UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

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Memorandum to Chief Engineer

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TESTS TO DETERMINE OPERATING CHARACTERISTICS OF TUNNEL-PLUG OUTLET WORKS AT BOULDER DAM

BOULDER CANYON PROJECT

By

Board of Engineers

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Denver, Colorado,
February 3, 1939

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Proj Book

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SUBJECT: TEST TO DETERMINE OPERATING

CHARACTERISTICS OF TUNNEL PLUG OUTLET WORKS

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Branch of Design and Construction
Engineering and Geological Control
and Research Division
Denver, Colorado
February 3, 1939

Laboratory Report No. 49
Hydraulic Laboratory
Compiled by: Board of Engineers

Subject: Operating characteristics of tunnel plug outlet works at Boulder Dam - Boulder Canyon project.

1. Description of tests. In accordance with office letter of November 22, 1938, and memorandum of December 7, 1938, to Acting Chief Engineer from Mr. J. L. Savage, on the above subject, the tunnel plug outlets at Boulder Dam were operated on December 13 and 14 under the surveillance of Messrs. Blomgren, Winter, Kinzie, Thomas, and Warnock of the Denver office, together with interested members of the field operating force. The flow and operating conditions in tunnel no. 3 were studied on December 13 with flows increasing progressively from 10,000 second-feet to full capacity of slightly over 20,000 second-feet. During the forenoon of December 14, similar studies were made on tunnel no. 2, with flows increasing progressively from no flow to full capacity. At the conclusion of the tunnel no. 2 studies, the flow was maintained at full capacity in that tunnel while the flow in tunnel no. 3 was increased progressively by 5,000 second-foot increments from no flow to full capacity. Full capacity flow from both tunnels was maintained for 30 minutes. During the entire program measurements were made of the pressure conditions in the tunnel below the needle valves and still and motion pictures were made of the flow conditions in the river below the portals. During the tests on tunnel no. 2 oscillograph measurements were made of the pressure and strain conditions at critical points on the penstocks. Observations of the difference in the elevation of the water surface in the intake towers and in the reservoir were made with one and two gates open. A complete record of the reservoir, tailrace, and river elevations was made in the Watermaster's office. On December 15 unwatering of tunnel no. 3 was started, and on December 17 and 18, a close inspection of the conditions in the invert of the tunnel was made by Messrs. Thomas and Warnock.

2. Pressure conditions in tunnels and needle-valve discharge guides. Throughout the tests, observations were made of pressures in the tunnels and in the discharge guides. Connections from manometer boards in the valve operating chambers were carried through the valves in the observation doors (dwg. no. 45-D-7777) to the tunnels. In the Arizona tunnel, an additional connection was made by tapping the 12-inch pipe used for the tube valve test. Observations of

pressures in the discharge guides were made by tapping outlets through the guides on the top center line. The discharge guides for valves nos. 9 and 10 in each outlet works were tapped in three positions, one tap near the downstream end of the valve, one near the wall, and one midway between those two. The discharge guides for valves nos. 8 and 11 in each outlet works were tapped midway between the **wall** and the downstream end of the valve. The discharge guides for valves nos. 7 and 12 in each outlet works were tapped in two positions, one near the downstream end of the valve and one near the wall. The connections from the taps in the discharge guides were arranged so that the pressure at a single tap could be observed or all connections in a single discharge guide could be manifolded together to give one reading at the manometer board. The manometer boards were equipped with both water and mercury columns in order that fluctuations, as well as average pressures, could be observed. For comparison all observations were reduced to feet of water below atmospheric pressure.

The results of the pressure measurements are given in table 1. The valves used for each run have been grouped together in the table. Pressures at the different taps in the discharge guides showed no consistent difference; hence, in cases where readings were taken at more than one tap, those pressures have been averaged and are shown in the table as an average reading for the particular discharge guide. Average pressure in the tunnel is given for each run. In instances where the difference between average and maximum pressure was large, the maximum pressure has been inserted in the table. Since the discharge through the valves was determined by two methods that are not in close agreement, the discharge for each run as determined by both methods is given in the table.

The worst condition of operation appeared with flows of 3,000 to 5,000 second-feet through the Nevada tunnel and no flow through the Arizona tunnel. Momentary negative pressures of 3.5 feet of water were observed on the water manometers connected into the upper tunnel transition. A similar condition was also noted in the Nevada tunnel when the tunnels were discharging a total of approximately 8,000 second-feet at the close of the test program on December 14. At those discharges disturbance in the tunnel caused splashing which seemed to completely seal the tunnel near the downstream end with spray. This momentary sealing caused irregular pressure conditions in the tunnel for an instant. This disturbance in the tunnel might be traced to two sources: (1) the lack of sufficient momentum in the jets to move the slack water from the tunnels at low flows, or (2) the excessive height of the water surface in the river immediately downstream from the tunnel portals.

TABLE 1 - PRESSURES IN TUNNELS AND DISCHARGE GUIDES

Reservoir Elevation 1168.4

Valve number	Per-cent open	Average pressure below atmospheric - Feet of water		Discharge in cubic feet per second	
		Discharge guide	50-foot tunnel	Theoretical curve	Watermaster's curve
A-7	53	0.88			
A-8	53	0.75	0.82	-	10,056
A-11	53	0.75			
A-12	53	0.85			
A-7	54	1.01			
A-8	55	1.01			
A-9	32	1.10	0.88	-	12,728
A-10	30	1.15			
A-11	55	1.15			
A-12	52	1.15			
A-7	54	0.92			
A-8	55	1.01	0.82		
A-9	57	1.01		16,730	15,540
A-10	57	1.01	Max.		
A-11	55	1.01	1.30		
A-12	52	0.95			
A-7	54	0.82			
A-8	55	0.88			
A-9	95	0.86	0.82	18,580	17,072
A-10	96	0.86			
A-11	55	0.88			
A-12	52	0.88			
A-7	95	0.95			
A-8	55	0.95			
A-9	95	0.95	0.88	22,840	18,804
A-10	96	0.92			
A-11	55	0.88			
A-12	95	0.95			
A-7	95	0.85			
A-8	94	0.88			
A-9	95	0.88	0.82	23,160	20,436
A-10	96	0.95			
A-11	95	0.88			
A-12	95	0.88			
N-9	40	-	2.25	4,150	3,880
N-10	40	-	Max. 3.80		
N-7	40	-			
N-9	40	-	2.60	8,440	7,660
N-10	41	-	Max. 3.50		
N-12	40	-			
N-7	40	0.82			
N-9	61	0.95	0.82	10,110	9,356
N-10	62	0.88	Max. 1.30		
N-12	40	0.95			
N-7	40	0.88			
N-9	80	0.75	0.75	11,460	10,310
N-10	80	0.88			
N-12	40	0.88			
N-7	60	0.68			
N-9	95	0.61	0.61	13,405	12,893
N-10	95	0.75			
N-12	59	0.82			
N-7	80	0.75			
N-9	95	0.68	0.68	14,900	13,317
N-10	95	0.75			
N-12	80	0.82			
N-7	96	0.82			
N-9	95	0.75	0.75	15,440	13,620
N-10	95	0.82			
N-12	93	0.88			
N-7	96	1.09			
N-8	30	1.09			
N-9	95	1.02	0.95	18,560	15,011
N-10	95	1.09			
N-11	29	1.22			
N-12	93	1.22			
N-7	96	1.09			
N-8	40	1.09			
N-9	95	1.09	0.95	19,590	17,348
N-10	95	1.22			
N-11	40	1.22			
N-12	93	1.22			

Valve number	Per-cent open	Average pressure below atmospheric - Feet of water		Discharge in cubic feet per second	
		Discharge guide	50-foot tunnel	Theoretical curve	Watermaster's curve
N-7	96	1.16			
N-8	60	1.09			
N-9	95	1.02	0.88	21,300	19,140
N-10	95	1.16			
N-11	60	1.09			
N-12	95	1.16			
N-7	96	1.09			
N-8	80	1.02			
N-9	95	0.95	0.75	22,640	20,150
N-10	95	1.09			
N-11	80	1.09			
N-12	95	1.16			
N-7	96	1.02			
N-8	95	0.95			
N-9	95	0.95	0.75	23,160	20,430
N-10	95	1.02			
N-11	95	1.02			
N-12	95	1.16			
N-7	96				
N-8	95		Nevada		
N-9	95		0.82		
N-10	95	1.22			25,430
N-11	95				
N-12	95				
A-9	53		Arizona		
A-10	53		2.80		
N-7	96				
N-8	95				
N-9	95		Nevada		
N-10	95	1.22	0.82		
N-11	95				30,430
N-12	95				
A-7	53		Arizona		
A-8	53		1.60		
A-9	53				
A-12	53				
N-7	96				
N-8	95		Nevada		
N-9	95		0.82		
N-10	95	1.22			
N-11	95				35,430
N-12	95				
A-7	53				
A-8	53		Arizona		
A-9	53		0.82		
A-10	53				
A-11	53				
A-12	53				
N-7	96		Nevada		40,974
N-8 to 12	95	N-10, 1.22	0.82		
A-7 to 12	95		Arizona 0.79		
N-7	70				
N-8	53				
N-9	95		Nevada		
N-10	95	1.22	-1.36		
N-11	53				
N-12	70				
A-7	95		Arizona		
A-8	53		0.92		36,508
A-9	95				
A-10	95				
A-11	53				
A-12	95				
N-7 to 12	53	N-10 1.22	Nevada 1.46		29,976
A-7 to 12	53		Arizona 1.12		
N-8	53				
N-9	53		Nevada		
N-10	53		2.10		
N-11	53		Arizona		19,984
A-8	53		1.30		
A-9	53				
A-10	53				
A-11	53				
N-8	53		Nevada		
N-11	53		2.50		
A-8	53		Arizona		9,992
A-11	53		3.00		

The maximum negative pressure for the maximum discharge was 0.75 foot of water for tunnel no. 2 and 0.82 foot of water for tunnel no. 3. At maximum flow the conditions were very steady.

3. Flow conditions in tunnels and river channel. The initial flow during the tests on the Arizona tunnel plug was 10,000 second-feet, so that there was no opportunity to see the conditions at lower flows; but the flow in the Nevada tunnel was increased from no flow to full capacity with sufficient time to observe, insofar as possible, the conditions in the tunnels and in the river channel below. A complete record of conditions at the downstream portals and in the river channel was made by still and motion pictures. The pertinent still pictures have been included as figures 1 to 16 in this report and the motion pictures will be edited by the hydraulic laboratory for future showing. When the needle valves in tunnel no. 2 were opened to a discharge of 4,000 second-feet (fig. 7A), the hydraulic jump appeared to form in the tunnel and there was little indication of the indraft of air over the outflow of water. It was at this flow that the negative pressures in the tunnel were the greatest. As the flow increased to 8,000 second-feet, the disturbance moved down and out of the tunnel as seen in figures 7B and 8. At this point the most spectacular explosions occurred. Water or heavy spray was shot into the air as if by detonation and the spray came halfway up the Stoney gate. The pulsations of air under the Stoney gate were sufficiently strong to sway a person leaning against the headworks column. As the flow was further increased, the disturbance was moved farther down the channel and decreased in intensity. The only explanation of the explosions is the inflow of the return eddy in the river over the outflowing high velocity stream. For an instant the return eddy covers the needle-valve stream and when the energy becomes too great the explosion occurs. At maximum discharge, the flow was comparatively stable and a steady flow of air into the tunnel portal prevailed.

4. Cavitation on needle valves. As a matter of interest, the cavitation which is occurring on the faces of the needle valves, both in the tunnel plug and in the canyon-wall outlets, was examined. Photographs of particular examples are included in figures 17 and 18. A peculiar condition was noted in the rust marks on the inside of the needle-valve body. The flow pattern through the valve body was manifested in the same way as shown by paint tests made in the laboratory. In places, due to cross flow, the direction as indicated by the rust marks was normal to the main stream. This particular condition is shown in figure 18.

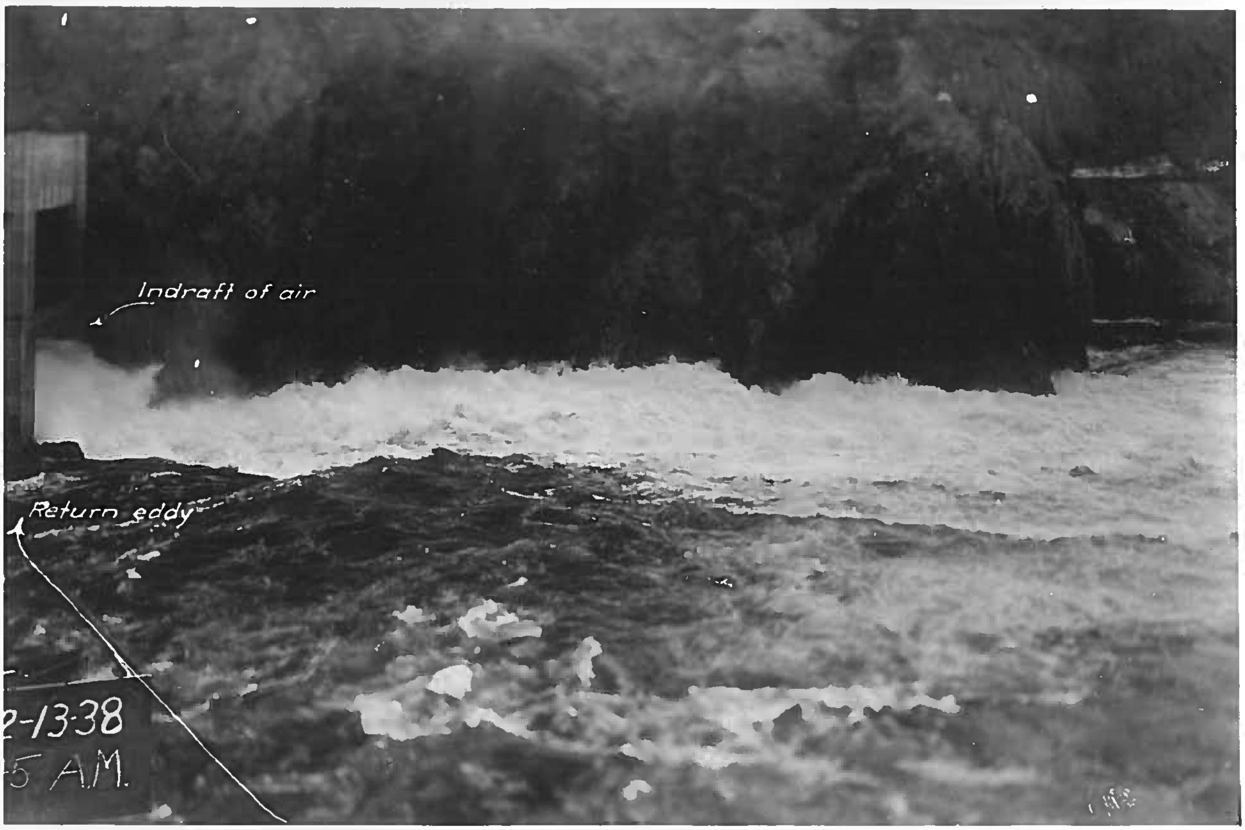
A. BAR IN RIVER BELOW SPILLWAY TUNNEL PORTALS ON DECEMBER 12, 1938, BEFORE TEST PROGRAM - AS SEEN FROM 150-TON HOIST

B. BAR IN RIVER BELOW SPILLWAY TUNNEL PORTAL ON DECEMBER 12, 1938, BEFORE TEST PROGRAM - AS SEEN FROM GARAGE LANDING.

A. ARIZONA STONEY GATE STRUCTURE AND CANYON WALL ON DECEMBER 12, 1938.

B. NEVADA STONEY GATE STRUCTURE AND CANYON WALL ON DECEMBER 12, 1938.

A. CONDITIONS BELOW ARIZONA TUNNEL NO. 3 WITH DISCHARGE OF 12,500 SECOND-FEET.



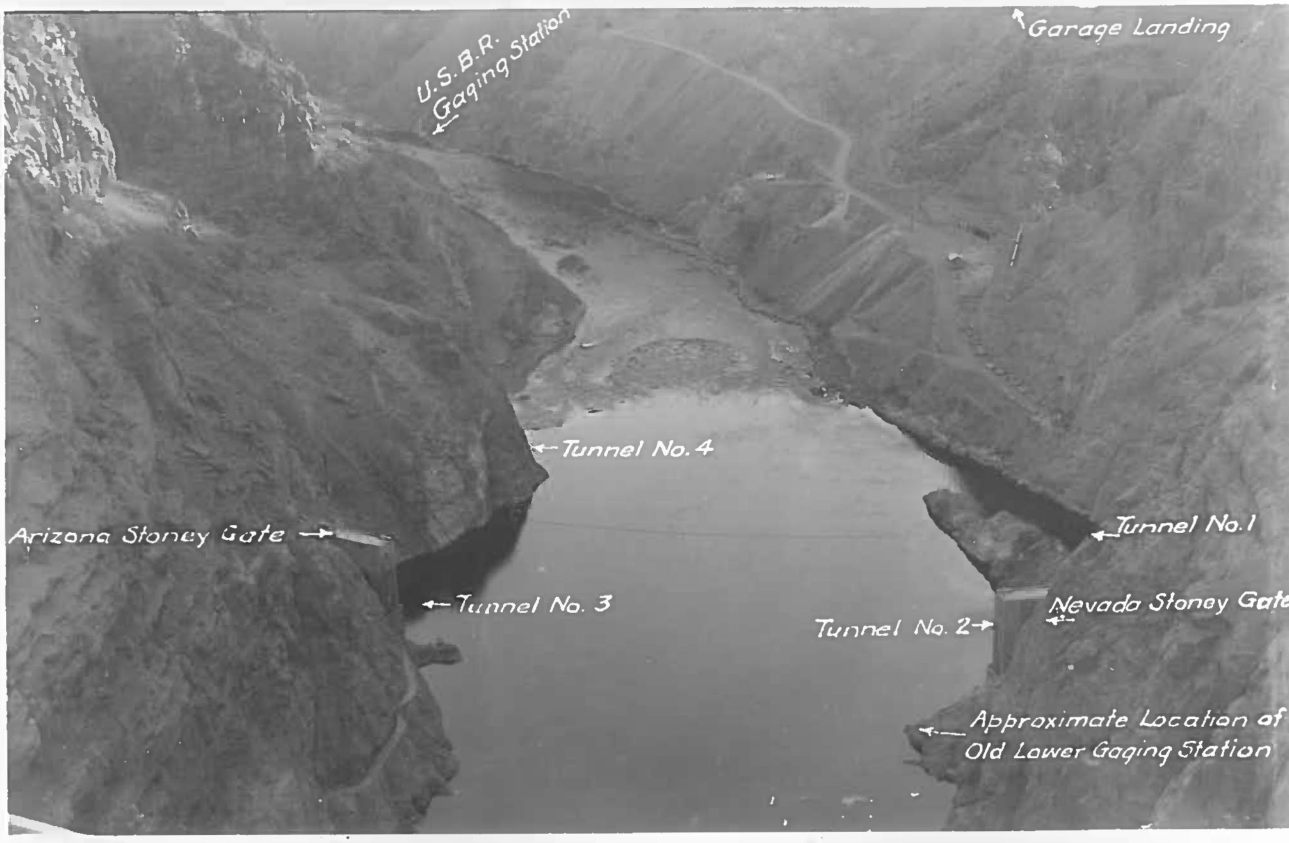
B. CONDITIONS BELOW ARIZONA TUNNEL NO. 3 WITH DISCHARGE OF 16,000 SECOND-FEET.

A. CONDITIONS BELOW ARIZONA TUNNEL NO. 3 WITH DISCHARGE OF 17,000 SECOND-FEET.

B. CONDITIONS BELOW ARIZONA TUNNEL NO. 3 WITH DISCHARGE OF 20.500 SECOND-FEET.

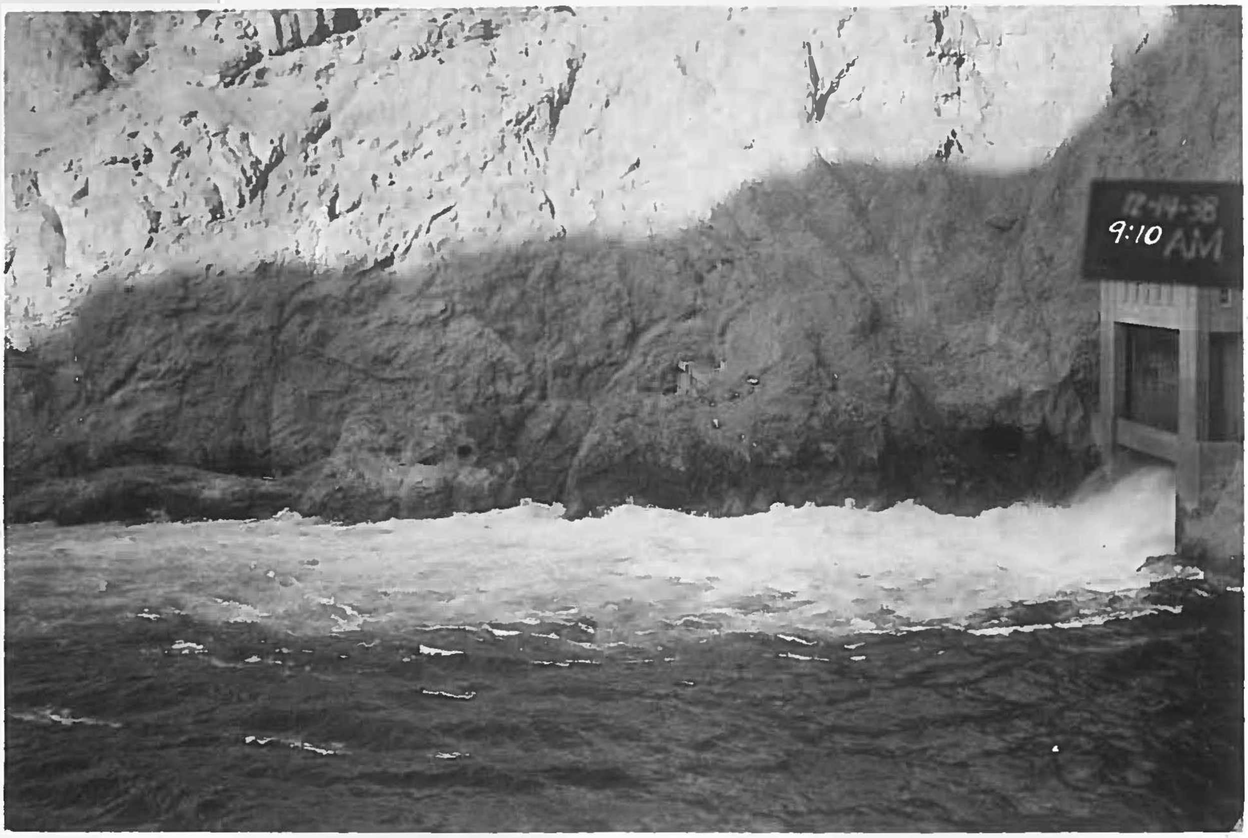
A. CONDITIONS BELOW ARIZONA TUNNEL NO. 3 WITH DISCHARGE OF 20,500 SECOND-FEET - AS SEEN FROM 150-TON HOIST.

B. CONDITIONS BELOW ARIZONA TUNNEL NO. 3 WITH DISCHARGE OF 20,500 SECOND-FEET - AS SEEN FROM GARAGE LANDING.

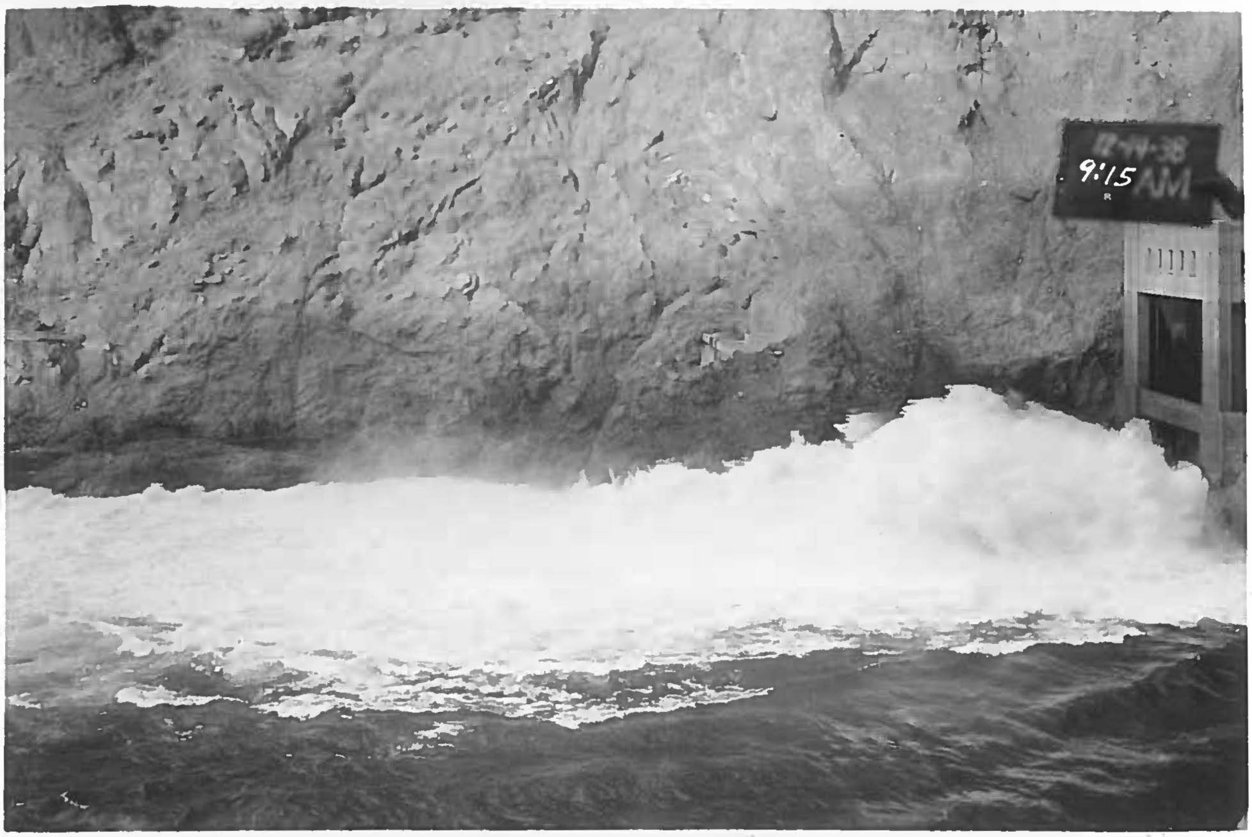


A. BAR IN RIVER BELOW SPILLWAY TUNNEL PORTALS ON DECEMBER 13, 1938.
AFTER OPERATION OF TUNNEL NO. 3 - AS SEEN FROM 150-TON HOIST.

B. BAR IN RIVER BELOW SPILLWAY TUNNEL PORTALS ON DECEMBER 13, 1938.
AFTER OPERATION OF TUNNEL NO. 3 - AS SEEN FROM 150-TON HOIST.



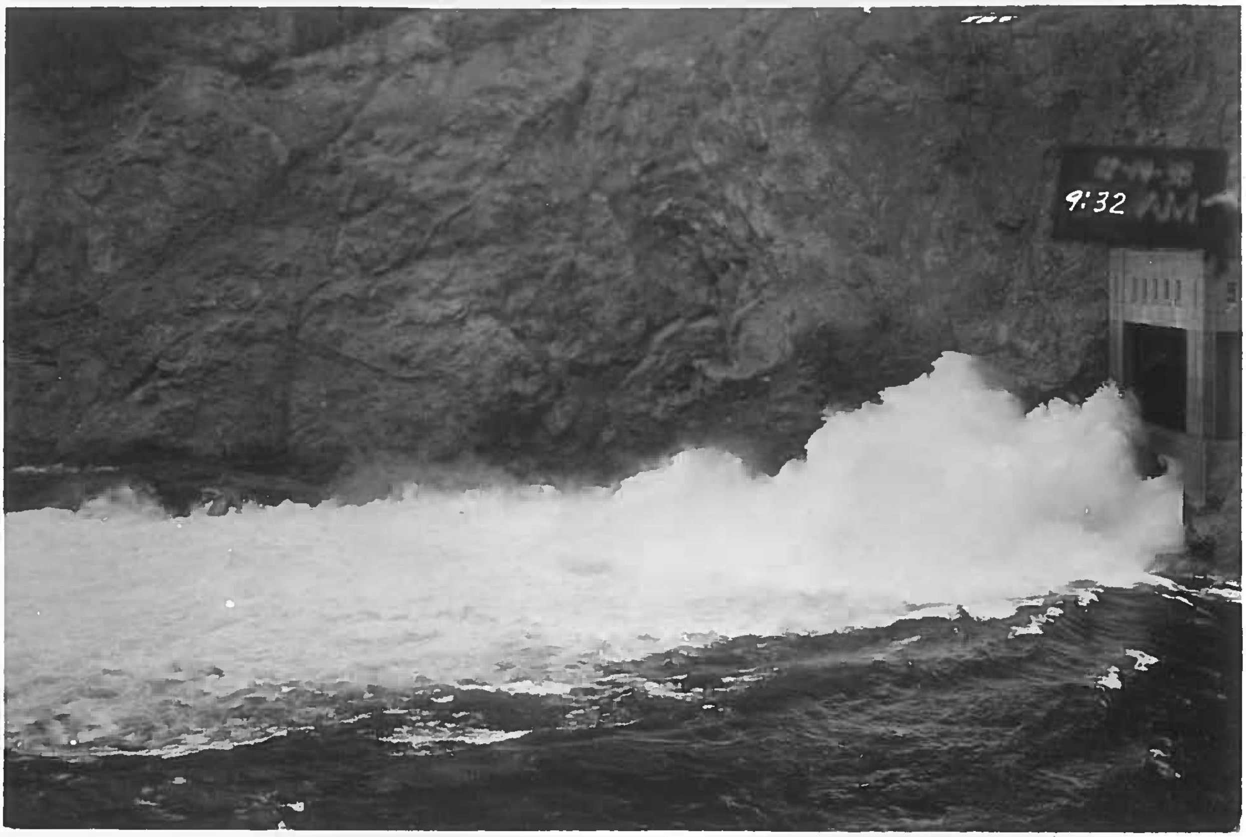
A. CONDITIONS BELOW NEVADA TUNNEL NO. 2 WITH DISCHARGE OF 4,000 SECOND-FEET



B. CONDITIONS BELOW NEVADA TUNNEL NO. 2 WITH DISCHARGE OF 8.000 SECOND-FEET.

A. CONDITIONS BELOW NEVADA TUNNEL NO. 2 WITH DISCHARGE OF 8,000 SECOND-FEET.

B. CONDITIONS BELOW NEVADA TUNNEL NO. 2 WITH DISCHARGE OF 8,000 SECOND-FEET

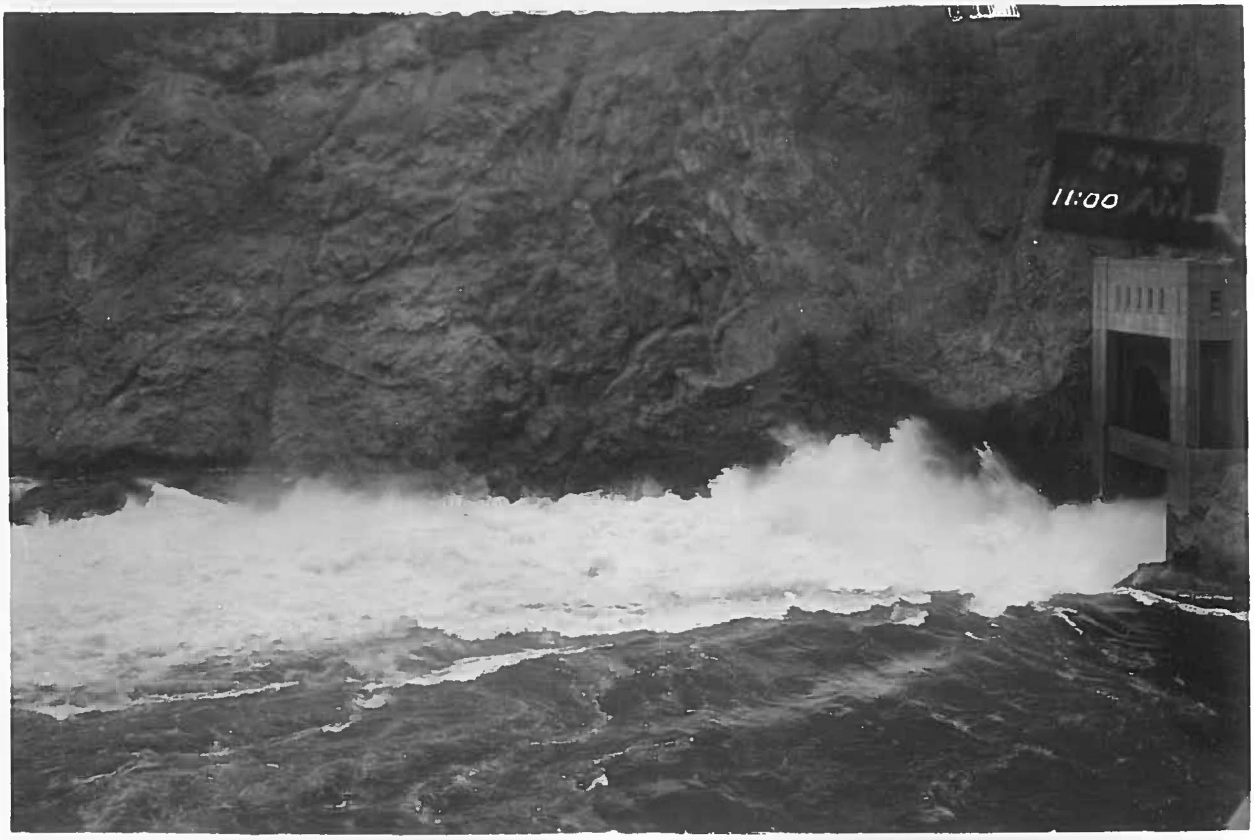


A. CONDITIONS BELOW NEVADA TUNNEL NO. 2 WITH DISCHARGE OF 10,000 SECOND-FEET.

B. CONDITIONS BELOW NEVADA TUNNEL NO. 2 WITH DISCHARGE OF 12,000 SECOND-FEET.

A. CONDITIONS BELOW NEVADA TUNNEL NO. 2 WITH DISCHARGE OF 14,000 SECOND-FEET.

B. CONDITIONS BELOW NEVADA TUNNEL NO. 2 WITH DISCHARGE OF 15,000 SECOND-FEET.



A. CONDITIONS BELOW NEVADA TUNNEL NO. 2 WITH DISCHARGE OF 17,500 SECOND-FEET.

B. CONDITIONS BELOW NEVADA TUNNEL NO. 2 WITH DISCHARGE OF 20,500 SECOND-FEET.

A. CONDITIONS BELOW NEVADA TUNNEL NO. 2 WITH DISCHARGE OF 20,500 SECOND-FEET - AS SEEN FROM 150-TON HOIST.

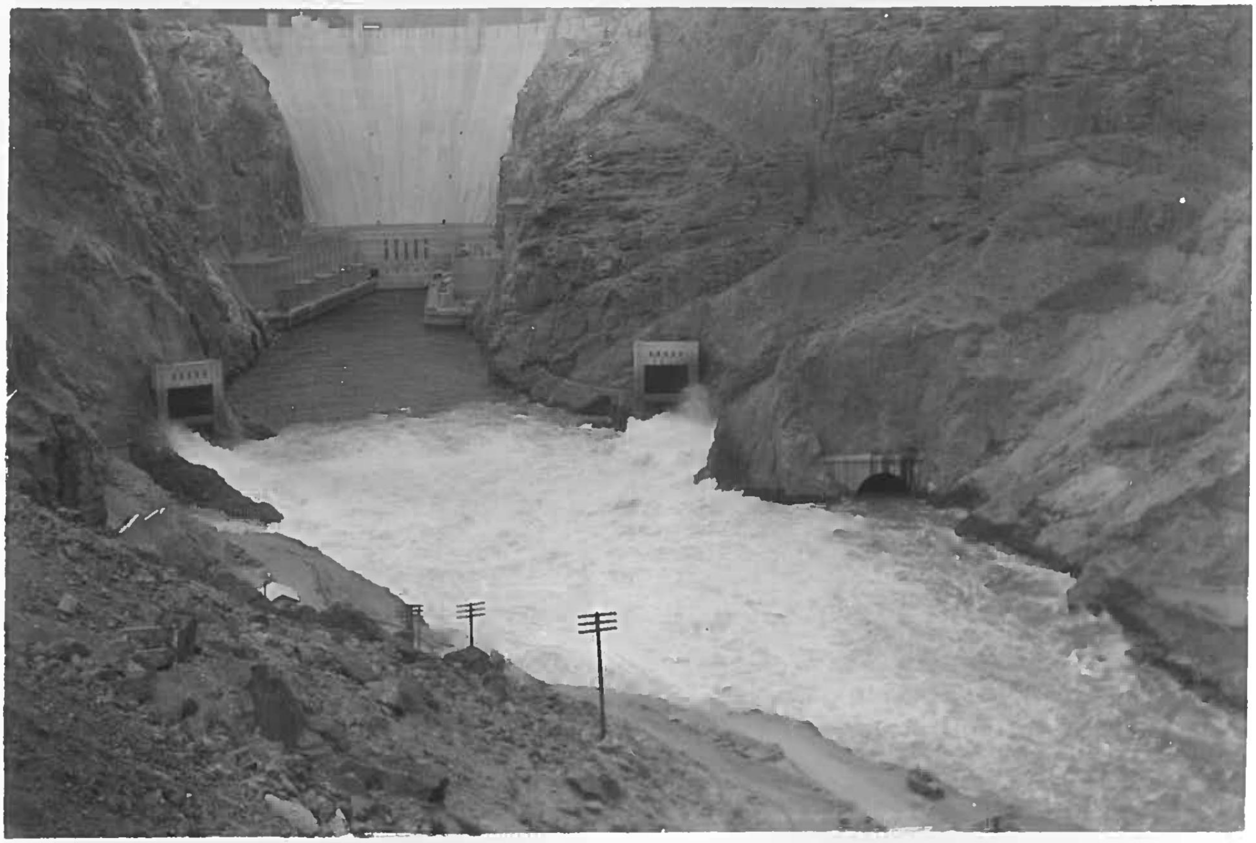
B. CONDITIONS BELOW NEVADA TUNNEL NO. 2 WITH DISCHARGE OF 20,500 SECOND-FEET - AS SEEN FROM GARAGE LANDING.

A. MAXIMUM DISCHARGE IN TUNNEL NO. 2 AND 5,000 SECOND-FEET IN TUNNEL NO. 3.

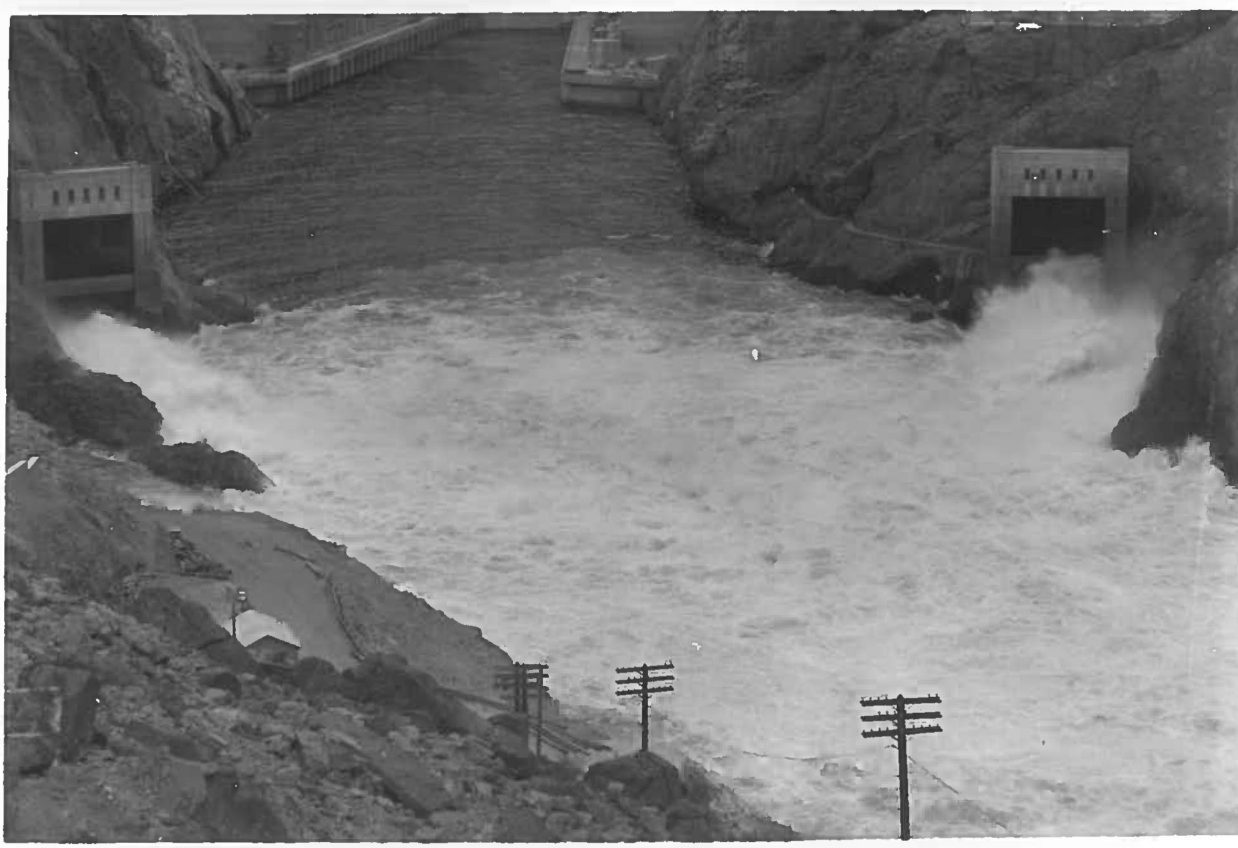
B. MAXIMUM DISCHARGE IN TUNNEL NO. 2 AND 10,000 SECOND-FEET IN TUNNEL NO. 3.

A. MAXIMUM DISCHARGE IN TUNNEL NO. 2 AND 15,000 SECOND-FEET IN TUNNEL NO. 3.

B. MAXIMUM DISCHARGE IN TUNNELS NO. 2 AND 3.



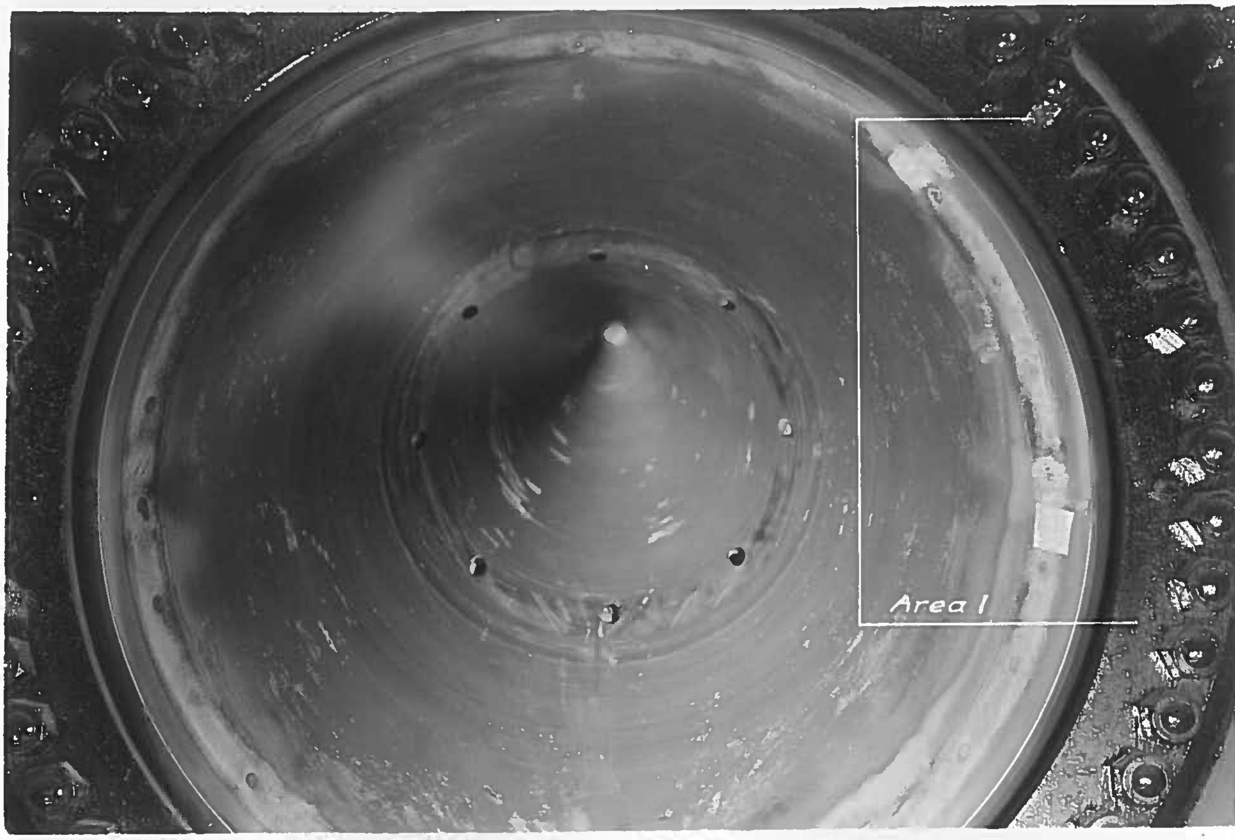
A. MAXIMUM DISCHARGE IN TUNNELS NO. 2 AND 3



B. MAXIMUM DISCHARGE IN TUNNELS NO. 2 AND 3.

A. BAR IN RIVER BELOW SPILLWAY TUNNEL PORTALS AT CONCLUSION OF TEST PROGRAM - AS SEEN FROM 150-TON HOIST.

B. BAR IN RIVER BELOW SPILLWAY TUNNEL PORTALS AT CONCLUSION OF TEST PROGRAM - AS SEEN FROM GARAGE LANDING.



A. ENTIRE NEEDLE

B. CLOSE-UP OF AREA 1

CAVITATION ON NEEDLE VALVE A-10 IN ARIZONA TUNNEL PLUG OUTLET WORKS.

A. CAVITATION AT DOWNSTREAM END OF NEEDLE GUIDE.

B. FLOW LINES IN RUST ON INSIDE OF NEEDLE VALVE BODY.

NEEDLE VALVE A-10 IN ARIZONA TUNNEL PLUG OUTLET WORKS

5. Debris in invert of tunnel no. 3. After the completion of the test program the unwatering of tunnel no. 3 was begun. As the unwatering progressed it was found that the entrance to the drainage pump in the tunnel plug control works was plugged by debris which was left in the tunnel at the completion of construction. This material extended from the headwall of the tunnel to a point slightly below the end of the upstream transition. It ended in a vertical drop of about four feet and appeared to be so firmly compacted as to require breaking tools for removal. This debris consisted of irregular masses of concrete, rock, gravel, castings, timber, rails, pipe, cable, etc., and was from 7 to 9 feet deep at the tunnel headwall. It was necessary to dislodge portions of the material before unwatering could be continued and the opinion was expressed by different members of this board that the remainder should be removed. The Director of Power was in agreement and it has been stated in a letter of January 18, 1939 from him that "The material in no. 3 tunnel will be removed by the end of the present week."

The first impression was that similar conditions existed in tunnel no. 2, but later detailed examination by the operating staff accompanied by Chief Designing Engineer J. L. Savage disclosed that the conditions were very different from those in no. 3. In a letter dated January 18, 1939, the Director of Power reports "There was very much less material and it was not cemented as in no. 3. Only a small portion remains in the tunnel and that does not extend downstream very far from the plug. There is no material near where the jet strikes."

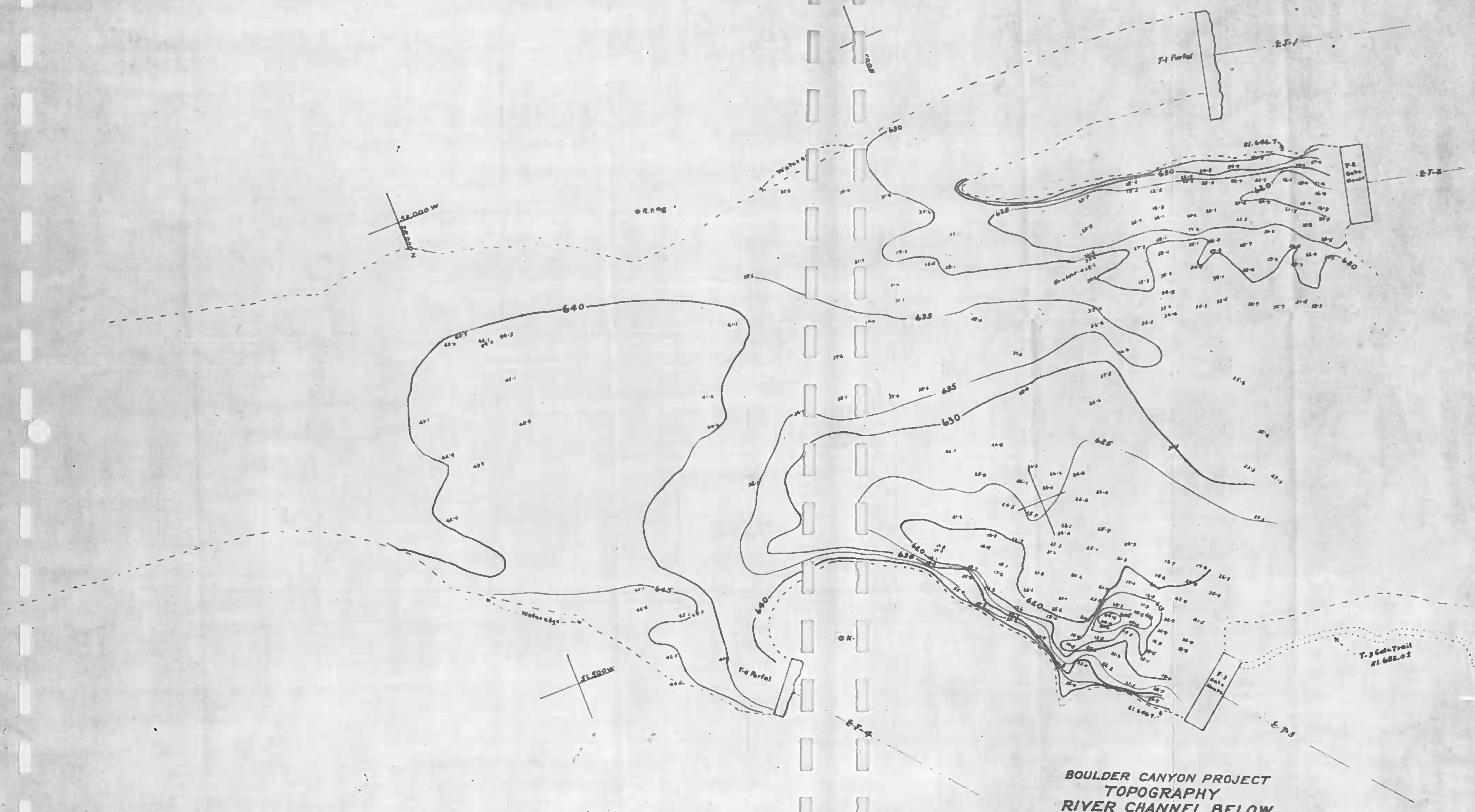
In a letter from the Construction Engineer to Chief Engineer dated May 13, 1937, subject, "Results of initial operation of needle valves in tunnel no. 2", it was reported that there was some damage to the concrete surface at the downstream end of the tunnel after continuous operation during the previous month. The opinion was expressed "Part or all of the wear may be due to loose rock fragments being moved along under comparatively high velocities. When diversion was first made through the tunnel needle valves, a comparatively large percentage of sand, gravel, and clay covered the invert of this tunnel downstream from the valve chamber. It was decided to permit the moving water to wash this material out and in so doing it is possible that scour occurred over the area shown. A second possible damage from scour was thought to be possible from loose rock in the channel immediately downstream from the portal being brought back in the tunnel by an undercurrent. Pieces of this rock as large as a foot in diameter have been shot upward 20 or 25 feet above water surface at the tunnel portal. However, at one of the periodic inspections the Stoney gate was lowered and the water pumped down to within a few feet of the tunnel invert and no loose rocks were observed on the bottom at the lower end of the tunnel. A third possibility of the cause of the damage was thought to be cavitation due to a vacuum."

A careful examination was made of these damaged surfaces after the test program had been completed but no evidence of fresh scouring was disclosed. It is believed that the original damage was caused more by the pounding or impingement of the rocks carried in suspension into the hydraulic jump, which presumably formed or tried to form immediately upstream from the portal. The Stoney gate seats were damaged during the initial operation by the impact of this debris being sluiced from the tunnel invert. The Nevada gate appears to be in a worse condition than the Arizona gate. No attempt was made to use the Nevada gate for unwatering. The leakage around the Arizona gate combined with the clogging of the intake to the 16-inch drainage pump by debris prevented the complete unwatering of the Arizona tunnel immediately following the test program.

6. <u>Erosion of channel immediately downstream from tunnel portals.</u> Soundings made for a distance of 125 feet below the Arizona portal after the operation during these tests indicated no change from similar soundings made in June and November 1938. Beyond this point loose material was removed for a depth of 10 feet in a distance of 125 feet, the extent of these soundings. This indicates that the rock at the portal is substantially stable and will withstand considerable operation of the outlet works in the present condition. Topography in the river channel below the tunnel plug outlets as of November 18 and December 15, 1938, is shown on figures 19 and 20. Comparisons of cross sections on the same dates with the final excavation are shown on figures 21 and 22. It is necessary, however, that a very close check be made from time to time to detect and avoid undercutting the gate structure and adjacent canyon walls. It is believed that a training wall and an apron immediately downstream from each portal would eliminate inflow of the eddy formed by the high-velocity water from the tunnel and prevent undercutting of the foundation of the Stoney gate structure and adjacent canyon walls. This condition is not considered to be serious for a limited operation. Such work if actually instigated would probably have to be deferred until after the coming operating season because of the time required for the construction of cofferdams and unwatering. Before any work of this nature is done a model study should be made based on the present river bed topography as determined by accurate surveys called for in the recommendation.

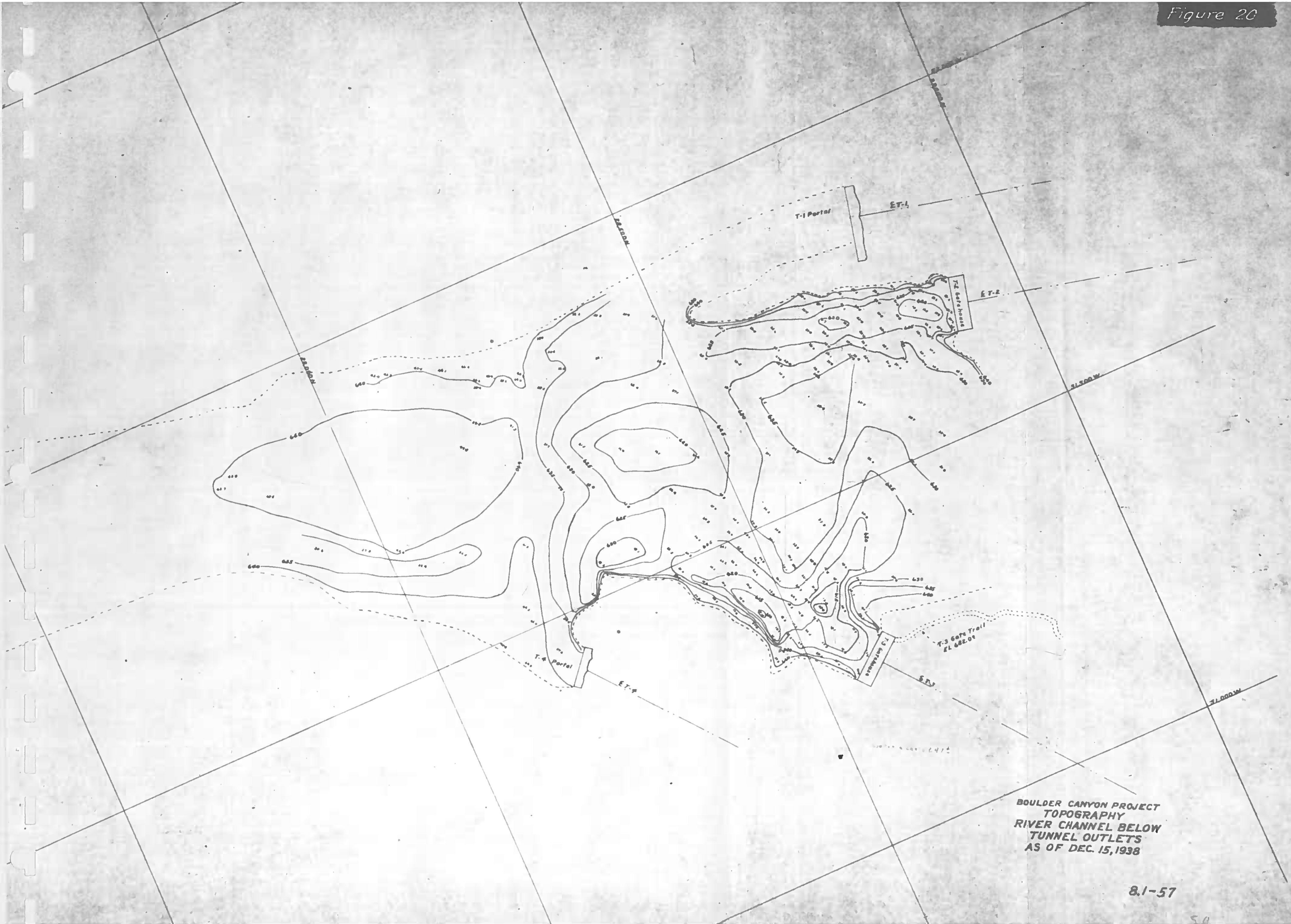
7. <u>Bar in river channel below spillway tunnel portals.</u> Material left in the river bed after construction, or washed in as a result of outlet operation, has formed a bar across the river channel immediately below the downstream portal of the spillway tunnel. The extent of this bar can be seen in figures 1, 6, and 16. The

Figure 19



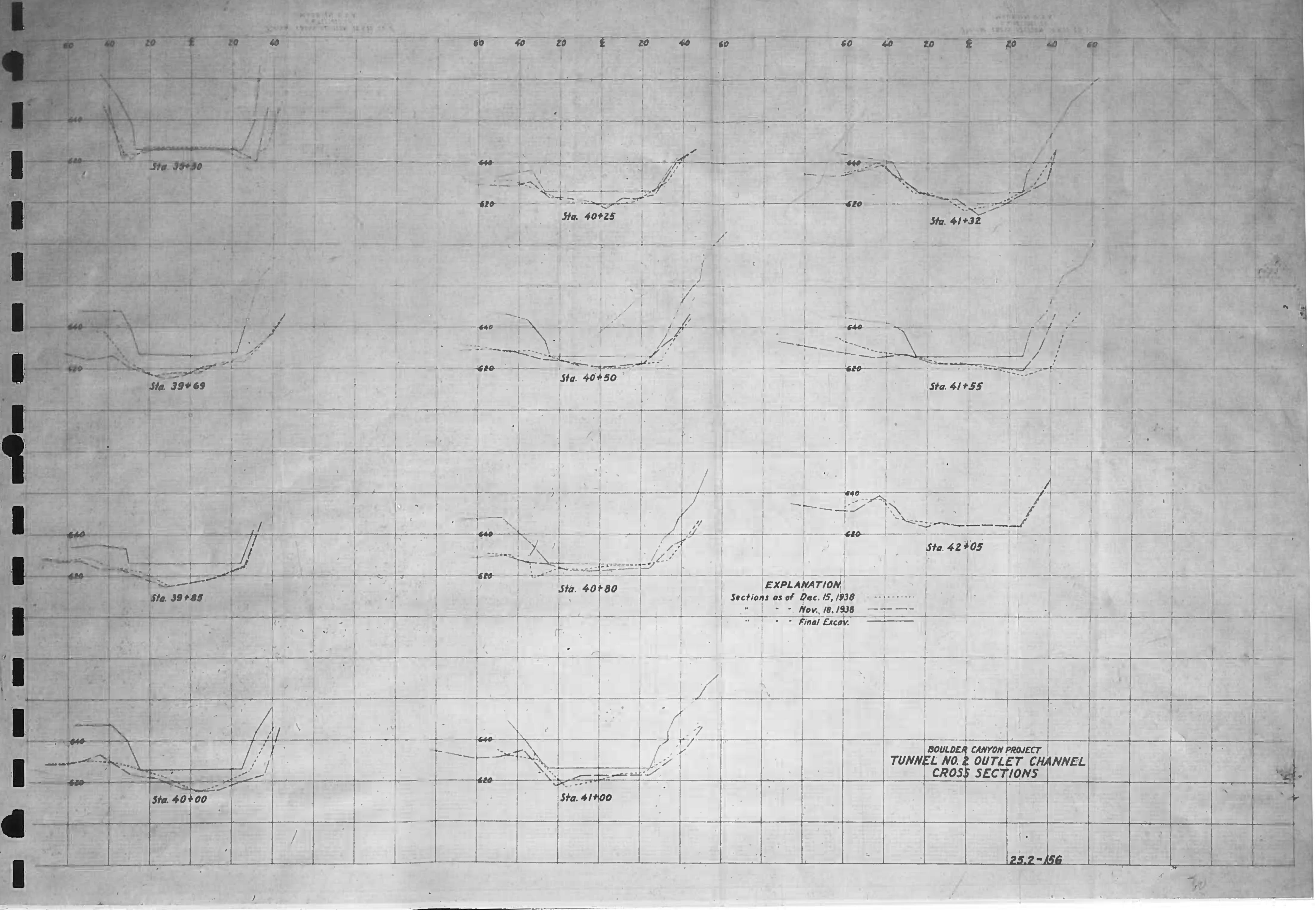
BOULDER CANYON PROJECT
TOPOGRAPHY
RIVER CHANNEL BELOW
TUNNEL OUTLETS
AS OF NOV. 18, 1938

8.1-56



BOULDER CANYON PROJECT
TOPOGRAPHY
RIVER CHANNEL BELOW
TUNNEL OUTLETS
AS OF DEC. 15, 1938

Figure 21



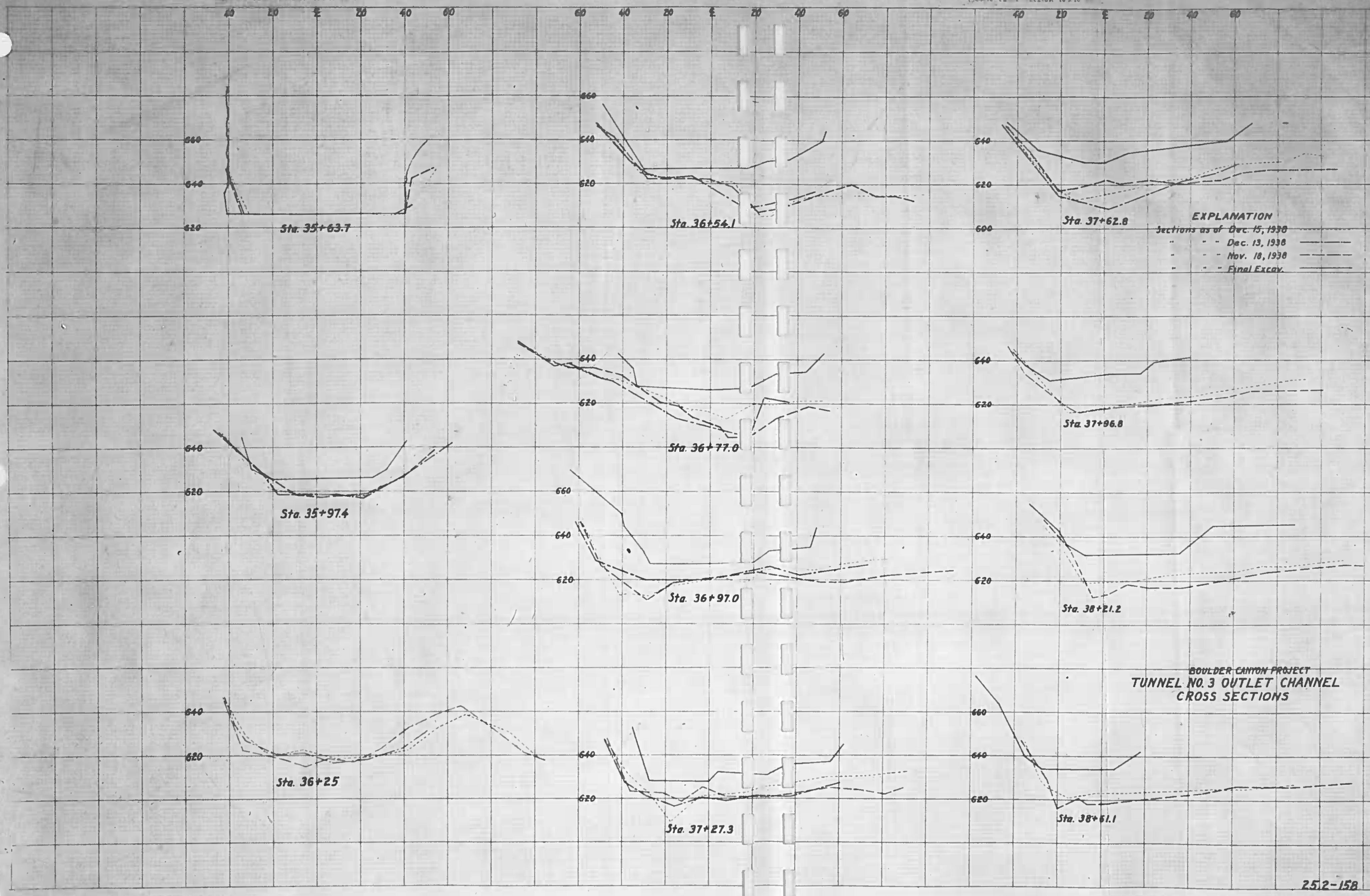
Sta. 39+30
Sta. 40+25
Sta. 41+32
Sta. 39+69
Sta. 40+50
Sta. 41+55
Sta. 39+85
Sta. 40+80
Sta. 42+05
Sta. 40+00
Sta. 41+00
EXPLANATION
Sections as of Dec. 15, 1938
" " Nov. 18, 1938
" " Final Excav.
BOULDER CANYON PROJECT
TUNNEL NO. 2 OUTLET CHANNEL
CROSS SECTIONS
25.2-156

material in this bar is too heavy to be moved any distance by operation of the tunnel plug outlets and will have to be removed from the channel by dredging. Its removal will improve the tailwater conditions and increase the head on the power plant. The effect of the excessive tailwater due to this bar is not serious so far as the tunnel plug outlets are concerned, but a lower tailwater will reduce the disturbance at the tunnel portals; tend to minimize the spray at the portal structure for flows of 5,000 second-feet or less; and allow the high-velocity water to continue into the river where it is less likely to do damage; and will increase the air supply to the turbines and thereby improve the surging characteristics of these units. The bar did not move appreciably under the full discharge from the tunnel plug outlets. Actually the tailwater was raised approximately 0.6 foot due to the deposit of more material in the bar. The tailwater curve at the powerhouse before and after the test program is shown on figure 23 compared to the discharge curve at the old lower gaging station as shown on drawing no. 45-D-908 and to the present gaging station, the location of which is shown on figure 6.

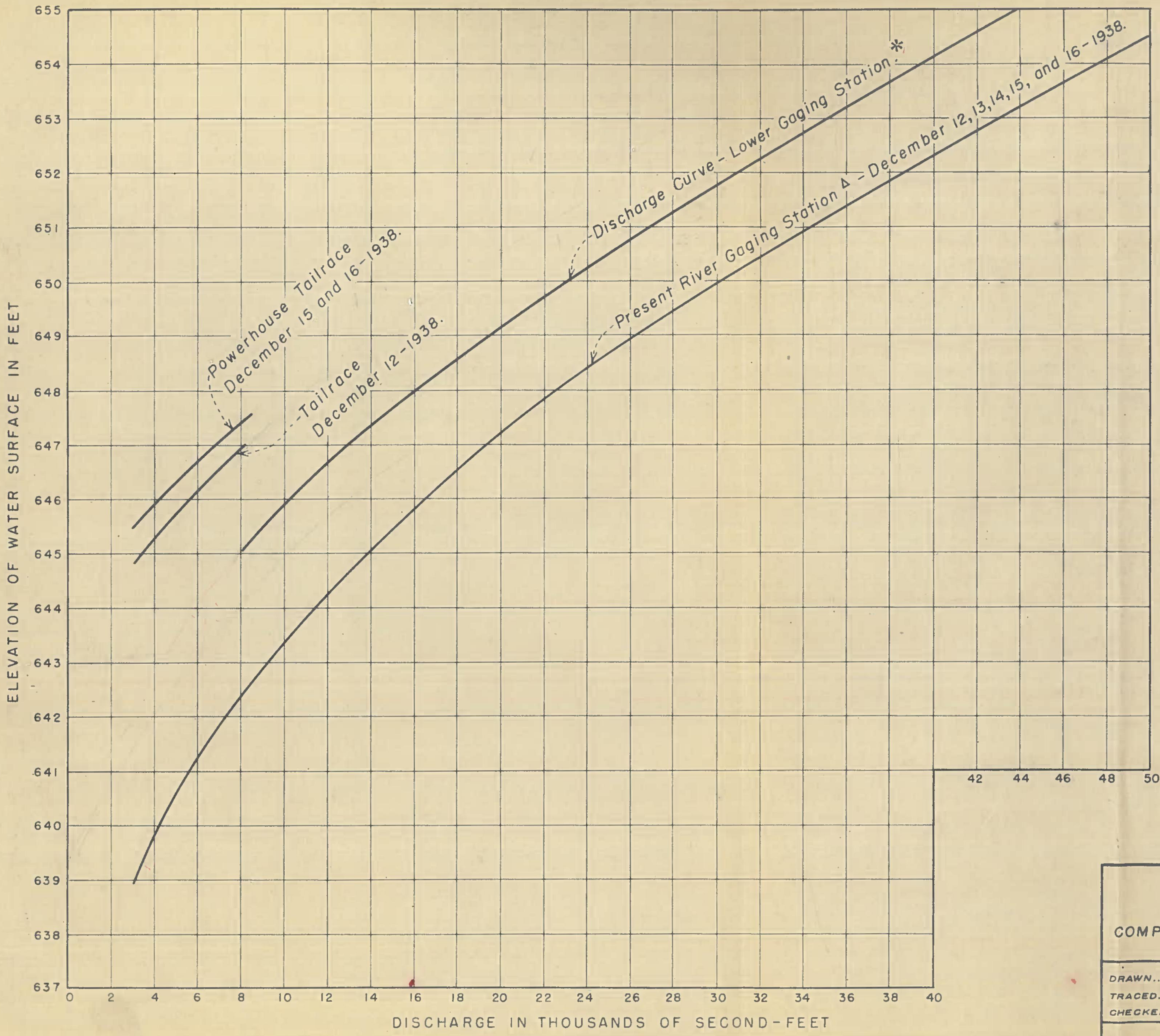
8. Calibration of flow through intake towers. During the test program, the flow conditions in the Arizona intake tower were observed with one cylinder gate only open and in the Nevada intake tower with both gates open. The difference in elevation of the water surface between the outside and the inside of the intake tower was measured and the condition of the water surface within the tower was observed. This difference in elevation is a measurable and steady condition. The water surface within the tower even at maximum discharge was very quiet and smooth, with practically no evidence of the formation of a vortex. At maximum discharge a large vortex developed about 75 feet from the Arizona intake tower between the tower and the canyon wall, as seen in figure 24. At maximum discharge, two areas of small vortices were noted between the Nevada intake tower and the canyon wall.

The discharge through the needle valves in the tunnel plug outlets was determined by two methods during the test program. A discharge curve for one valve has been plotted from calculations of velocity and areas in the valves at different openings of the valves and different reservoir elevations. This curve is referred to as a theoretical discharge curve since it is based on calculations and an assumed coefficient of discharge. All valves were considered identical and when more than one valve was opened the discharge was calculated by multiplying the discharge for one valve by the number of valves opened which is inaccurate since the head losses are proportionately higher with all valves opened than with one valve opened and the head losses in the penstocks vary with the load demand in the powerhouse. The curve used by the watermaster, which is probably

Figure 22



Sta. 35+63.7
Sta. 36+54.1
Sta. 37+62.8
EXPLANATION
Sections as of Dec. 15, 1938
" - - Dec. 13, 1938
" - - Nov. 18, 1938
" - - Final Excav.
Sta. 35+97.4
Sta. 36+77.0
Sta. 37+96.8
Sta. 36+97.0
Sta. 38+21.2
Sta. 36+25
Sta. 37+27.3
Sta. 38+61.1
BOULDER CANYON PROJECT
TUNNEL NO. 3 OUTLET CHANNEL
CROSS SECTIONS
252-158



* Curve as shown on Dwg. 45-D-908 which is the discharge curve for the old gaging station 1500 feet below damsite. If the old station were still in operation the gage heights would be practically identical to those from the present tailrace gage. See Figure 6-A for approximate location.

Δ U.S.B.R. River Gaging Station $1\frac{1}{2}$ miles below dam.

?

DEPARTMENT OF THE INTERIOR
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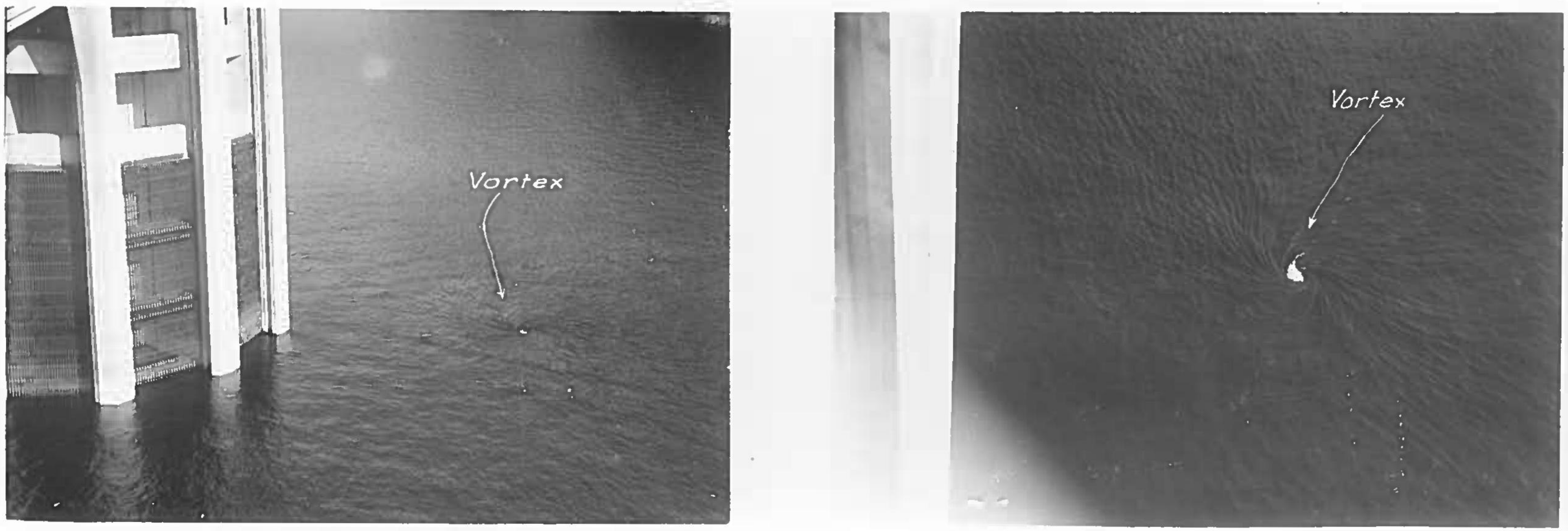
BOULDER CANYON PROJECT

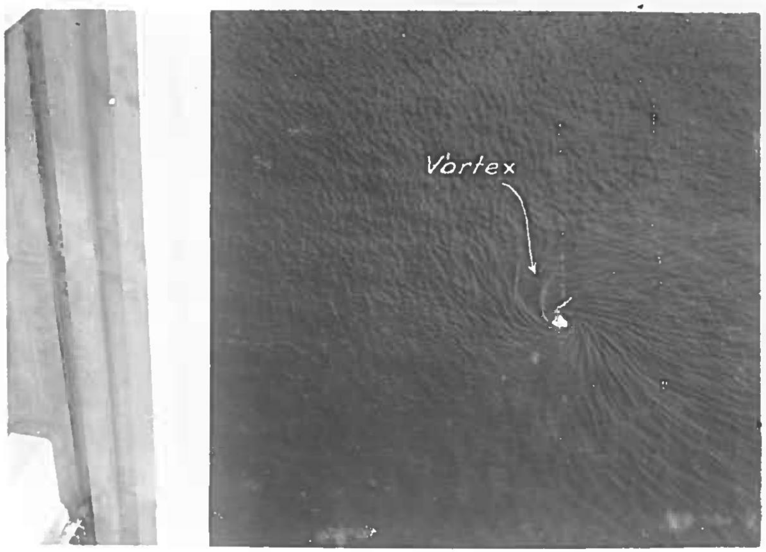
BOULDER DAM

COMPARISON OF DISCHARGE CURVES BELOW BOULDER DAM

DRAWN A.N.S.	SUBMITTED
TRACED E.F.J.-F.B.	RECOMMENDED
CHECKED J.H.D.	APPROVED
DENVER, COLO. - FEB. 1, 1939	45-D-12444



VORTEX NEAR ARIZONA TOWER - ARIZONA OUTLETS WIDE OPEN - DECEMBER 13, 1938



VORTEX NEAR ARIZONA TOWER - DECEMBER 13, 1938

INTAKE TOWERS

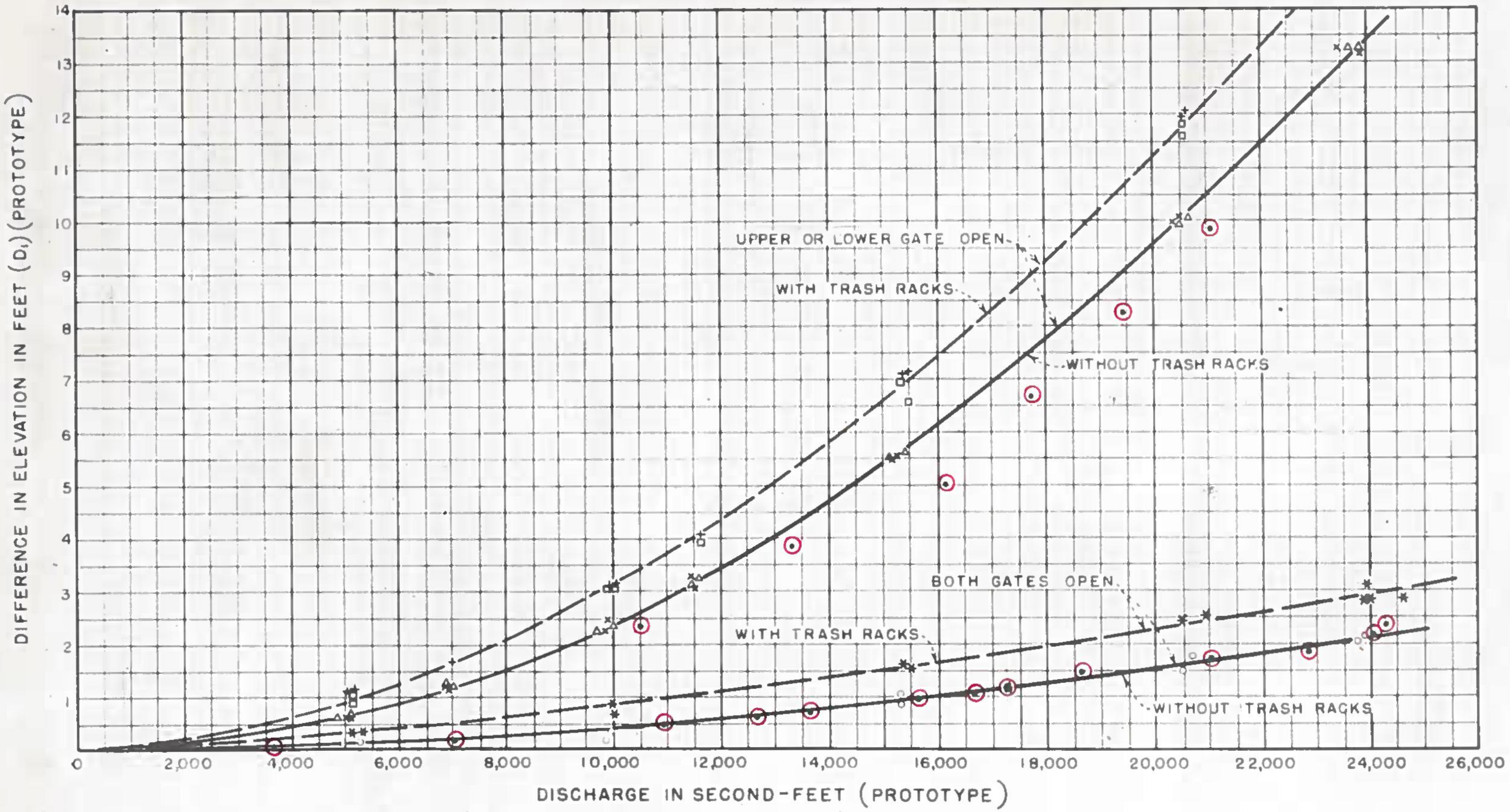
FIGURE 24

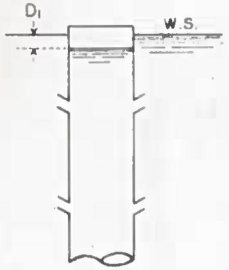
the more accurate, was constructed from data obtained by gagings at the river gaging station 1-1/2 miles below the dam during normal operation of the valves. This curve was based on numerous gagings with one or more valves open and was constructed to show discharge through one valve at different openings and different reservoir elevations. Such treatment also assumes that each valve discharges an equal quantity under similar conditions of opening and reservoir elevation, which is an incorrect premise since the same fluctuation of head exists as in a theoretical curve. Neither method can be considered an accurate means of determining the release through the valves. Both methods are in error in that they are related to reservoir elevations, which is not a measure of pressure at the valves. In the case of more than one valve open, the losses in the conduit system are higher than with one valve open, hence the pressure at the valves will be less, resulting in a decrease in discharge. This error is partly compensated for in the watermaster's curve since much of the data were taken with more than one valve operating. There is also a difference in loss when one or both gates in the intake tower are opened. The accuracy of the theoretical curve is dependent upon a coefficient of discharge for the various openings of the valves. Little data are available regarding the value of these coefficients. The accuracy of the watermaster's curve is dependent upon the accuracy of the gaging stations in the river below the dam. Here again the accuracy of the gagings at the river station is questionable because of the constant fluctuation of the water surface due to load variation in the powerhouse.

With the present storage available in Lake Mead, the present power load at Boulder Dam, and with Parker Dam in operation, extreme accuracy of measurement in releasing water at Boulder Dam does not appear to be so important. Close regulation of release does not appear advisable as such procedure will require that some of the needle valves be operated at partial openings over long periods of time with the attendant rapid erosion of their needles and seats due to cavitation. It will probably be more satisfactory to operate the needle valves only at wide open positions and regulate the flow by operating part of the valves wide open all the time and opening others wide open part of the time to meet the requirements for a 24-hour period. Equalization of flow can be accomplished at Parker Dam where the flow can be regulated by release through the spillway gates to the projects below.

Since apparent discrepancies exist in the present methods of discharge measurements, consideration should be given to obtaining an accurate means of measuring release of water in order that the necessary calibration may be completed prior to the time that closer regulation becomes necessary. All normal release of water is through the intake towers. Therefore calibration of these structures would afford a means of obtaining total release as well as establishing a standard from which other units could be calibrated. Gibson calibrations of the power units have already been made. The results of these tests could be transferred to the towers and with the existing model data only a few additional runs made by some reliable method would be necessary to obtain an accurate discharge curve suitable for all normal release. As previously stated, the difference in elevation of the water surface between the outside and the inside of the intake towers was measured at different discharges with one cylinder gate open and with both cylinder gates open. The indications are that these prototype data are comparable to the model data as shown in Boulder Canyon Reports, Part VI, Bulletin 2, "Model Studies of Penstocks and Outlet Works", page 99. The results obtained from the observations made during this test program have been plotted on a print of the curves showing the model results (fig. 25). The discharges shown in this figure were obtained from the watermaster's curve. The discussion of the results of the model tests in the above reference states: "The relation of D_1 to discharge has been plotted on figure 54 for both conditions, with and without trashracks in place. It is believed that the curves shown for the prototype without trashracks are essentially correct. It has been previously stated that the friction loss through the model trashracks was undoubtedly excessive. Therefore it can definitely be stated that the curves on figure 54, calculated from the model tests with trashracks, are higher than would be similar curves made from actual tests on the prototype". Observations have been made of drop in head through the trashracks on the prototype but no consistent results were obtained. It was concluded that the loss is so small that it is practically negligible. In such case the prototype observations of drop in head into the intake towers should agree quite closely with the curves plotted from model results obtained without trashracks. Such agreement may be seen in figure 25. The observations made during these tests emphasize the possibility of utilizing the drop in head into the intake towers as an accurate measure of flow through the outlet works.

9. Pressure and vibration in penstock system. Throughout the tests on both the lower Arizona and lower Nevada tunnel outlets, observations were made on the penstock system to determine if any transitory pressure wave or surges were transmitted from the valve discharge chambers into the penstock systems. It was determined that the vibrations set up by the high-velocity water discharged from the valve under full capacity were noticeable for a distance of approximately 300 feet upstream from the gate valve chamber. These vibrations were of rapid frequency and low magnitude, such as is noticeable when standing over a needle valve, and disappeared entirely at the upper anchor leading to the intake tower where no sound of flowing water could be detected by placing the ear to





EXPLANATION

TRASH RACKS IN PLACE		TRASH RACKS REMOVED
+	UPPER GATE OPEN	×
□	LOWER GATE OPEN	△
✱	BOTH GATES OPEN	○

⊙ — PROTOTYPE OBSERVATIONS MADE DURING TUNNEL PLUG OUTLET WORKS TESTS - DEC. 1938 DISCHARGE OBTAINED FROM WATERMASTERS CURVE.

DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
BOULDER CANYON PROJECT

BOULDER DAM HYDRAULIC EXPERIMENTS

INTAKE TOWER STUDIES

RELATION OF D_1 TO DISCHARGE (PROTOTYPE)

DRAWN J.N.B. SUBMITTED J. N. Bradley
TRACED J.N.B. O.R.S. RECOMMENDED
CHECKED J.D.M. APPROVED

DENVER, COLO., JAN. 2, 1936 — 45-D-9769

the penstock pipe. Oscillograph charts were made at the take-off of the 13-foot diameter penstock at unit N-3 to determine the effect of the turbulence set up by 2,500 second-feet of water being taken from the 30-foot penstock, which carried a total of approximately 27,000 second-feet. Pressure gages and strain gages were placed on both the 13-foot and the 30-foot penstocks. These gages indicated pressure and strain changes of such low magnitude that these factors are definitely of no importance. A sensitive high-pressure Borden-type gage was connected to the 30-foot pipe just below the take-off of the 13-foot penstock for unit N-3. This gage showed no evidence of hydraulic surges being transmitted from the needle valves even under the most severe conditions obtained at low discharges when a maximum surge of approximately three feet of water was recorded by the water manometers connected with the needle-valve discharge tunnel. From these observations it was concluded that the relatively slight pressure changes developing in the tunnel below the plug, reaching a maximum of 3 feet of water in a total head of 500 feet, were effectively dampened out, and offered no hazard to the penstock systems.

10. Summary of results and conclusion. As a result of these tests and inspections the following conclusions have been reached concerning future operation of the tunnel plug outlets:

(a) Under the relatively high head existing during this particular test program, the general behavior of the tunnel plug outlet works throughout the entire range of operation was considered satisfactory. There was no evidence of distress in any part of the outlet works system at any time during the tests. However, if in the future the storage in the reservoir should be evacuated to the minimum reservoir elevation, the behavior of the tunnel plugs and particularly the Nevada tunnel plug, should be observed under these conditions.

(b) Air shafts or inlets to supply air to the needle-valve jets are not considered necessary. When recommended remedial measures are completed, sufficient air will be supplied by the area of open tunnel above the stream. With proper flow conditions established in the tunnels, the maximum depth of flow will not exceed 3 or 4 feet at the outlet portal with full discharge. At certain stages of low discharge a supplementary air supply might be advantageous but this condition will be improved and the advantage would not justify the high cost of construction of the air shafts.

(c) The worst condition of operation appeared with flows of 3,000 to 5,000 second-feet through the Nevada tunnel and no flow through the Arizona tunnel. The completion of recommended improvements should result in better flow conditions even at those discharges.

(d) A training wall and apron immediately downstream from each portal would materially improve the flow conditions at that point and possibly prevent further undercutting of the foundations of the Stoney gate structure and adjacent canyon walls. However, before any work of this nature is instigated a model study should be made based on accurate surveys of the present river bed condition.

(e) Removal of the bar across the river channel immediately below the downstream portals of the spillway tunnels will reduce the disturbance and minimize spray conditions at the portals of the outlet works tunnels for flows of 5,000 second-feet or less and will lower the water level in the tailrace. By lowering the tailrace water level the air supply to the turbines will be increased, thereby improving the surging characteristics of these units.

(f) Close examination of the invert and walls of the concrete lining of the tunnel plug outlet tunnels failed to disclose any evidence of fresh scouring beyond that which occurred during the initial operation.

(g) The Stoney gate seats at the downstream end of the outlet works tunnels were so severely damaged during the initial operation by the impact of debris sluiced from the tunnel invert that they cannot be satisfactorily used for unwatering the tunnels. The Nevada gate structure appears to be in a worse condition than the Arizona gate.

(h) Observations of the flow conditions in the intake towers during the test program lead to the conclusion that the difference in elevation between the water surface in the reservoir and the water surface within the tower, with either one or two gates open, should be used as an accurate measure of release from Lake Mead.

(i) The air demand of the needle valve is greatest at small openings. At those openings the raveling of the jet is more severe. Two needle valves in each tunnel plug outlet might be adjusted to produce minimum spray at small openings. The other four valves can then be operated at full opening, thus reducing the amount of repairs to the valves. Until such time as a better scheme is determined, the operation of the valves as recommended in Boulder Canyon Reports, Part 6, Bulletin 2, page 128, should be followed. Further experiments during the coming operating season in regard to percentage of opening and choice of valves might produce an improvement of operating conditions for low flows.

(i) Observations of pressures and strains at critical points in the penstock showed no sign of distress at any point of operation.

(j) The tailrace at the powerhouse was steady under all conditions of flow. The rise of the tailrace for a total river flow of approximately 51,000 second-feet was 10 feet and at no time did the tailrace elevation drop below normal. The tailrace elevation at the conclusion of the test program was approximately 0.6 foot higher than at the beginning of the program and about two feet higher than the stages before construction of the dam.

11. Recommendations. The following recommendations are offered as a means of improving the hydraulic conditions in the tunnel and river channel and to improve the operation of the outlet works:

(a) The compacted debris covering the invert of the upper transition of the Arizona tunnel plug outlet works has already been removed at the suggestion of certain members of this board. The material in the Nevada tunnel plug outlet works should be removed at the first opportunity, to reduce the possibility of further damage to the Stoney gate seat.

(b) The guides and seats of the Stoney gates on the downstream portals of the tunnels should be repaired to permit unwatering operations for which they were designed and installed.

(c) An accurate survey of the entire stream bed for a considerable distance below the tunnel portals should be made at the present time and should be repeated after each period of operation as a check on the possible undercutting of the Stoney gate structures. The soundings previously made have very well served their purpose but a more accurate control is needed in future surveys. Plane table or a stadia control for this work has been suggested to the operating engineers.

(d) The bar across the river channel below the spillway tunnels should be removed.

(e) A gage should be installed in each intake tower and connected by remote control to the operating panel in the watermaster's office as a means of more accurately measuring the release of water below, either through the turbines or the outlet works. A calibration of one intake tower with one and both gates open should be made.

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W. E. Blomgren
I. A. Winter
P. A. Kinzie
C. W. Thomas
J. E. Warnock

ABSTRACT OF CORRESPONDENCE

5-11-37 - Memorandum to Chief Designing Engineer from John Parmakian. Preliminary report of discharge tests on Nevada tunnel plug outlet works. Described debris in bottom of tunnel and in channel downstream. Reported wear of concrete lining near downstream end of tunnel and damage to Stoney gate seat.

5-13-37 and 5-14-37 - Letters from Construction Engineer to Chief Engineer. Results of initial operation of needle valve in no. 2 tunnel - Boulder Canyon project. Suggests cavitation as cause of damage to tunnel lining.

8-19-37 - Letter from Acting Construction Engineer to Chief Engineer. Description of conditions of river channel below outlet works as described by Mr. Dana.

6-22-38 - Letter from Acting Construction Engineer to Chief Engineer. Description of hydraulic jump in river below Boulder Dam.

6-30-38 - Letter from Acting Construction Engineer to Chief Engineer. Information regarding needle-valve discharge behavior, etc., Boulder Dam.

7- 1-38 - Letter from Acting Construction Engineer to Chief Engineer. Sequel to letter of 6-30-38.

11-22-38 - Letter from Chief Engineer to Director of Power outlining test program for Arizona and Nevada tunnel plug outlet works to be performed as soon as feasible.

12- 2-38 - Letter from Director of Power to Chief Engineer discussing proposed test programs.

12- 5-38 - Letter from Director of Power to Chief Engineer amplifying letter of 12-2-38.

12- 7-38 - Memorandum from Chief Designing Engineer J. L. Savage to Acting Chief Engineer requesting authorization for travel in connection with test program on tunnel plug outlet works.

12-20-38 - Letter from Director of Power to Chief Engineer. Transmittal of readings made by watermaster during test program of December 13 to 15, 1938.

12-22-38 - Letter from Director of Power to Chief Engineer. Description of debris in tunnel no. 3 and steps being taken to remove it.

12-27-38 - Letter from Chief Engineer to Director of Power. Request for additional test data.

1- 6-39 - Letter from Director of Power to Chief Engineer. Transmittal of test records and retrogression studies.

1-11-39 - Letter from Director of Power to Chief Engineer. Requesting return of certain records.

1-18-39 - Letter from Director of Power to Chief Engineer. Description of material left in tunnel no. 2.

1-25-39 - Letter from Chief Engineer to Director of Power requesting additional data on tests made December 13 to 15, 1938.

2- 4-39 - Letter from Director of Power to Chief Engineer transmitting photographs of pressure recorder records.