UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

DISCHARGE CURVES 102-INCH RESERVOIR OUTLETS--GRAND COULEE DAM

Hydraulic Laboratory Report HYD-440

DIVISION OF ENGINEERING LABORATORIES

COMMISSIONER'S OFFICE
DENVER, COLORADO

November 27, 1957

CONTENTS

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Commissioner's Office--Denver
Division of Engineering Laboratories
Hydraulic Laboratory Branch
Hydraulic Investigation Section
Denver, Colorado
November 27, 1957

Laboratory Report No. Hyd-440
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Reviewed and
checked by: C. W. Thomas
Submitted by: H. M. Martin

DISCHARGE CURVES 102-INCH RESERVOIR OUTLETS, GRAND COULEE DAM

PURPOSE

The purpose of this report is to review the background for, cite references to, and explain the methods of computation of experimental data used to prepare Drawing No. 222-D-19, 622, Discharge Curves 102-Inch River Outlets, Grand Coulee Dam, which supersedes in part Drawing No. 222-D-1903, Area, Capacity and Discharge Curves.

INTRODUCTION

Drawing No. 222-D-1903, Area, Capacity, and Discharge Curves, Grand Coulee Dam, Figure 1, was approved in October 1937. This drawing has been the basis for releases from the reservoir for river control since that time.

In January 1957, a review of the adequacy of the river outlet capacity curves was requested to provide the most recent information for future flood routing programs of the Columbia River. The capacity curves in question are contained in Figure 1 for the lower, intermediate, and upper levels of outlets which total 60 in number, 20 at each level. An inspection of Drawing No. 222-D-1908, Figure 2, approved on the same date as the capacity curves, indicates that the discharges were computed for outlets at all levels having a parabolic profile. Outlets of this type had been studied as early as 1934 for Norris Dam of the Tennessee Valley Authority, but no capacity curves were prepared from the model study.

Between 1937 and 1940 the possible erratic performance and severe subatmospheric pressures in outlets of parabolic profile were investigated. A new design incorporating an elbow and a reducing cone at the downstream end of a horizontal conduit was proposed for the intermediate and upper outlets. At the time of this decision no modification of the lower outlets was proposed because they were to be used under a limited head and were to be abandoned as discharge controls after the spillway crest and the intermediate and upper outlets were completed.

The development of the design of outlet with horizontal profile for Grand Coulee Dam was materially aided by hydraulic model studies[1/] which thoroughly explored experimentally and analytically the pressure conditions, discharge capacity, spillway discharge and adjacent outlet effects on the hydraulic operation of model outlets. Drawing No. 222-D-6162, issued in July 1940, showed outlets with horizontal profiles, Figure 3. There was no evidence available that the capacity curves shown on Figure 1 had been revised as a result of the study to reflect the change in design and resulting change of capacity.

In early 1940, field tests were made at Grand Coulee Dam to correlate the hydraulic characteristics of the model and prototype outlets.[2/] A program for measurement of prototype discharges was started by laboratory personnel during this trip and subsequently completed by project personnel in November 1941.

In 1942, a paper written for a symposium on model-prototype conformity compared a part of the measured prototype discharges with those of the model and concluded that those predicted from the model were slightly below the actual prototype discharges.[3/] [4/]

Information was obtained in 1941 and 1949 on the pressure distribution in both an intermediate and an upper outlet in which piezometers had been installed.[5/] The effect of spillway flow over the outlet exits

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1/Report, Hyd-83, "Experimental study of the hydraulic characteristics of the river outlets for Grand Coulee Dam--Columbia Basin Project" (Thesis) 1940, D. M. Lancaster.

2/Field Trip Report No. 4 (also Report Hyd-81) from C. W. Thomas to Chief Engineer, May 15, 1940, subject: "Report on inspection trip to correlate Hydraulic Laboratory design and the field operation of 102-inch river outlets--Grand Coulee Dam--Columbia Basin Project."

3/Report Hyd-101, Model-prototype Comparisons of Hydraulic Structures, January 1942, J. E. Warnock.

4/Paper No. 2207 reprinted from ASCE Transactions, Volume 109 (1944) Conformity Between Model and Prototype, Hydraulic Structures, J. E. Warnock and H. G. Dewey, Jr.

5/Unpublished field data obtained in 1941 and 1949 by J. W. Ball and D. M. Lancaster on pressure distribution for operating combinations of intermediate and upper outlets at Grand Coulee Dam.

and the effect of adjacent outlet operation on the pressure distribution was studied in these tests. Accurate discharge measurements could not be obtained in 1949 because of the operation of the powerplants and spillway.

The recently completed review of the available information for the river outlets did not disclose a comparison of the discharge capacity of the horizontal outlet with that of the parabolic outlet, nor any revision of the curves in Drawing No. 222-D-1903. The review disclosed that a complete capacity curve based on all available information had not been prepared for each of the outlets. As a result the curves of Drawing No. 222-D-19, 622 were prepared, (Figure 4).

CAPACITY CURVES

General

Two sources of discharge data were utilized in the preparation of the revised capacity curves: (1) field measurement of the discharges of the river outlets at the dam in the years 1939, 1940, 1941, and pressures in the years 1941 and 1949; and (2) model data. Since it was impracticable to operate any single prototype outlet alone, the discharge applicable to all levels of outlets was computed by both direct and indirect methods.

Lower and Intermediate Outlets

First, a rating curve was obtained for one lower outlet before the water surface in the reservoir reached the intermediate outlets. This curve was obtained from 1939, 1940 and 1941 field measurements of the reservoir and tail-water elevations, river discharges at the gaging station one-half mile downstream from the dam, and the number of operating outlets. The head effective in causing flow through the outlet was defined as the difference between the reservoir and tail-water elevations. The effective head was plotted with its respective discharge for the lower outlet rating curve in Figure 4.

In the preparation of this curve, it was realized that the tail-water elevation measured adjacent to the spillway at the power house did not completely define the effective head on the lower outlets when the spillway or higher outlets were operating. The effect of this operation on the lower outlet capacity could not be evaluated because the depth immediately above the conduit exit, and thus the pressure, was unknown. In spite of this unknown effect, the head causing flow through the outlet has been defined in the capacity curve as the difference between the reservoir elevation, and the tail-water elevation measured at the power house. This should be a valid representation of the discharge.

A direct method of computing individual discharges (total river discharge divided by the number of lower outlets operating) was possible until the intermediate outlets were opened. These outlets can be used for reservoir elevations over 1032 or at heads approximately 100 feet above the center line of the lower outlet. For reservoir elevations above 1032 an indirect method was used to obtain the discharge for measurements made when the intermediate outlets were open. From the equation $C = \frac{Q}{A\sqrt{2gH}}$, a coefficient of discharge was determined for the lower outlets. In the equation, C is the coefficient of discharge, Q is the discharge in cfs measured by the river gage, A is the area of the 102-inch-diameter conduit in square feet, g is gravitational acceleration, and H (the effective head), the difference between the reservoir and tail-water elevations because of the submergence of the conduit exit. The coefficient of discharge computed from the equation was found to be essentially a constant value of 0.83 for measured effective heads between approximately 65 and 181 feet. The use of this coefficient permitted extrapolation of the lower outlet rating curve for effective heads greater than that corresponding to the elevation of the intermediate outlets when both levels of outlets were operating.

The intended operation of the lower outlets restricted the maximum head to 250 feet of water. This restriction was later relaxed which necessitated further extrapolation of the capacity curve. The equation $Q = CA\sqrt{2gH}$ and the coefficient of discharge of 0.83 were used for this extrapolation.

As soon as the intermediate outlets became operable, the total release increased and the discharges of the two levels of outlets were separated. Knowing the effective head on the lower outlets and the number operating, it was possible to obtain the discharge per outlet from the capacity curve and thus the total discharge contributed by the lower outlets. Subtracting this value from the measured flow in the river and dividing by the number of intermediate outlets gave the discharge for one outlet at this level. This procedure was possible because the power houses were not completed and there was no flow through the low blocks of the dam. The rating curve for an intermediate outlet (elevation 1036.67) has been plotted, Figure 4. The extension of the capacity curve of the intermediate outlets to a reservoir elevation greater than the elevation of the upper outlets was accomplished in a manner similar to that used for the lower outlets. A coefficient of discharge curve was computed and plotted from the known data. Since the coefficient was not a constant for the intermediate outlet, but could be readily defined, values from the coefficient curve were used to extend the capacity curve above the maximum discharge available from the field tests.

The effective head on the intermediate outlets was taken as the difference between the reservoir elevation and the center line elevation of the outlet for all heads submerging the inlet. This differs from the effective head on the lower outlets because there normally is no submergence of the conduit exit of the intermediate outlets unless the spillway and outlets above are operating.

Upper Outlets

With increasing reservoir depth, it became possible to operate combinations of the intermediate and upper outlets with the lower outlets closed. Following the procedure used for determining discharges through the lower and intermediate outlets, the known quantities from the capacity curve for the intermediate outlets were used to separate the discharges of the intermediate and upper outlets. The discharge of the operating intermediate outlets was subtracted from the total river discharge (all through outlets) to obtain the discharge of the upper outlets. This quantity was divided by the number of open upper outlets to obtain the discharge for one outlet. The upper outlet rating curve appears in Figure 4 with the reservoir elevation plotted with respect to discharge.

The shape of the capacity curves for the intermediate and upper outlets was dictated by several factors. In the lower range of discharge the outlets operate in open channel flow. With submergence of the bellmouth entrance and filling of the conduit, there is an apparent shift of discharge control. The control shifts from the entrance to the reducing cone at the exit of the elbow at the end of the conduit. Operation of the outlet in this range of reservoir elevation produces a range of discharges for apparently the same effective head. The abrupt break in the rating curves for the intermediate and upper outlets was drawn near the average of this range of discharge. As the reservoir elevation increases, the cone at the downstream end of the outlet remains the discharge control and the rating curve is predictable.

Outlet Pressures

Pressures in the intermediate and upper outlets were measured during the discharge tests from field installed piezometers. These pressures were used to verify the outlet capacity as obtained from the discharge measured in the river. A complete laboratory study had been made of the bellmouthed entrance during the design of the outlets.[6] From these studies the relationship between coefficient of discharge and pressure drop in the bellmouth had been determined. This coefficient of 0.98 was applied to the field measured pressure in the equation $Q = CA\sqrt{2gH_e}$ as a second method of obtaining the outlet discharge. In the equation, Q is the discharge in cfs; C the coefficient of discharge, 0.98; A is the area of the bellmouth at the piezometer station in square feet; and H_e is the head difference from the reservoir elevation to the average pressure head measured at the piezometer, both referred to the outlet center line. The location of the piezometers used for the pressure measurement corresponds to the exit of the bellmouth studied in the laboratory. These piezometers have been designated No. 11 at the top, bottom, left and right of the bellmouth on construction Drawing No.

6/Report Hyd-66, Hydraulic Model Studies for the Design of Sluice Entrances for Grand Coulee Dam--Columbia Basin Project, L. Reid, 1939.

222-D-2132 Figure 5. The diameter of the prototype bellmouth at this section is 8.8125 feet.

Discharges computed by this method for the upper outlets could be plotted on the same curve as that obtained from the river discharge measurements. For the intermediate outlets the computed discharges from the bellmouth pressure agreed within 10 percent at a 50-foot head and within 3 percent at a 230-foot head. Available data were insufficient to determine the reason for the close agreement of discharges by the two methods for the upper outlets and the differences in discharges for the intermediate outlets.

Pressures lower than those for a freely discharging outlet were measured in the field study when either the spillway or the outlets immediately above were operating. Some of the discharge measurements used in determining the capacity curve for the intermediate outlets, thus, may have been affected by flow over the exit of the conduit.

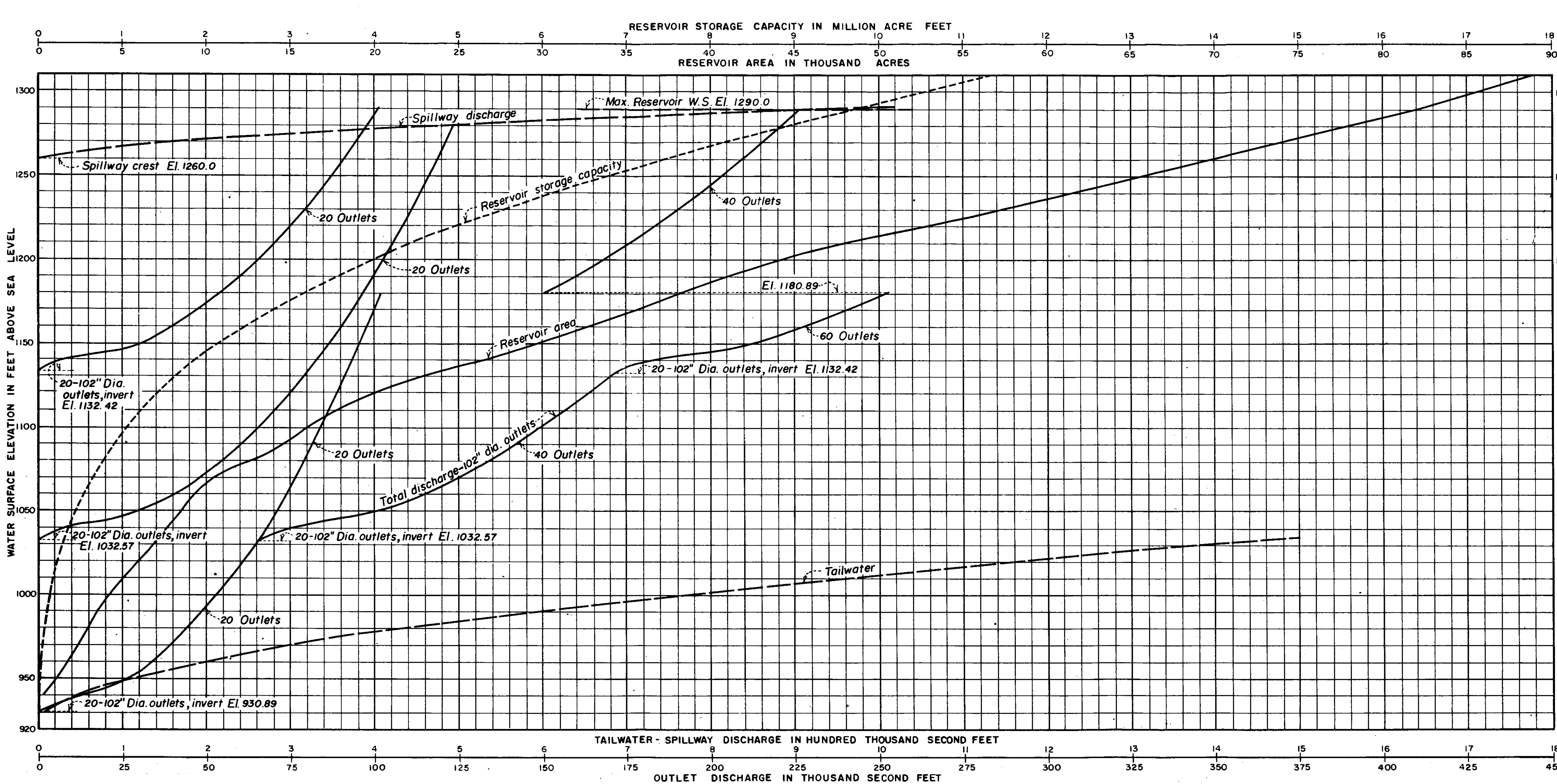
In addition to the effect of flow over the exits, the pressure measurements showed that the operation of adjacent outlets changed the pressure distribution in the bellmouthed entrances from that which occurred for the operation of a single outlet. This, too, may have produced a change in the discharge capacity that could not be accounted in the capacity curves. There was no flow over the spillway to affect the discharge through the upper outlets during the field measurements, however, adjacent pairs were operated.

CONCLUSIONS

1. The discharge capacity curve designated 20- 102-inch-diameter outlets, invert elevation 930.89 Figure 1, should have been based on the effective head (difference between reservoir and tail-water elevations) instead of only the reservoir water surface elevation because of the submerged exit and variable tail-water elevation.

2. The discharge capacity curves of Figure 1 were not revised to reflect the change of outlet design from a parabolic profile to a horizontal profile with elbow and reducing cone.

3. It is believed that the curves for the three levels of river outlets Figure 4 present the best discharge capacity information presently available, although some uncertainty exists concerning hydraulic conditions in the outlets.



NOTES

Reservoir storage capacity and reservoir area curves superseded by Drawing No. 222-117-13106 (Revised 8-25-53).
Discharge curves for outlets superseded by Drawing No. 222-D-19622.

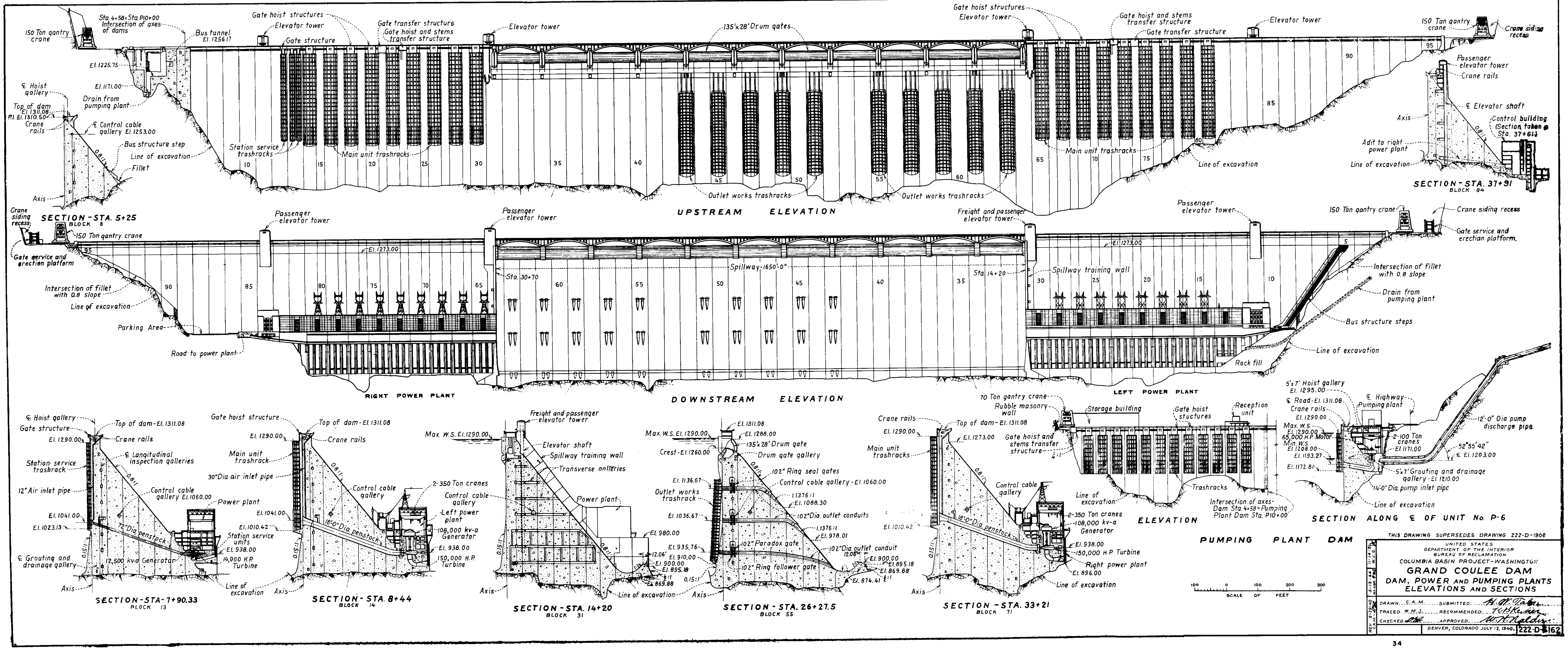
4-30-57 NOTES ADDED

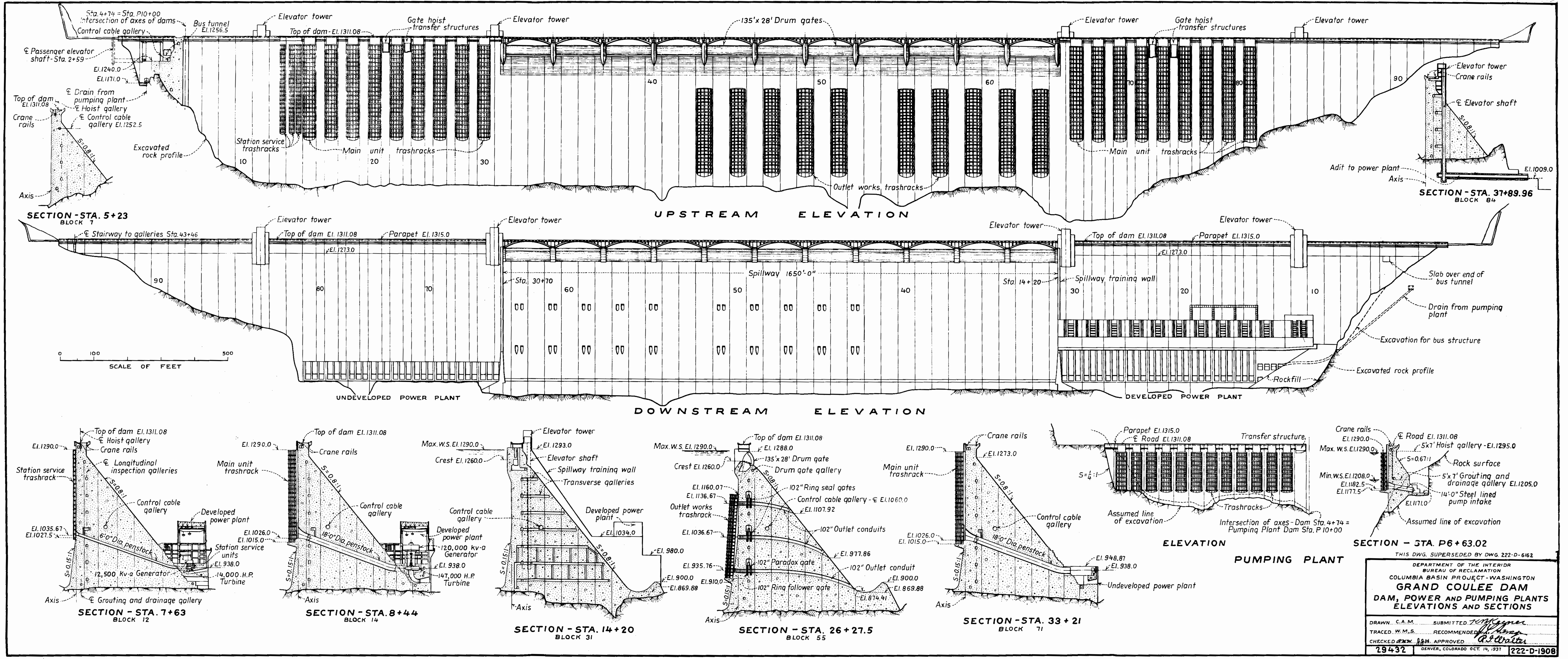
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLUMBIA BASIN PROJECT-WASHINGTON

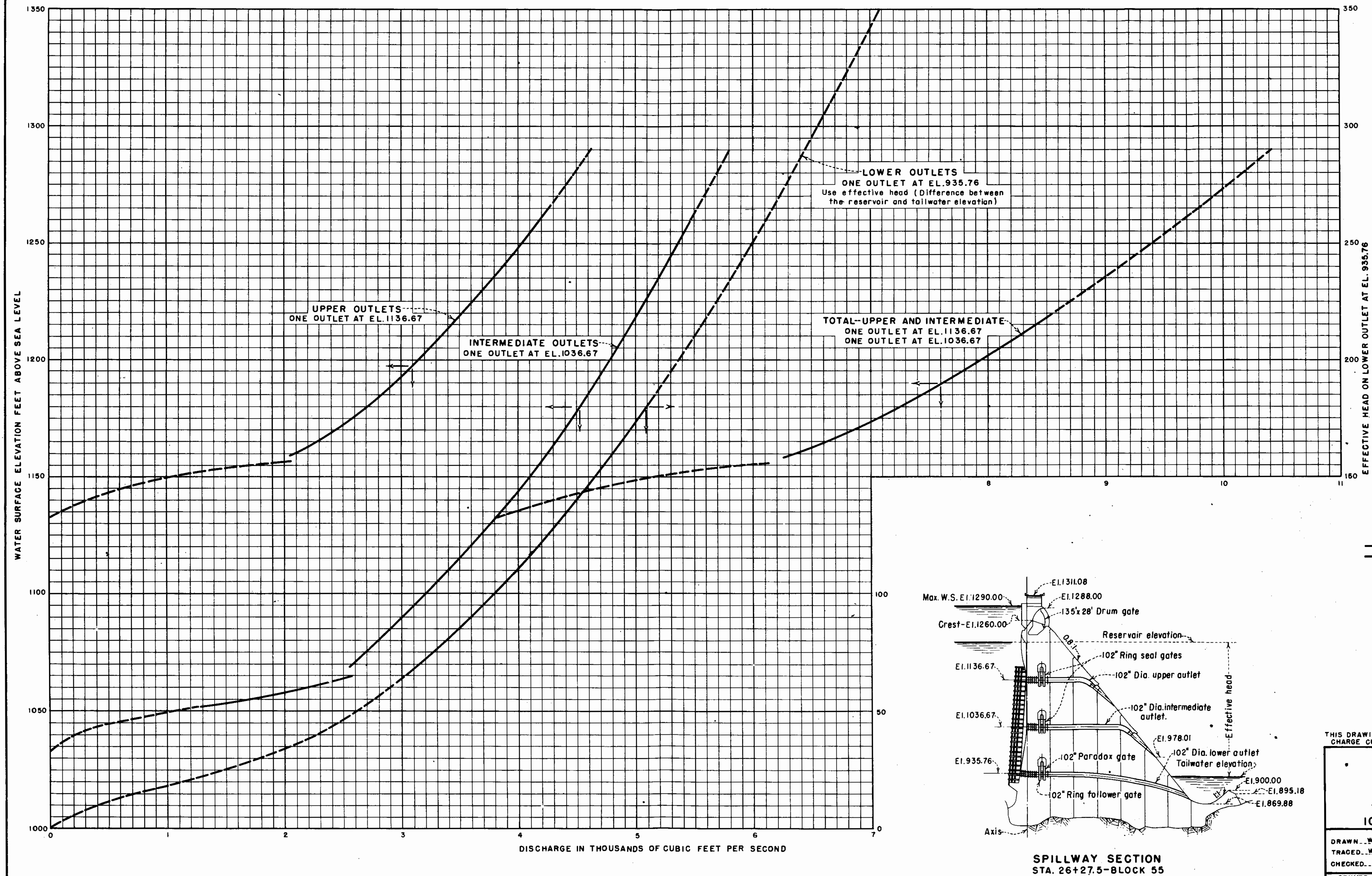
GRAND COULEE DAM
AREA, CAPACITY AND DISCHARGE CURVES

DRAWN E.W.M.-D.E.C. SUBMITTED [signature]
TRACED E.W.C. RECOMMENDED [signature]
CHECKED [signature] APPROVED [signature]

29427 | DENVER, COLORADO, OCT. 14, 1937 | 222-D-1903


UPSTREAM ELEVATION
DOWNSTREAM ELEVATION
RIGHT POWER PLANT
LEFT POWER PLANT
SECTION - STA. 5+25
BLOCK 8
SECTION - STA. 37+91
BLOCK 84
SECTION - STA. 7+90.33
BLOCK 13
SECTION - STA. 8+44
BLOCK 14
SECTION - STA. 14+20
BLOCK 31
SECTION - STA. 26+27.5
BLOCK 55
SECTION - STA. 33+21
BLOCK 71
ELEVATION
SECTION ALONG ℄ OF UNIT No. P-6
PUMPING PLANT DAM
135'x28' Drum gates
Spillway-1650'-0"
Gate hoist structures
Elevator tower
Passenger elevator tower
Freight and passenger elevator tower
150 Ton gantry crane
Main unit trashracks
Outlet works trashracks
Station service trashracks
Line of excavation
Bus tunnel El. 1256.17
Sta. 4+58=Sta. P10+00 Intersection of axes of dams
El. 1273.00
Road to power plant
Parking Area
Rock fill
Bus structure steps
Drain from pumping plant
THIS DRAWING SUPERSEDES DRAWING 222-D-1908
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLUMBIA BASIN PROJECT-WASHINGTON
GRAND COULEE DAM
DAM, POWER AND PUMPING PLANTS
ELEVATIONS AND SECTIONS
SCALE OF FEET
DENVER, COLORADO JULY 12, 1940.
222-D-8162


UPSTREAM ELEVATION
DOWNSTREAM ELEVATION
135'x 28' Drum gates
Elevator tower
Gate hoist transfer structures
Top of dam - El. 1311.08
Sta. 4+74 = Sta. P10+00 Intersection of axes of dams
Bus tunnel El. 1256.5
Control cable gallery
℄ Passenger elevator shaft - Sta. 2+59
El. 1240.0
El. 1171.0
Station service trashracks
Main unit trashracks
Outlet works trashracks
Excavated rock profile
SECTION - STA. 5+23
BLOCK 7
SECTION - STA. 37+89.96
BLOCK 84
Adit to power plant
Axis
El. 1009.0
℄ Stairway to galleries Sta. 43+46
Parapet El. 1315.0
El. 1273.0
Spillway 1650'-0"
Sta. 30+70
Sta. 14+20
Spillway training wall
Slab over end of bus tunnel
Drain from pumping plant
Excavation for bus structure
Rockfill
UNDEVELOPED POWER PLANT
DEVELOPED POWER PLANT
SCALE OF FEET
SECTION - STA. 7+63
BLOCK 12
12,500 Kv-a Generator
14,000 H.P. Turbine
℄ Grouting and drainage gallery
SECTION - STA. 8+44
BLOCK 14
18'-0" Dia. penstock
120,000 kv-a Generator
147,000 H.P. Turbine
SECTION - STA. 14+20
BLOCK 31
Transverse galleries
Developed power plant
SECTION - STA. 26+27.5
BLOCK 55
Drum gate gallery
102" Ring seal gates
102" Outlet conduits
102" Paradox gate
102" Ring follower gate
SECTION - STA. 33+21
BLOCK 71
Undeveloped power plant
ELEVATION
PUMPING PLANT
SECTION - STA. P6+63.02
Intersection of axes - Dam Sta. 4+74 = Pumping Plant Dam Sta. P10+00
THIS DWG. SUPERSEDED BY DWG. 222-D-6162
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLUMBIA BASIN PROJECT - WASHINGTON
GRAND COULEE DAM
DAM, POWER AND PUMPING PLANTS
ELEVATIONS AND SECTIONS
DRAWN C.A.M.
TRACED W.M.S.
SUBMITTED
RECOMMENDED
APPROVED
29432
DENVER, COLORADO OCT. 14, 1937
222-D-1908



EXPLANATION
—— Curve prepared from available data.
– – – Data extrapolated.

THIS DRAWING SUPERSEDES ALL PREVIOUSLY PREPARED DISCHARGE CURVE DRAWINGS FOR RESERVOIR OUTLETS

UNITED STATES
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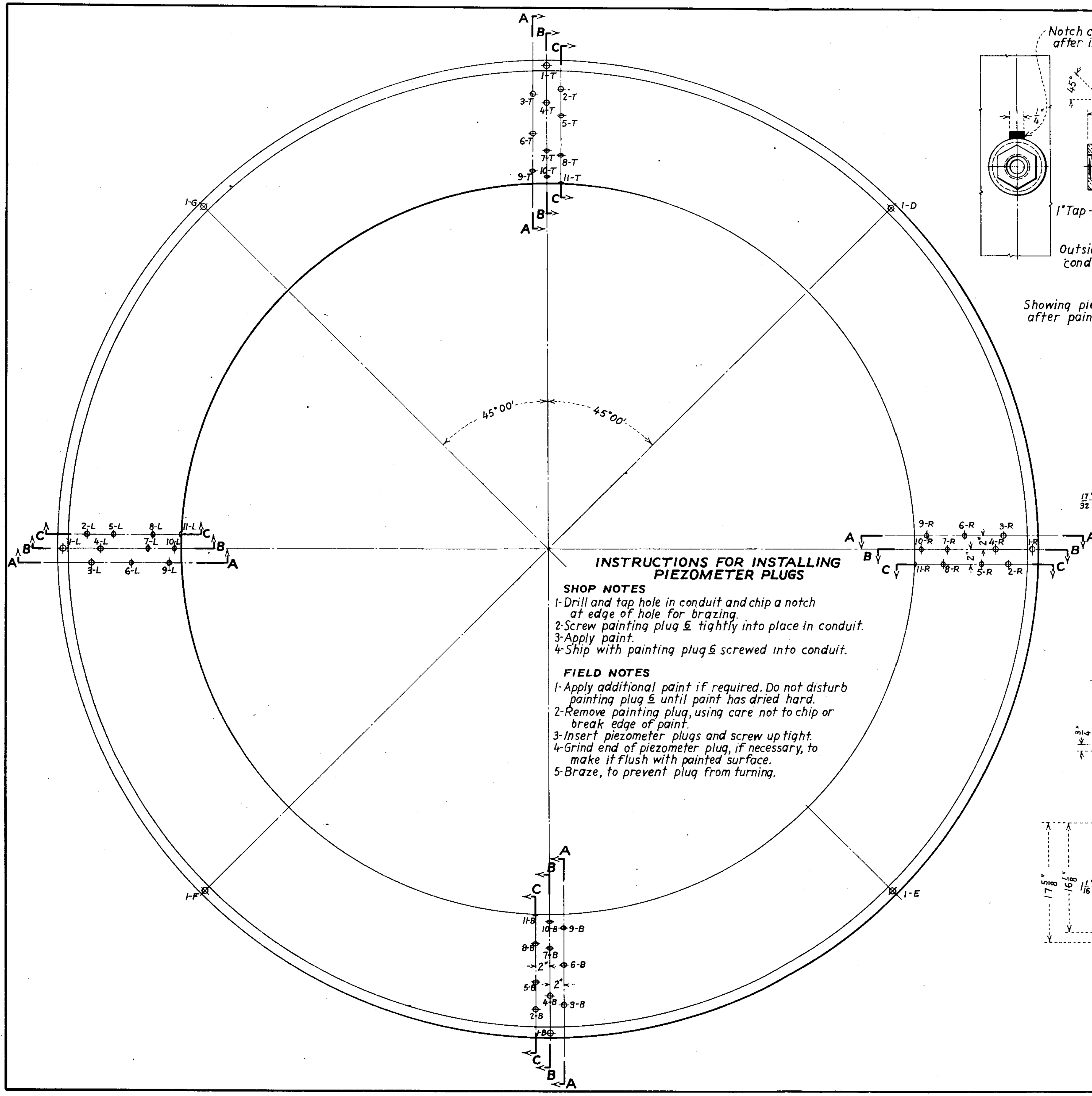
COLUMBIA BASIN PROJECT-WASHINGTON

GRAND COULEE DAM
DISCHARGE CURVES
102-INCH RESERVOIR OUTLETS

DRAWN W.H.C. SUBMITTED Charles W. Thomas
TRACED W.A.W. RECOMMENDED Walter H. Price
CHECKED J.C.S. APPROVED L.N. McClellan

DENVER, COLORADO. APRIL 18, 1957 | 222-D-19622



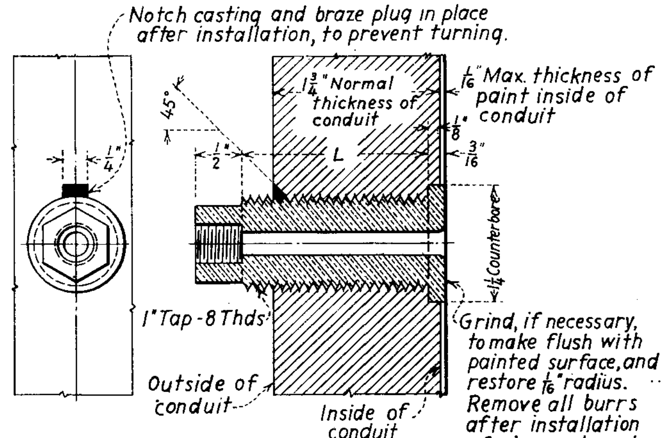
INSTRUCTIONS FOR INSTALLING PIEZOMETER PLUGS

SHOP NOTES

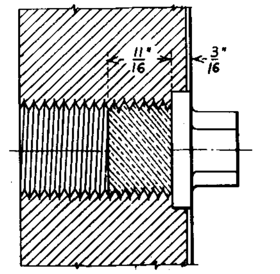
1- Drill and tap hole in conduit and chip a notch at edge of hole for brazing.
2- Screw painting plug 6 tightly into place in conduit.
3- Apply paint.
4- Ship with painting plug 6 screwed into conduit.

FIELD NOTES

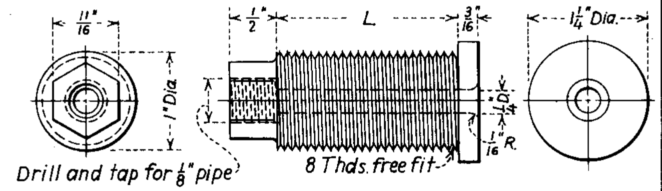
1- Apply additional paint if required. Do not disturb painting plug 6 until paint has dried hard.
2- Remove painting plug, using care not to chip or break edge of paint.
3- Insert piezometer plugs and screw up tight.
4- Grind end of piezometer plug, if necessary, to make it flush with painted surface.
5- Braze, to prevent plug from turning.



DETAIL "H"
Showing piezometer plug installed after painting



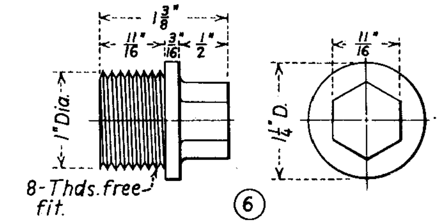
DETAIL "J"
Showing painting plug in position prior to painting.



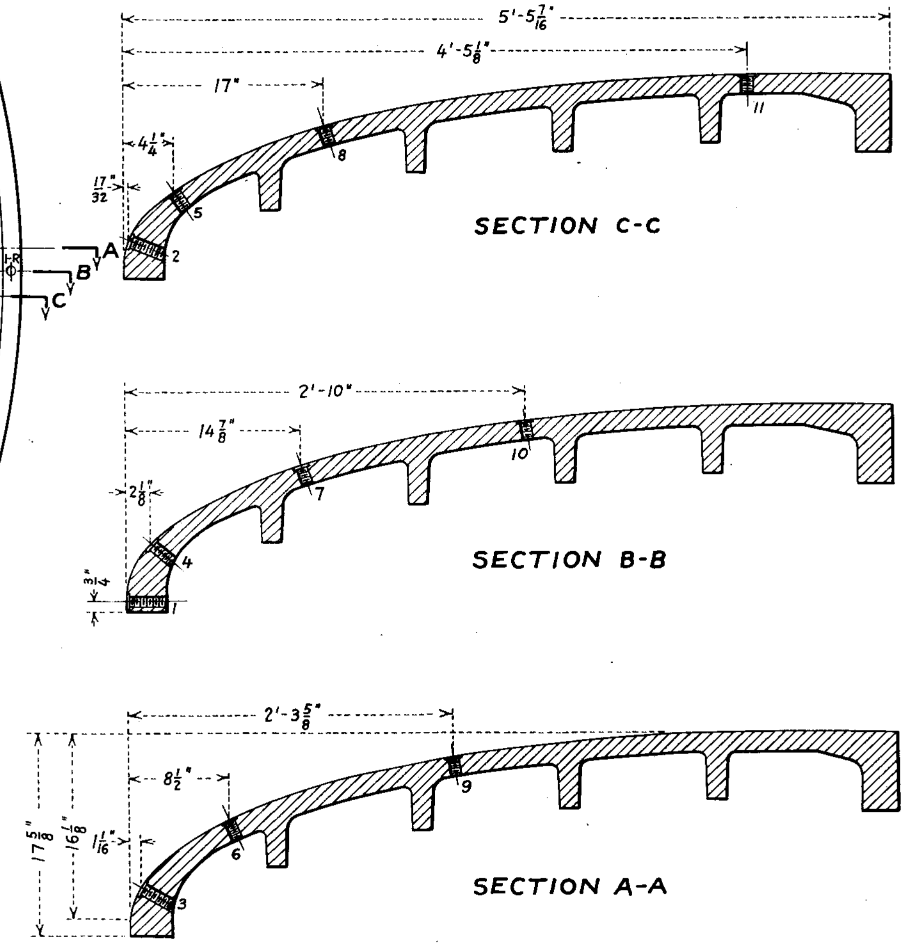
TYPICAL PIEZOMETER PLUG
HIGH TENSILE BRONZE
Finish all over

PART NO.	LENGTH-L	NO. REQ'D.	WHERE USED	
1	3 3/4"	32	Part 1	†
2	3 1/4"	8	Part 1	†
3	3"	8	Part 1	†
4	2"	112	Parts 1, 2, 3, 4, 5,	†
5	1 1/2"	4	Upper bonnet cover	‡

† See Dwg. 222-D-2064 and 222-D-2067.
‡ See Dwg. 222-D-2105.



PAINTING PLUG (6)
BRONZE - 164 REQUIRED
Finish all over



NOTES

The centerlines of the 1/4" holes through the piezometer plugs must be normal to the tangent to the inside surface of the conduit at the point of installation.
The surface of the end of the plug must be flush with the paint surface on the inside of the conduit and all burrs must be removed from the openings of the 1/4" holes.
Two castings that conform most nearly to the curve shown on Dwgs. 222-D-2065 and 2068 will be selected from the forty castings and the piezometers will be installed in only these two. Quantities shown on this sheet are total required for both conduits.

DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLUMBIA BASIN PROJECT - WASHINGTON

GRAND COULEE DAM
OUTLET WORKS - EL. 1036.67 AND EL. 1136.67
102" RING SEAL GATE CONDUITS
PLUGS - PIEZOMETER LOCATIONS IN BELLMOUTH

DRAWN S.P.C.B. SUBMITTED [signature]
TRACED S.H.R. - A.E.L. RECOMMENDED [signature]
CHECKED A.A.B. APPROVED R. F. Walter

REV. 12-5-38 H.E.S.

38-48 | DENVER, COLORADO, DEC. 18, 1937 SHEET 1 OF 1 | 222-D-2132