure 2). The length of each penstock will be approximately 3,000 ft (944 m). The maximum water-surface elevation in the forebay (upper) reservoir will be 9646.8 ft (2940.3 m) while the absolute minimum water-surface elevation will be 9615 ft (2930.7 m). The lower water supply for the pump-turbine units will be Twin Lakes (Figure 2). The maximum active water surface for Twin Lakes will be 9208.5 ft (2806.8 m) and the minimum active water surface will be at 9168.7 ft (2794.7 m). The maximum static head will therefore be 478.1 ft of water (145.6 m). The maximum discharge through each penstock will be about 3,600 cfs (101.94 cu m/sec) during the generating cycle and 3,090 cfs (87.50 cu m/sec) during the pumping cycle. Initially, only one unit and one complete penstock will be installed with the other following at a future date. The first unit to be installed will be the west one and will be referred to as the initial unit in this report. The east unit will be referred to as the future unit.

Because of the possibility of unsatisfactory flow conditions, a hydraulic model study of the forebay

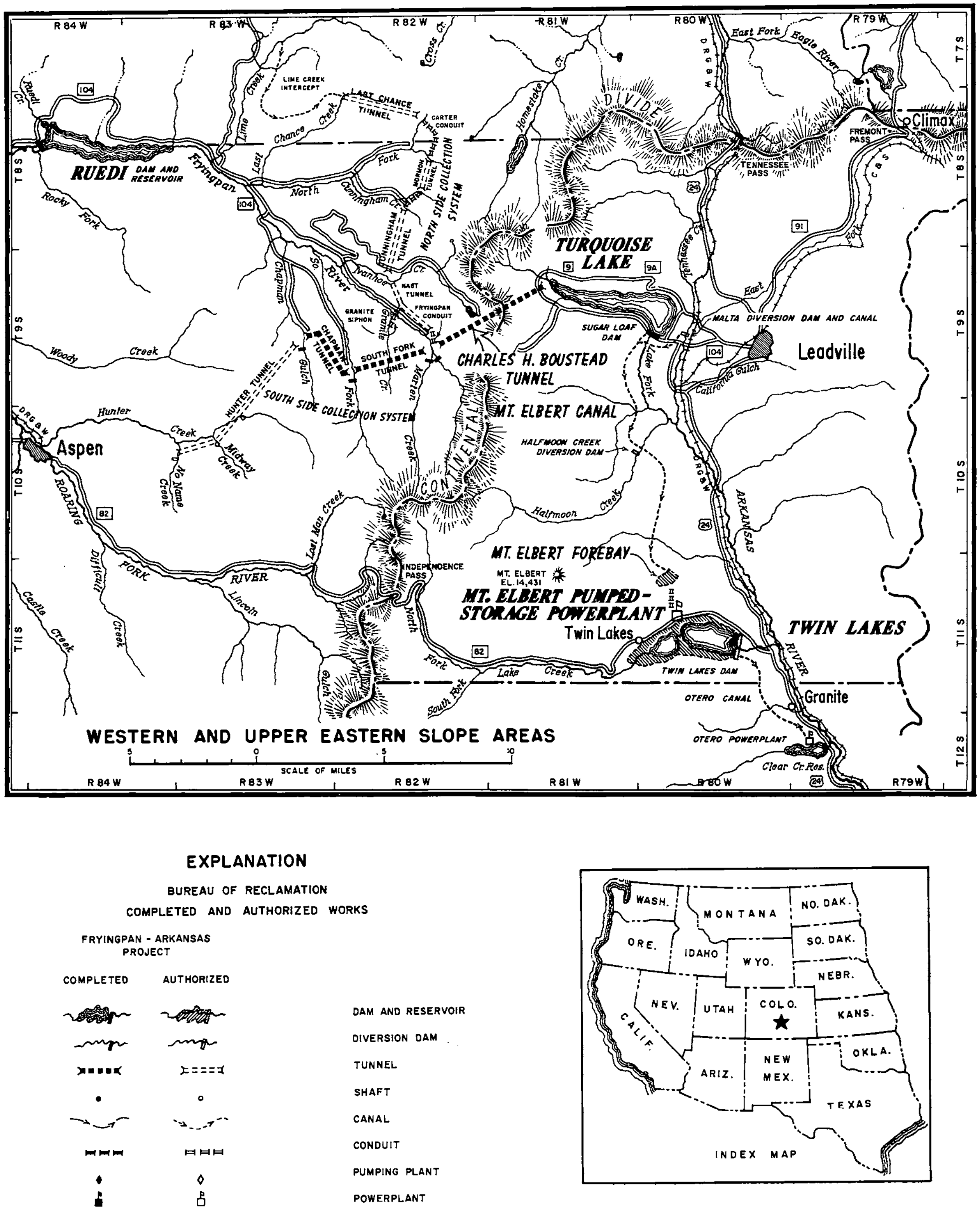


Figure 1. Location map.

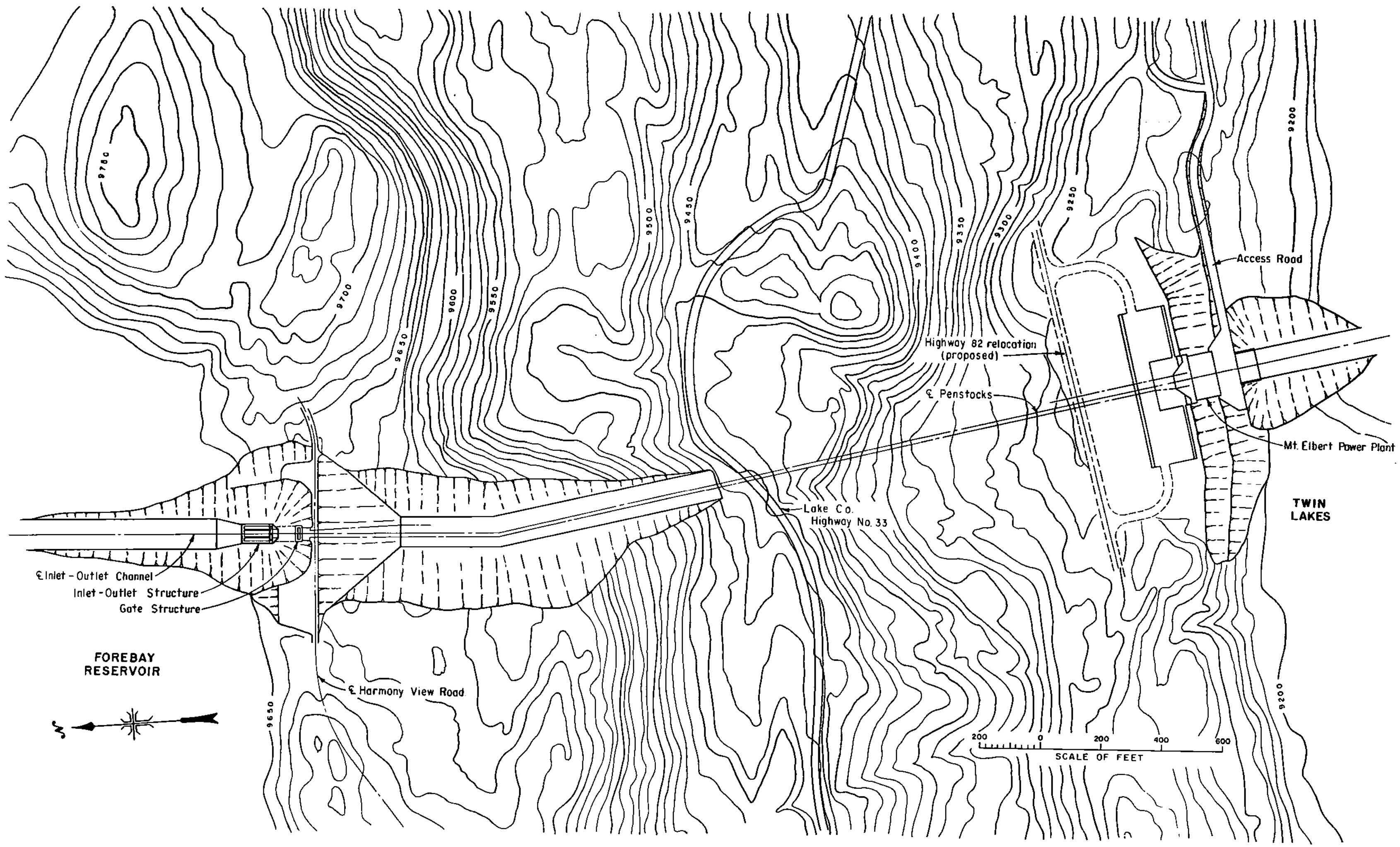


Figure 2. Project map.

reservoir inlet-outlet structure was initiated. The main reason for the model study was to obtain a design which would insure a proper velocity distribution at the trashracks so that there would be no high-velocity areas, jets, or reverse flows present. This would eliminate any chance for formation of strong vortex shedding and vibration and thus insure a trashrack which would not be subject to fatigue failure. The testing would also provide information to insure satisfactory flow conditions during the generating cycle. This would include control or elimination of surface vortices. Finally, the testing would evaluate head loss through each unit for both the pumping and generating cycles.

Dimensions used in this report, unless otherwise stated, refer to the prototype structure. Minor modifications were made to the structure design after the completion of the model study but their effect on the study results is considered negligible.

THE MODEL

Because of the availability of 7.75-inch (19.7-cm) inside diameter clear plastic pipe, and with consideration given to the physical properties of the prototype, a model scale of 1:23.23 was selected. The 7.75-inch (19.7-cm) clear plastic pipe was therefore used to represent the upper portions of both penstocks (Figures 3 and 4). The remaining portions of the penstocks were modeled with steel pipe. The rectangular-to-circular transitions, the gate sections, and inlet-outlet structure were fabricated from sheet metal (Figures 3 and 4). The topography at the forebay reservoir was modeled in concrete (Figure 4). The maximum discharges of 3,090 cfs (87.50 cu m/sec) for the pumping cycle and 3,600 cfs (101.94 cu m/sec) for the generating cycle for one unit were represented in the model by 1.187 cfs (0.0336 cu m/sec) and 1.385 cfs (0.0392 cu m/sec), respectively. The model was arranged so that both pumping and generating flow could be simulated. Discharges were measured with venturi and venturi-orifice meters.

THE INVESTIGATION

Test Procedure

In the analysis of the inlet-outlet structure, velocity distribution data were taken at two sections in the system. One section contained the trashracks and the other contained the stoplog slots. A majority of the velocities was measured with a small propeller-type flowmeter. A cup-type flowmeter and a Pitot tube

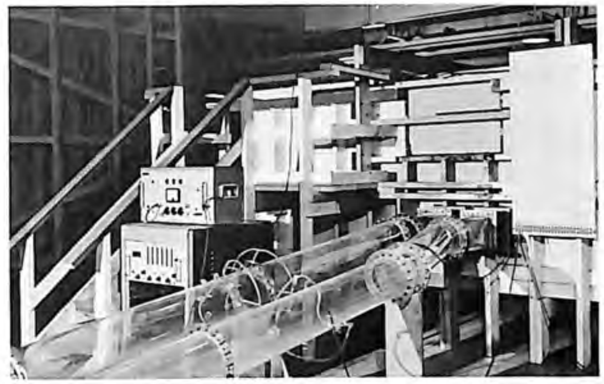


Figure 3. 1:23.23 scale model penstocks. Photo PX-D-70819

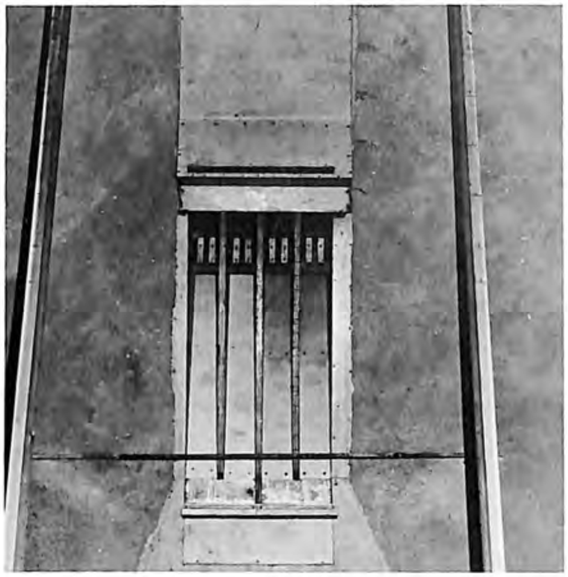
were also used. In all cases, however, only average flow velocity data were taken. The severity of the velocity fluctuations was evaluated by the author as the average flow velocity data were collected. The velocities were measured in a grid-type pattern at each section.

Head loss data were obtained for the inlet-outlet structures including 124 ft (37.8 m) of attached penstock. The data were obtained through the use of two piezometer ring-manifolds (one tapping each penstock), one piezometer that tapped the reservoir, and three open water-manometers (Figure 4). The piezometer ring-manifolds were approximately 124 ft (37.8 m) from the section where the penstock attaches to the circular-to-rectangular transitions.

Data were taken with various reservoir water-surface elevations. It is, however, believed that the 9615 ft (2930.7 m) water-surface elevation is critical with respect to velocity distribution and vortex formation. This elevation is the absolute minimum operating water surface for the forebay reservoir.

Pumping Cycle

Hydraulic analysis of the inlet-outlet structure began with the realization, based on previous experience, that a deflector would be required to obtain a satisfactory pumped flow velocity distribution through the trashrack sections. To verify this experience and to obtain knowledge of the flow distribution that would be modified, the initial inlet-outlet structure (Figure 5) was studied without a deflector. Coarse, rapid velocity distribution data were taken at the trashrack section and at a section near the stoplog section. The cup flowmeter was used to obtain these data. It was observed that the flow was concentrated over an area covering approximately one-half of the total stoplog



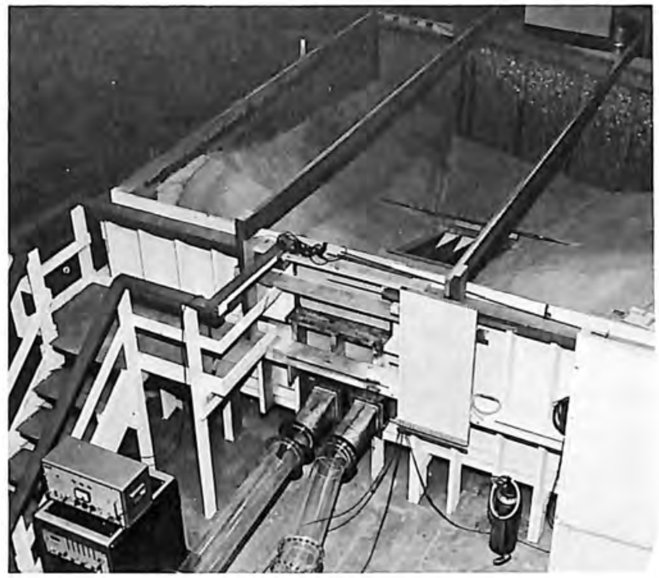


Figure 4. 1:23.23 scale model of inlet-outlet structure and penstocks. Left Photo PX-D-70820, right Photo PX-D-70818

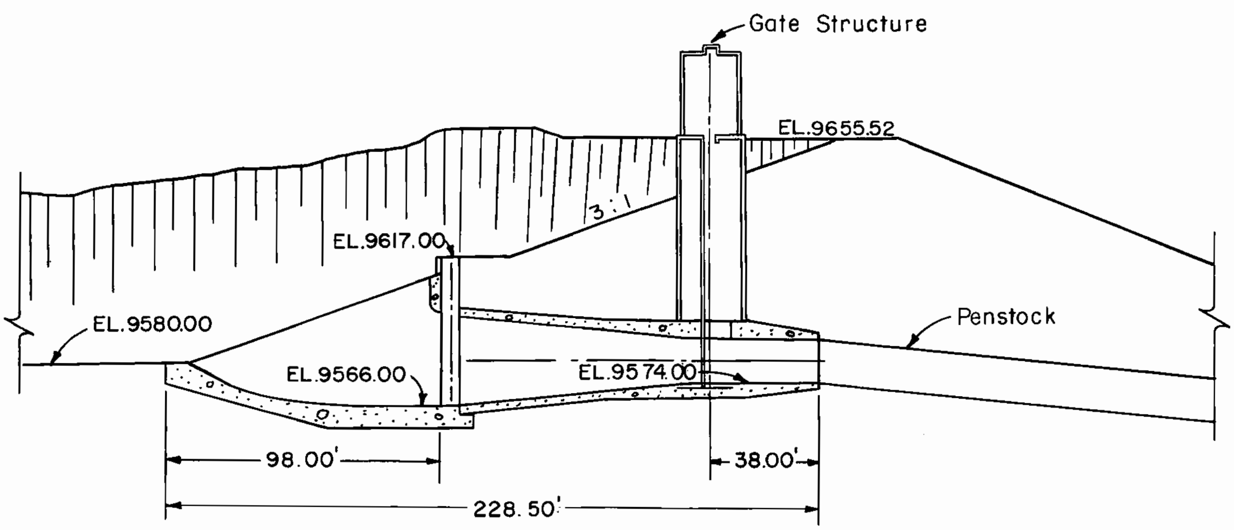
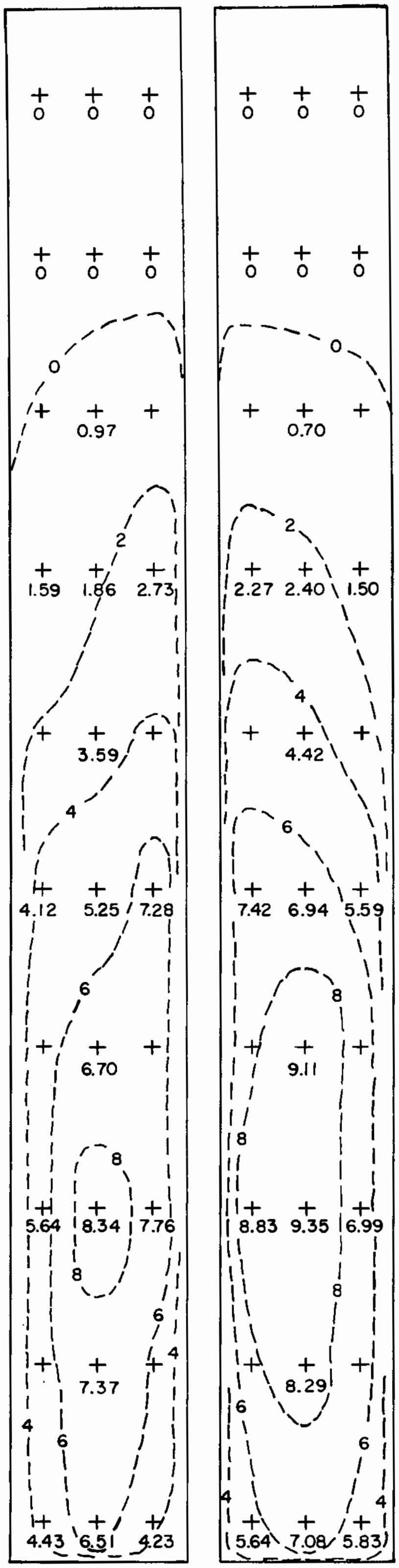


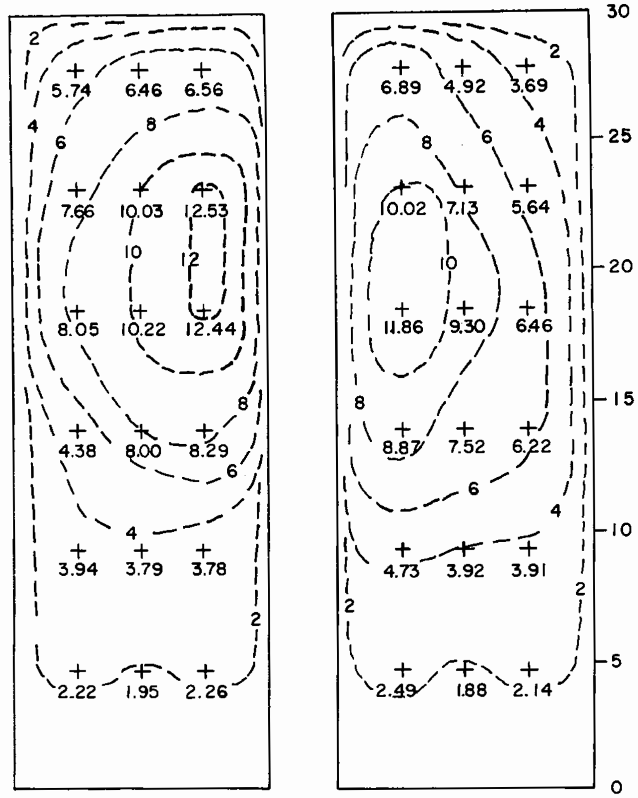
Figure 5. Preliminary inlet-outlet structure.

section area (Figure 6). The total height of the stoplog section was 30 ft (9.14 m). It was also observed that the same flow was concentrated in the lower half of the trashrack section. The maximum velocity observed at the trashrack section was 9.35 fps (2.85 m/sec). From this information, it was concluded that as the pumped flow leaves the penstock it rises for a short distance. It is believed that this flow rise is a result of the momentum established by the rising penstocks. It was, however, observed that there was very little flow rise between the stoplog section and the trashrack section; the flow was nearly horizontal. It was also observed that the rising floor concentrated the flow and therefore increased the flow velocities near the bottom.

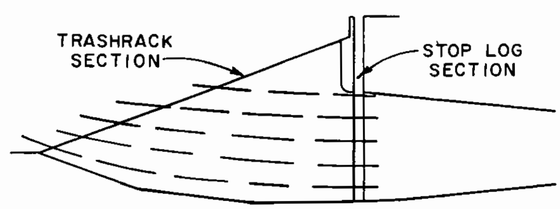
To improve the velocity distribution at the trashrack section, several flow deflectors were tried. Initial deflectors (Figure 7), both straight and doglegged upward, were constructed to represent 1-ft (0.30-m) thick flat slabs. The angle of rise, from horizontal, for the deflectors varied from 10° to 22°. The deflectors



TRASHRACK SECTION VELOCITY DISTRIBUTION
LOOKING IN DIRECTION OF GENERATING FLOW



STOP LOG SECTION VELOCITY DISTRIBUTION
LOOKING IN DIRECTION OF PUMPED FLOW



APPROXIMATE STREAMLINES

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

Figure 6. Velocity distribution, preliminary inlet-outlet structure, pumping cycle (initial unit).

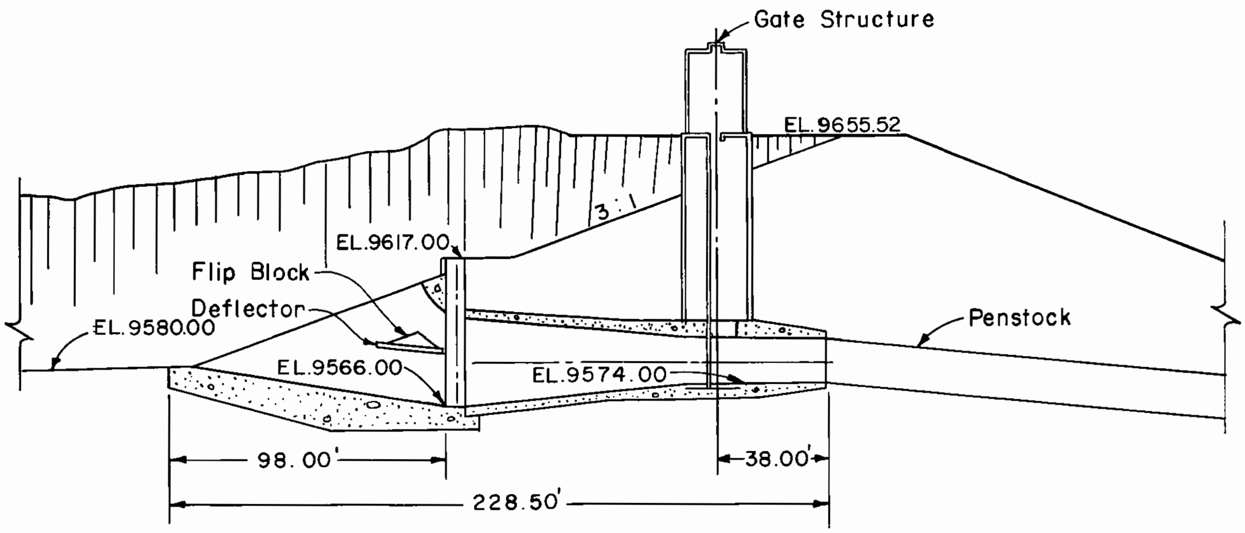


Figure 7. Final inlet-outlet structure.

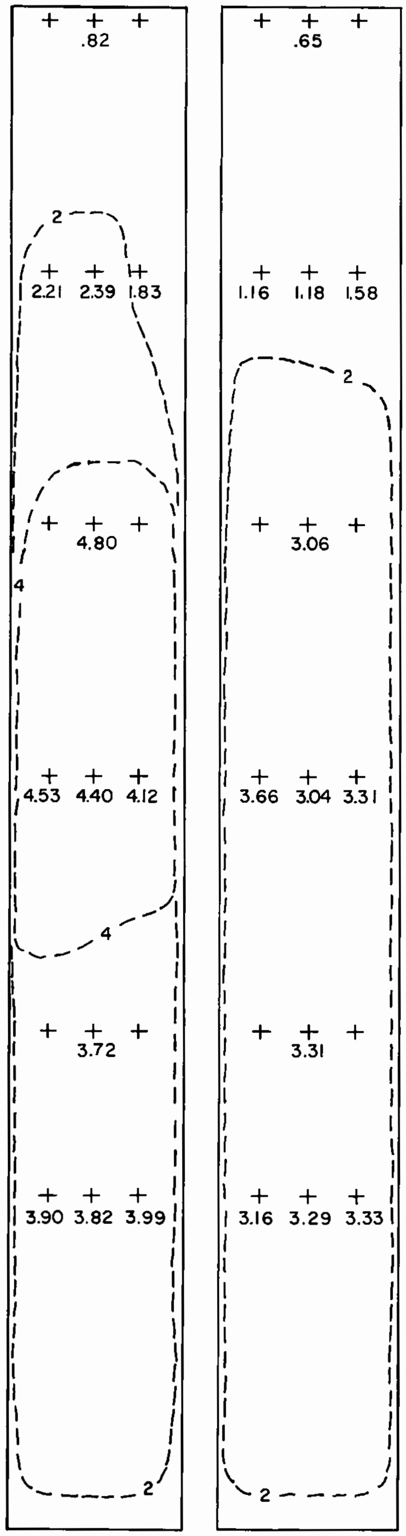
were located at several levels in the structure in an attempt to find their most effective position. It was observed that very high-velocity areas were created just above the deflector and low-velocity areas were created just below. When such deflectors were allowed to run from the stoplog section to the trashrack section, velocities as high as 9.20 fps (2.82 m/sec) were observed at the trashrack section. It was also noticed that the deflectors were only partially successful in increasing flow in the upper half of the trashrack section. To improve the deflector operation, two alterations were tried. The first was to shorten the deflector's length to 25 ft (7.62 m). The deflector therefore ran from the stoplog section to a position approximately halfway between the stoplog section and the trashrack section (Figure 7). This allowed mixing of the pumpedflow downstream from the deflector prior to reaching the trashrack section. Flow at the trashrack section was more uniform and flow velocity variations were less pronounced. Flip-type blocks were also placed on the upper face of the deflector. The blocks forced a portion of the pumpedflow into the upper areas of the trashrack section (Figure 8). With these two modifications, the final deflector design was obtained (Figure 7). It was observed that a maximum flow velocity of 4.8 fps (1.46 m/sec) occurred at the trashrack section (Figure 8).

Less complete velocity distribution data were collected for the future inlet-outlet structure. The observed velocity distributions were similar to those obtained for the initial structure. It was observed, however, that the flow was mildly concentrated in the right-hand bay (looking in the direction of pumped flow). It was felt that this concentration was probably due to the miter bends in the future penstock (Figures 3 and 4). These bends do not exist in the initial penstock. The obtained trashrack velocity distribution was satisfactory and the deflector appeared to be effective.

A final consideration was given to the necessity of an upward facing concave floor in the inlet-outlet structures. Testing was done to evaluate a straight, upward sloping floor (Figure 7) that ran from the stoplog section to the end of the structure. No worsening of the velocity distribution was observed. With the modification of this floor, the final recommended inlet-outlet structure was obtained (Figure 7).

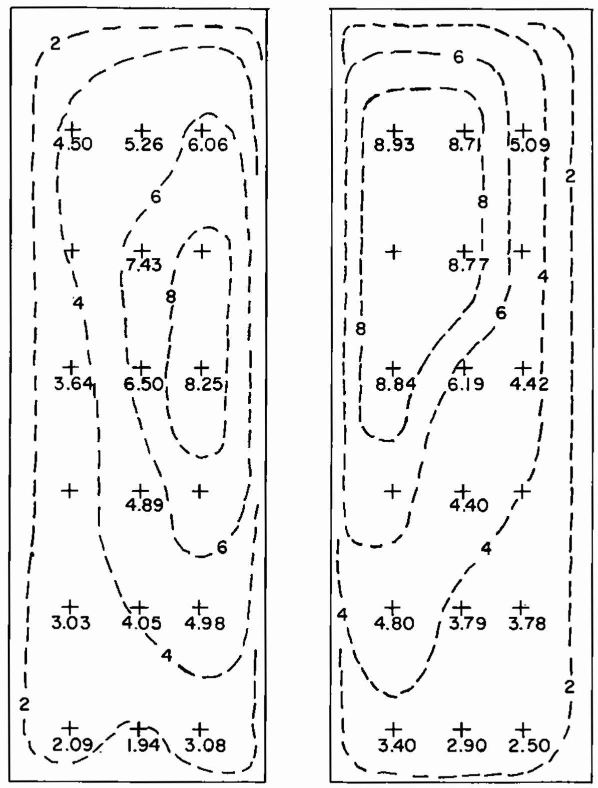
With the final configuration of the inlet-outlet structure determined, the forebay reservoir water surface conditions were evaluated during pumped operation. It was noted that the severity of the water surface disturbance was not increased for two-unit operation as compared to one-unit operation. The extent of the disturbance was, however, wider spread for two-unit operation. The disturbance consisted of mild boils extending approximately 100 ft (30.5 m) downstream from the area directly above the trashracks. The maximum observed boil height was approximately 1 ft (0.3 m).

Head loss data were taken for the recommended inlet-outlet structure with the deflector in place. The observed head loss coefficients (the ratio of head loss through the system to the velocity head of the flow in the penstock) stabilized with respect to Reynold's number (VD/ν where V is the average flow velocity in



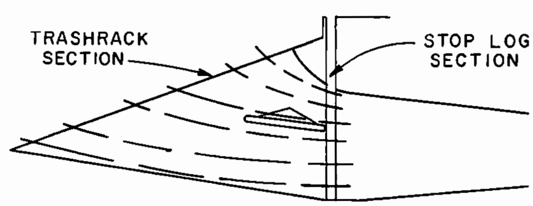
TRASHRACK SECTION VELOCITY DISTRIBUTION

LOOKING IN DIRECTION OF GENERATING FLOW



STOP LOG SECTION VELOCITY DISTRIBUTION

LOOKING IN DIRECTION OF PUMPED FLOW



APPROXIMATE STREAMLINES

VELOCITY DISTRIBUTION

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

Figure 8. Velocity distribution, final inlet-outlet structure, pumping cycle (initial unit)

the penstock, D is the diameter of the penstock, and υ is the kinematic viscosity) at 0.48 for the initial unit and 0.52 for the future unit (Figure 9). The Reynold's number values are related to the values of the resistance coefficients to show that above a certain value the resistance coefficient becomes constant. It was observed that the above resistance coefficients became constant at Reynold's numbers of 5.4 by 10^4 and 4.3 by 10^5, respectively (Figure 9). Corresponding Reynold's numbers in the prototype will be several times greater than those at which the model loss coefficients become constant, and therefore the obtained resistance coefficients are applicable to the prototype.

Generating Cycle

The recommended design obtained through evaluation of the pumping cycle flow (Figure 7) was then evaluated for generating cycle flow. Once again velocity distribution data were taken at the trashrack and stoplog sections. For these tests, the reservoir water level was held at elevation 9615 ft (2930.6 m). Velocity distribution data were taken for the inlet-outlet structure with and without the deflector. Head loss data were also taken for the generating cycle.

Initial observation revealed that a vortex problem existed for the generating cycle (Figures 10 and 11). Testing was done at 100 and 200 percent of design discharge for single-unit operation and at 100 and 125 percent of design discharge for two-unit operation.

Discharges greater than those representing the design conditions were studied because of uncertainty in the accuracy of vortex modeling. Vortex modeling presents similitude problems that, as of yet, have not been answered. It is felt that the high discharge tests represent conditions that are as bad as, if not worse than, actual prototype conditions. There was a strong tendency for vortex formation with both one- and two-unit operations. It should be noted that strong air cores were observed at all water surface levels when the initial unit was operated at 200 percent of design discharge (Figure 10). Although this indication of air intake was present, no bubbles were noted moving down the penstock. The trashracks were simulated to see if they would reduce the vortex tendency. Only a slight reduction, if any, was observed.

Possible solutions to the vortex problem included raising the height of the piers and walls, closing off upper portions of the trashrack section, placing walls so that they would alter the flow configuration, and floating a raft over the vortex. It was decided that either the raft-type suppressor (Figure 12) or a suppressor consisting of a lattice-like wall (Figure 13) extending from the top edge of the trashracks to an elevation of 9621 ft (2932.3 m) would be the most effective. The raft studied (Figure 12) was composed of six 16-ft (4.88-m) by 20-ft (6.10-m) segments. The cross members of the segments were spaced at 2-ft (0.61-m) centers for both directions. The depth of the segments was 2 ft (0.61 m) as was the diameter of the supporting cylindrical pontoons. The lattice wall (Figure 13) extended out over the trashracks on a 1:3 slope which is perpendicular to the trashrack face. Lattice walls corresponding to both steel and reinforced concrete structures were tested and found satisfactory. The lattice wall shown in Figure 13 corresponds to the reinforced concrete structure. The cross members in both directions are at 4-ft (1.22-m) spacings. The depth of the wall was 1 ft (0.30 m). Neither the raft nor the lattice wall stopped the rotation in the flow, but both eliminated air intake into the penstocks. Figure 14 shows the lattice wall operating under various flow conditions.

The velocity distributions obtained at the trashrack section were nearly uniform (Figure 15). The maximum velocity observed was 3.90 fps (1.19 M/sec) and this was in the portion of the trashrack section affected by the vortex. The velocity distributions at the stoplog section were also quite uniform (Figure 15). Mild flow concentrations were observed in the lower left-hand corner (when looking in the direction of pumped flow) of the stoplog section. Flow disturbances were also observed at the stoplog section near the deflector. From this it was concluded that the flow distribution for the generating cycle was satisfactory.

Head loss data were taken for the recommended inlet-outlet structure with the deflector in place. The observed head loss coefficients stabilized with respect to Reynold's number at 0.34 for the initial unit and at 0.37 for the future unit (Figure 6). It was observed that this stabilization occurred at Reynold's numbers of 3.75 by 10^5 and 4 by 10^5, respectively (Figure 16).

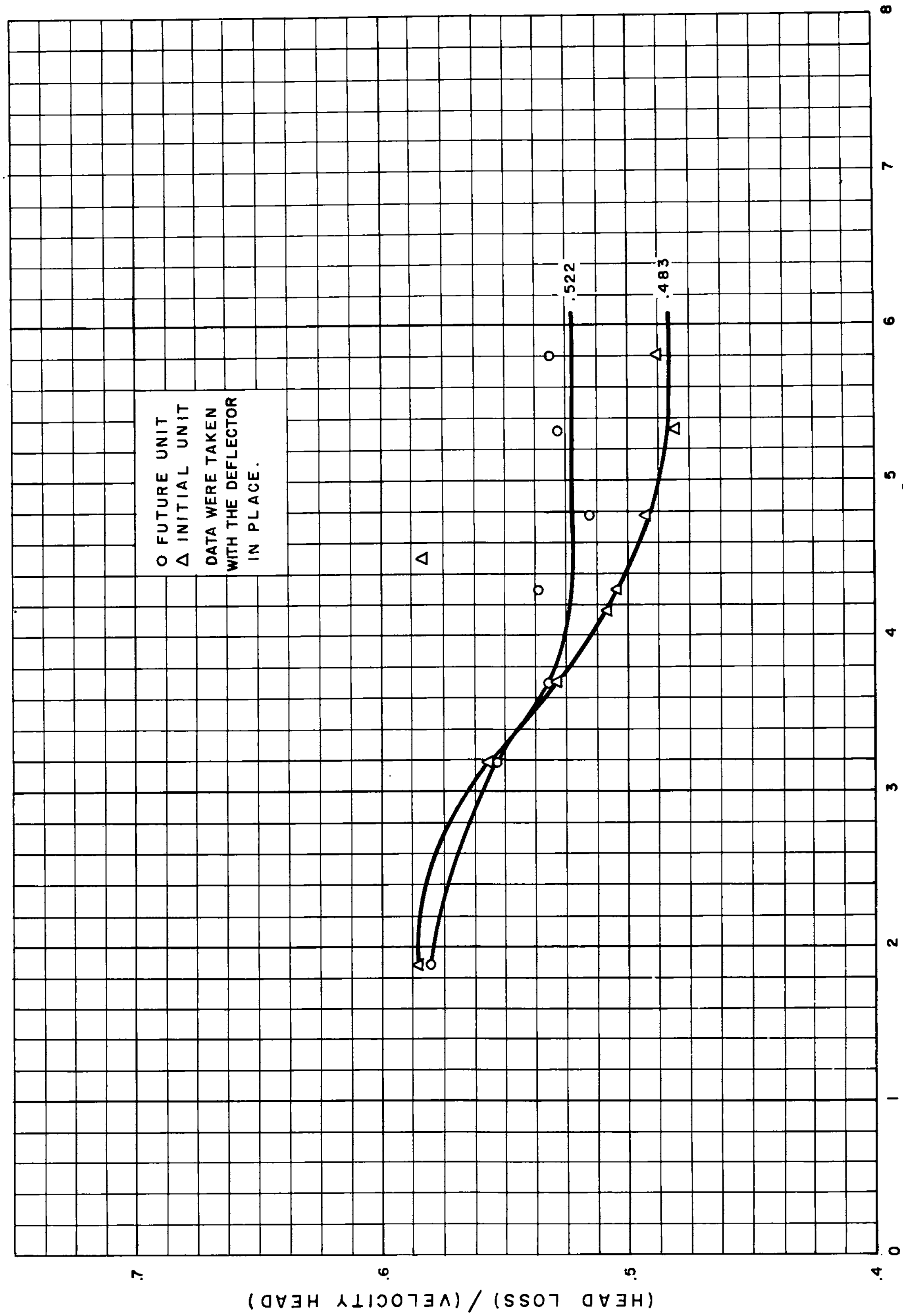
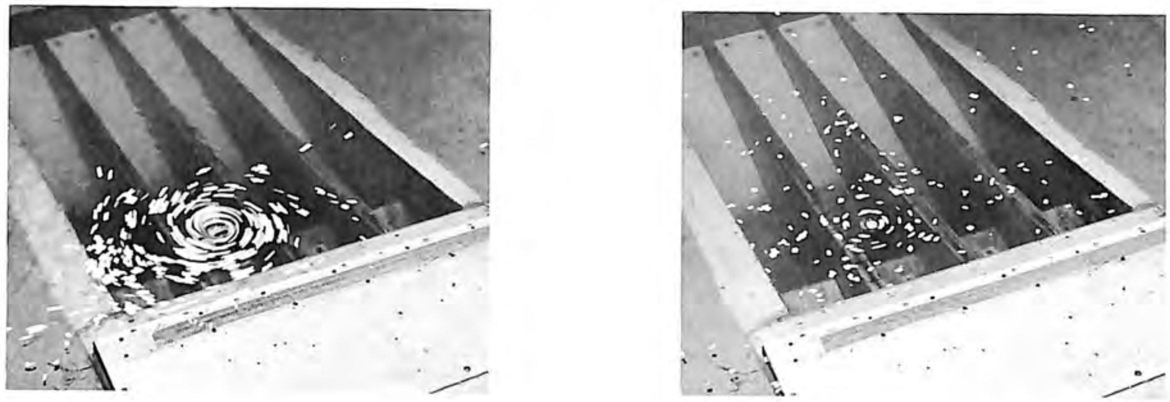


Figure 9. Pumping cycle head loss curves.



9615 ft water surface elevation. Left Photo PX-D-70822, right Photo PX-D-70825

9630 ft water surface elevation. Left Photo PX-D-70823, right Photo PX-D-70826

9645 ft water surface elevation. Left Photo PX-D-70824, right Photo PX-D-70827

200% discharge 100% discharge

Figure 10. Vortices, generating cycle, one-unit operation.

9615 ft. Photo PX-D-70828

9630 ft. Photo PX-D-70829

9645 ft water surface elevation. Photo PX-D-70830

Figure 11. Vortices, generating cycle, two-unit operation.

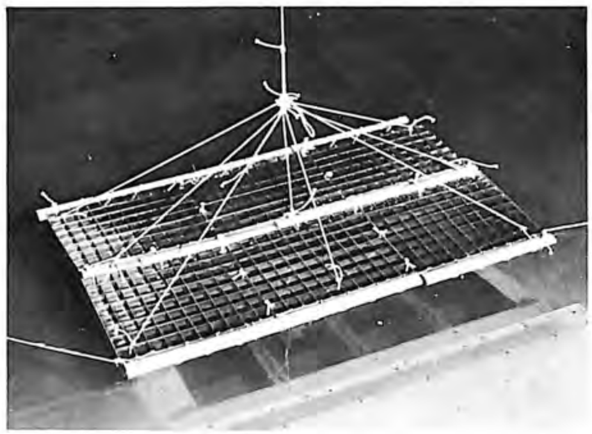


Figure 12. Raft-type vortex suppressor. Photo PX-D-70821

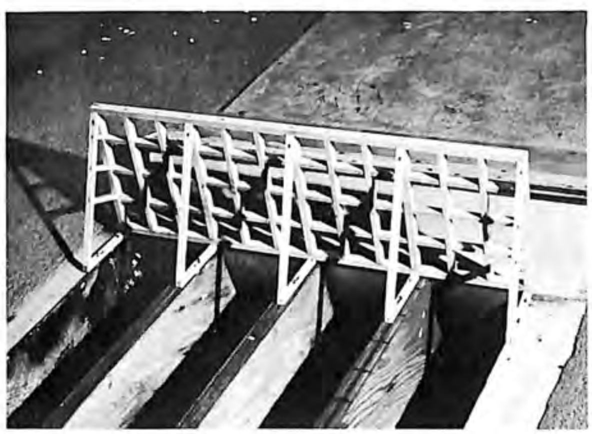
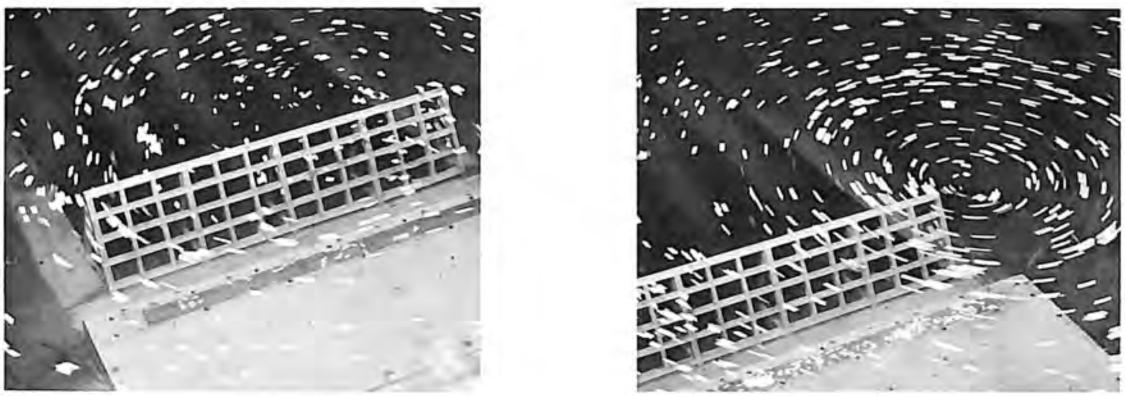
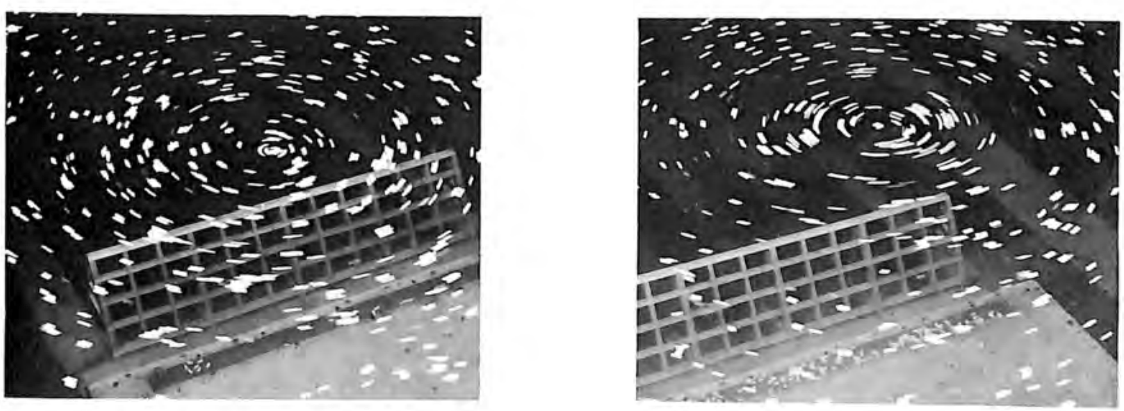


Figure 13. Lattice wall vortex suppressor. Photo PX-D-70837

9615 ft water surface elevation. Left Photo PX-D-70831, right Photo PX-D-70834



9630 ft water surface elevation. Left Photo PX-D-70832, right Photo PX-D-70835



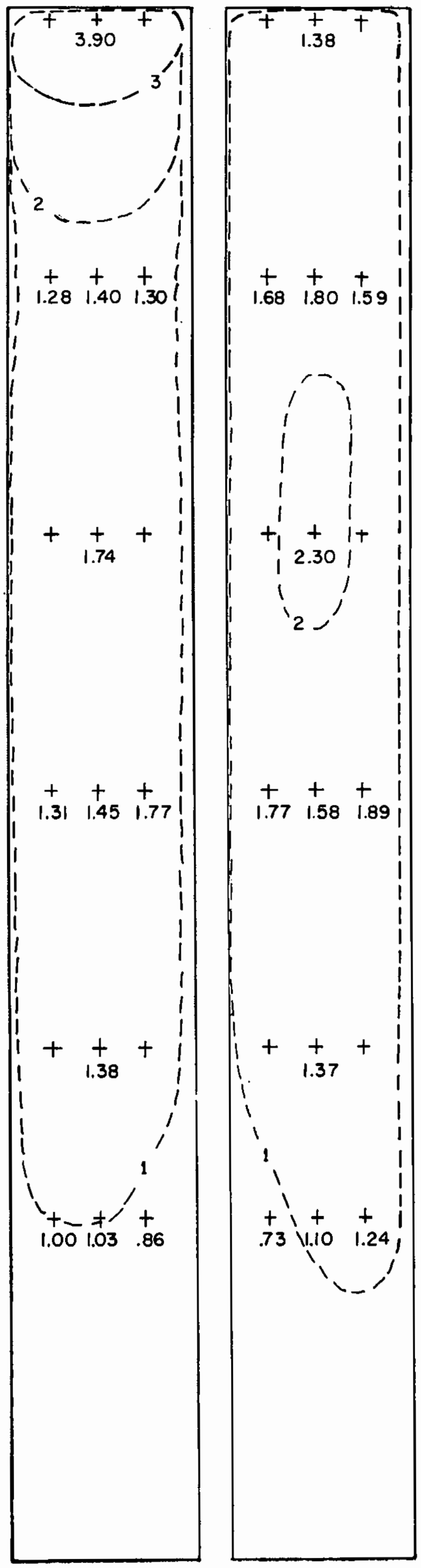
9645 ft water surface elevation. Left Photo PX–D-70833, right Photo PX-D-70836

One-unit operation
200% discharge

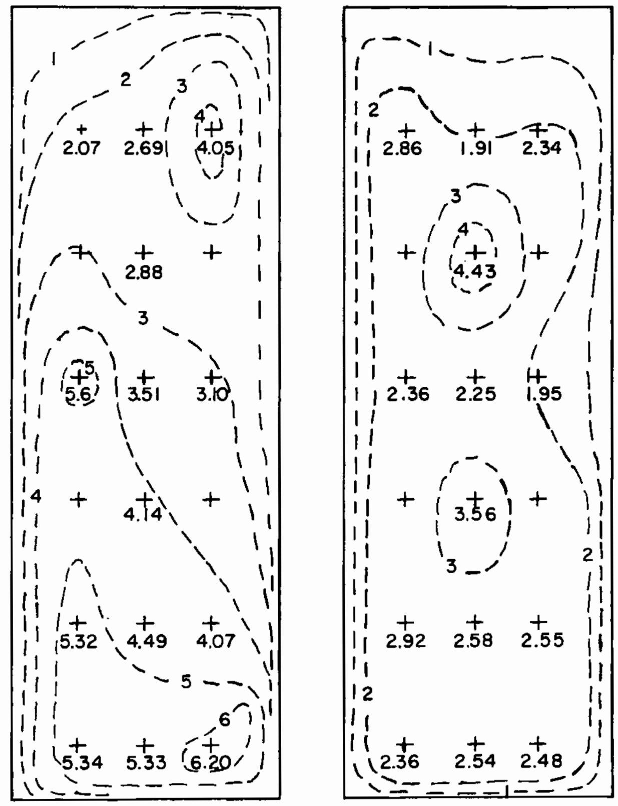
Two-unit operation
125% discharge

Generation vortices with suppression structure.

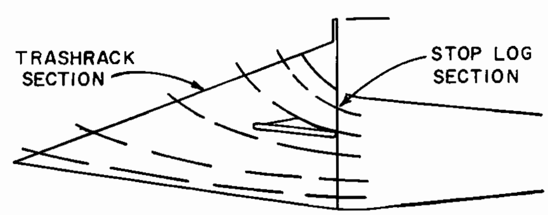
Figure 14. Vortices, generating cycle with suppression structure.



TRASHRACK SECTION VELOCITY DISTRIBUTION
LOOKING IN DIRECTION OF GENERATING FLOW



STOP LOG SECTION VELOCITY DISTRIBUTION
LOOKING IN DIRECTION OF PUMPED FLOW



APPROXIMATE STREAMLINES

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

Figure 15. Velocity distribution, final inlet-outlet structure, generating cycle (initial unit)

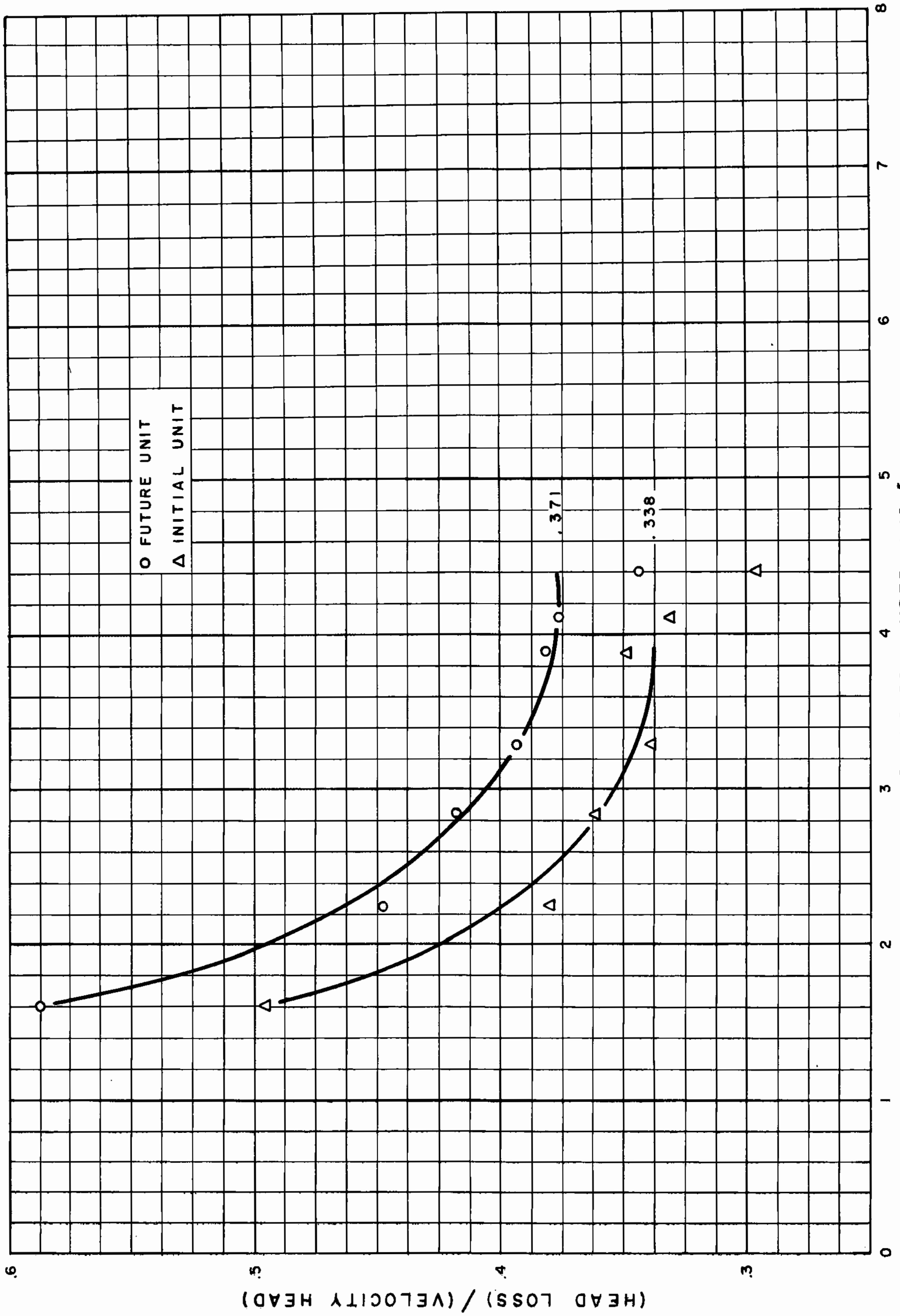


Figure 16. Generating cycle head loss curves.

GPO 840-357

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	*0.965873×10^{-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	*4.4482×10^5	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

GPO 835 - 188

ABSTRACT

Hydraulic model studies were performed to assure satisfactory flow conditions through the forebay reservoir inlet-outlet structure for Mt. Elbert Pumped-Storage Powerplant, Colorado. The main purpose for the studies was to develop a design to provide a uniform velocity distribution at the trashracks during the pumped cycle. Uniform velocity distribution would minimize the possibility of forming strong vortex shedding and reduce the forces causing trashrack fatigue failure. Flow conditions for the generating cycle were evaluated to ensure a uniform velocity distribution free of air entraining surface vortices. Head loss measurements were made for the inlet-outlet structure. A horizontal deflector with flip blocks was developed to improve the vertical velocity distribution at the trashrack position. A flat upward sloping floor was developed to replace the original concave floor in the structure. Two devices were developed to suppress generation of surface vortices.

ABSTRACT

Hydraulic model studies were performed to assure satisfactory flow conditions through the forebay reservoir inlet-outlet structure for Mt. Elbert Pumped-Storage Powerplant, Colorado. The main purpose for the studies was to develop a design to provide a uniform velocity distribution at the trashracks during the pumped cycle. Uniform velocity distribution would minimize the possibility of forming strong vortex shedding and reduce the forces causing trashrack fatigue failure. Flow conditions for the generating cycle were evaluated to ensure a uniform velocity distribution free of air entraining surface vortices. Head loss measurements were made for the inlet-outlet structure. A horizontal deflector with flip blocks was developed to improve the vertical velocity distribution at the trashrack position. A flat upward sloping floor was developed to replace the original concave floor in the structure. Two devices were developed to suppress generation of surface vortices.

ABSTRACT

Hydraulic model studies were performed to assure satisfactory flow conditions through the forebay reservoir inlet-outlet structure for Mt. Elbert Pumped-Storage Powerplant, Colorado. The main purpose for the studies was to develop a design to provide a uniform velocity distribution at the trashracks during the pumped cycle. Uniform velocity distribution would minimize the possibility of forming strong vortex shedding and reduce the forces causing trashrack fatigue failure. Flow conditions for the generating cycle were evaluated to ensure a uniform velocity distribution free of air entraining surface vortices. Head loss measurements were made for the inlet-outlet structure. A horizontal deflector with flip blocks was developed to improve the vertical velocity distribution at the trashrack position. A flat upward sloping floor was developed to replace the original concave floor in the structure. Two devices were developed to suppress generation of surface vortices.

ABSTRACT

Hydraulic model studies were performed to assure satisfactory flow conditions through the forebay reservoir inlet-outlet structure for Mt. Elbert Pumped-Storage Powerplant, Colorado. The main purpose for the studies was to develop a design to provide a uniform velocity distribution at the trashracks during the pumped cycle. Uniform velocity distribution would minimize the possibility of forming strong vortex shedding and reduce the forces causing trashrack fatigue failure. Flow conditions for the generating cycle were evaluated to ensure a uniform velocity distribution free of air entraining surface vortices. Head loss measurements were made for the inlet-outlet structure. A horizontal deflector with flip blocks was developed to improve the vertical velocity distribution at the trashrack position. A flat upward sloping floor was developed to replace the original concave floor in the structure. Two devices were developed to suppress generation of surface vortices.

REC-ERC-72-5
Johnson, P L
HYDRAULIC MODEL STUDIES OF THE FOREBAY RESERVOIR INLET-OULET STRUCTURE FOR MT. ELBERT PUMPED-STORAGE POWERPLANT FRYINGPAN-ARKANSAS PROJECT, COLORADO
Bur Reclam Rep REC-ERC-72-5, Div Gen Res, Jan 1972, Bureau of Reclamation, Denver, 16 p, 16 fig

DESCRIPTORS—/ *pumped storage/ hydraulic models/ *intake transitions/ *outlets/ flow characteristics/ flow distribution/ head losses/ trashracks/ model tests/ *velocity distribution/ vortices/ water surface/ design modifications/ disturbances/ *model studies
IDENTIFIERS—/ Fryingpan-Arkansas Proj, Colo/ Mount Elbert Pump-Storage Plt, Colo

REC-ERC-72-5
Johnson, P L
HYDRAULIC MODEL STUDIES OF THE FOREBAY RESERVOIR INLET-OULET STRUCTURE FOR MT. ELBERT PUMPED-STORAGE POWERPLANT FRYINGPAN-ARKANSAS PROJECT, COLORADO
Bur Reclam Rep REC-ERC-72-5, Div Gen Res, Jan 1972, Bureau of Reclamation, Denver, 16 p, 16 fig

DESCRIPTORS—/ *pumped storage/ hydraulic models/ *intake transitions/ *outlets/ flow characteristics/ flow distribution/ head losses/ trashracks/ model tests/ *velocity distribution/ vortices/ water surface/ design modifications/ disturbances/ *model studies
IDENTIFIERS—/ Fryingpan-Arkansas Proj, Colo/ Mount Elbert Pump-Storage Plt, Colo

REC-ERC-72-5
Johnson, P L
HYDRAULIC MODEL STUDIES OF THE FOREBAY RESERVOIR INLET-OULET STRUCTURE FOR MT. ELBERT PUMPED-STORAGE POWERPLANT FRYINGPAN-ARKANSAS PROJECT, COLORADO
Bur Reclam Rep REC-ERC-72-5, Div Gen Res, Jan 1972, Bureau of Reclamation, Denver, 16 p, 16 fig

DESCRIPTORS—/ *pumped storage/ hydraulic models/ *intake transitions/ *outlets/ flow characteristics/ flow distribution/ head losses/ trashracks/ model tests/ *velocity distribution/ vortices/ water surface/ design modifications/ disturbances/ *model studies
IDENTIFIERS—/ Fryingpan-Arkansas Proj, Colo/ Mount Elbert Pump-Storage Plt, Colo

REC-ERC-72-5
Johnson, P L
HYDRAULIC MODEL STUDIES OF THE FOREBAY RESERVOIR INLET-OULET STRUCTURE FOR MT. ELBERT PUMPED-STORAGE POWERPLANT FRYINGPAN-ARKANSAS PROJECT, COLORADO
Bur Reclam Rep REC-ERC-72-5, Div Gen Res, Jan 1972, Bureau of Reclamation, Denver, 16 p, 16 fig

DESCRIPTORS—/ *pumped storage/ hydraulic models/ *intake transitions/ *outlets/ flow characteristics/ flow distribution/ head losses/ trashracks/ model tests/ *velocity distribution/ vortices/ water surface/ design modifications/ disturbances/ *model studies
IDENTIFIERS—/ Fryingpan-Arkansas Proj, Colo/ Mount Elbert Pump-Storage Plt, Colo