HYD-143

HYD 143

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UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

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HYDRAULIC LABORATORY REPORT NO. 143

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IMPROVEMENTS IN RIVER CHANNEL BELOW BOULDER DAM— BOULDER CANYON PROJECT

By

J. N. BRADLEY

- - -

Denver, Colorado

April 19, 1944

COPY

Denver 2, Colorado, June 15, 1944.

MEMORANDUM TO CHIEF DESIGNING ENGINEER:
(J. N. Bradley through J. E. Warnock)

Subject: Improvements in river channel below Boulder Dam--Boulder Canyon Project.

1. Subsequent to the completion of the enclosed hydraulic laboratory memorandum of April 19, 1944, contained herewith, a study was completed relative to the backwater effect expected in the Boulder Dam tailrace by dredging of the river channel downstream and by the proposed future [illegible]lation of Davis Dam Reservoir. As various parties are interes[illegible] in the channel improvement problem, an attempt has been made [illegible]clude all pertinent material on the subject under one cover. [illegible] this reason a memorandum to the Chief Electrical and [illegible]nical Engineer by Engineer I. A. Winter has been included. In addition, a record of the more important previous correspondence on the subject has been placed at the back of the laboratory report.

2. For the purpose of clarification it is here repeated that any reduction in tailwater level, as proposed in Mr. Winter's memorandum, will not constitute a factor in the operation of the modified outlet and spillway tunnels. The modified tunnels will perform equally well over a wide range of tailwater depths. Mr. Winter's data, therefore, are important only with respect to improvement in power head [illegible]t the two plants, and the extent of dredging should be judged solely from this standpoint. The hydraulic laboratory report recommends dredging and removal of loose bank material from the tunnel portals to the river gaging station involving a 0.4 mile reach of the river. Removal of this material is necessary to prevent the formation of bars in the river. Mr. Winter's memorandum constitutes a study of backwater conditions relating to dredging from the tunnel portals to Ringbolt Rapids approximately 3.5 miles downstream.

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J. N. Bradley

COPY

Denver 2, Colorado, May 17, 1944.

MEMORANDUM TO CHIEF ELECTRICAL AND MECHANICAL ENGINEER:
(I. A. Winter)

Subject: River-channel improvements below Boulder Dam--Boulder Canyon Project.

1. Reference is made to Mr. S. E. Rockwell's memorandum to Mr. Savage dated August 7, 1943, requesting data on the effect of backwater from Davis Dam for use by the laboratory in connection with model studies.

2. Mr. Debler's memorandum of September 25, 1943, to the Chief Designing Engineer in reply to Mr. Rockwell's request states that a maximum forebay elevation of 647 has been set by storage requirements at Davis Dam and that studies have not been made on the effect of backwater encroachment on the tailwater at Boulder Dam, either for normal operation as affecting power or under extreme flood conditions.

3. Mr. Savage requested the Hydraulic Design Section to study the effect of backwater from Davis Dam on the operation of turbines at Boulder Dam. This study has been completed and results are shown on drawing 351-D-260 and table I.

4. These studies show that with the river-channel improvements extending below Ringbolt Rapids and the forebay at Davis Dam held at 647, the effective head on the turbines at Boulder will be reduced only two feet for a flow of 25,000 c.f.s. and 3/4 of a foot for a flow of 15,000 c.f.s. It is not unreasonable to expect at least two percent higher over-all efficiency at Davis Dam, and it may be to the Government's best interests to obtain the greatest practicable operating head at Davis at a sacrifice of head at Boulder.

5. The backwater curves for 25,000 c.f.s. show a net gain in power head of 3.5 feet by holding the forebay at Davis Dam at elevation 647. This would indicate that the forebay at Davis should be held at the highest possible elevation at all times. This is the conclusion expressed in Mr. Debler's memorandum. For a flow of 15,000 c.f.s. under extreme drawdown conditions the tailwater at Boulder would reach approximately elevation 622, with Davis forebay at all points below elevation 626. Under these operating conditions, the turbines at Boulder would gain 16 feet in effective head, while the turbines at Davis would lose 21 feet. These comparisons illustrate the advantages to the Government to operate the Davis forebay at the highest possible elevation consistent with the requirements for reregulation of Boulder releases to suit downstream irrigation demands. The turbines at Boulder will operate satisfactorily either with the present elevation of tailwater or with the tailwater lowered by river dredging. From a power standpoint the dredging would result in an increase in energy production prior to completion of Davis Dam, due to increase of 12.5-foot effective head and also after Davis Dam is completed, when the increase in head would be reduced to four feet. Under present river channel conditions the backwater from Davis Dam would reduce the head on Boulder only ½-foot, for a flow of 25,000 c.f.s.

6. Study of the effect of backwater from Davis Dam under flood conditions was not a part of this assignment, but it appears from the values obtained in the power studies that the effect at Boulder Dam of backwater from Davis Dam for flows above 30,000 second-feet will be unimportant.

Table I

Curve No.	Flow c.f.s.	Elevation in Feet: Boulder	Elevation in Feet: Davis	Elevation in Feet: Difference Boulder to Davis	Channel Excavation: Cubic Yards	Channel Excavation: Length in Miles
1	25,000	640.00	631.00	9.00	3,000,000	3.64
2	25,000	640.00	634.41	5.60	4,000,000	7.04
3	15,000	631.70	625.74	6.00	4,000,000	7.04
4	25,000	649.00	647.00	2.00	4,000,000	7.04
5	15,000	647.77	647.00	.75	4,000,000	7.04

- - -

I. A. Winter

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

Branch of Design and Construction
Engineering and Geological Control
and Research Division
Denver, Colorado
April 19, 1944

Laboratory Report No. 143
Hydraulic Laboratory
Compiled by: J. N. Bradley

Reviewed by: R. F. Blanks and
J. E. Warnock

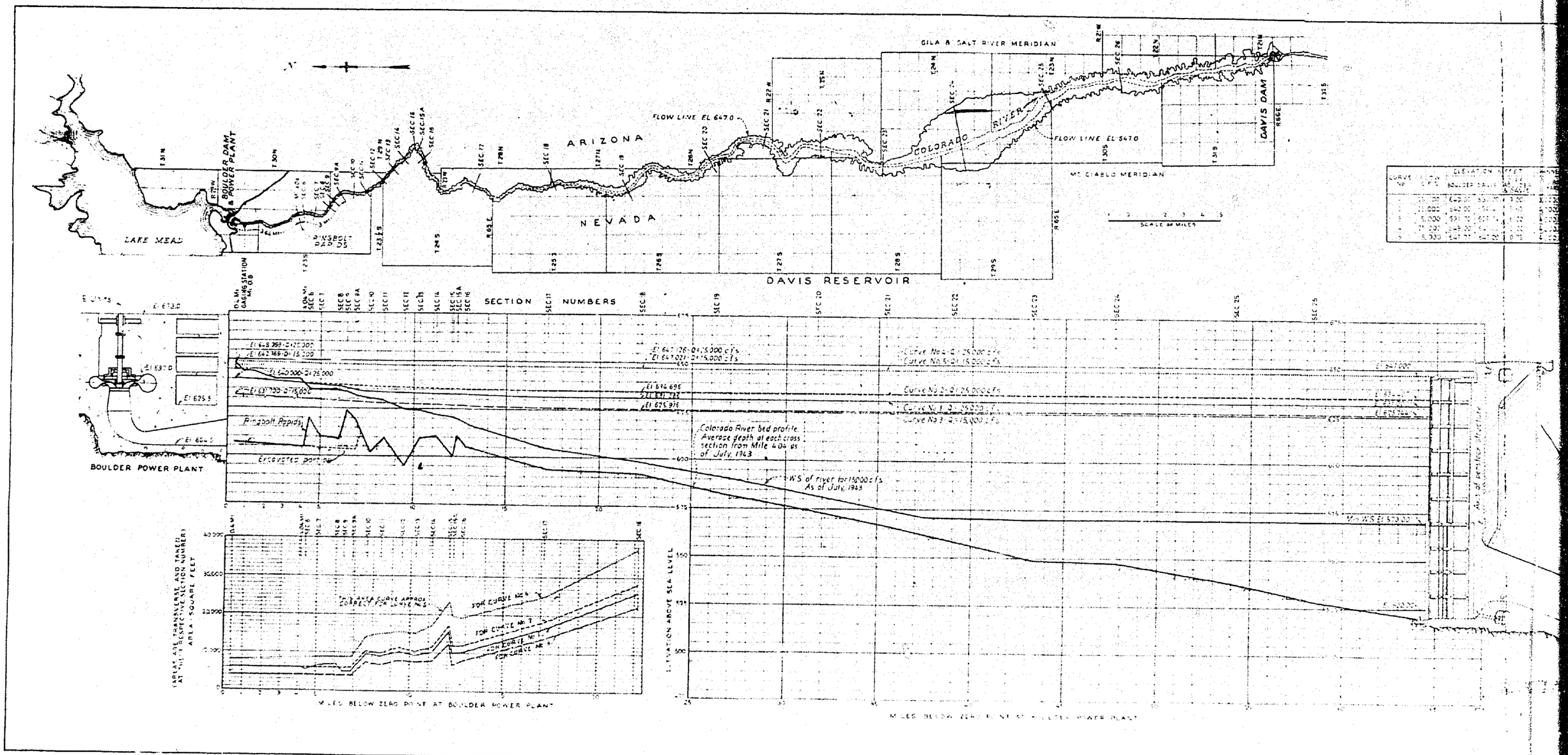
Subject: Improvements in river channel below Boulder Dam--Boulder Canyon Project.

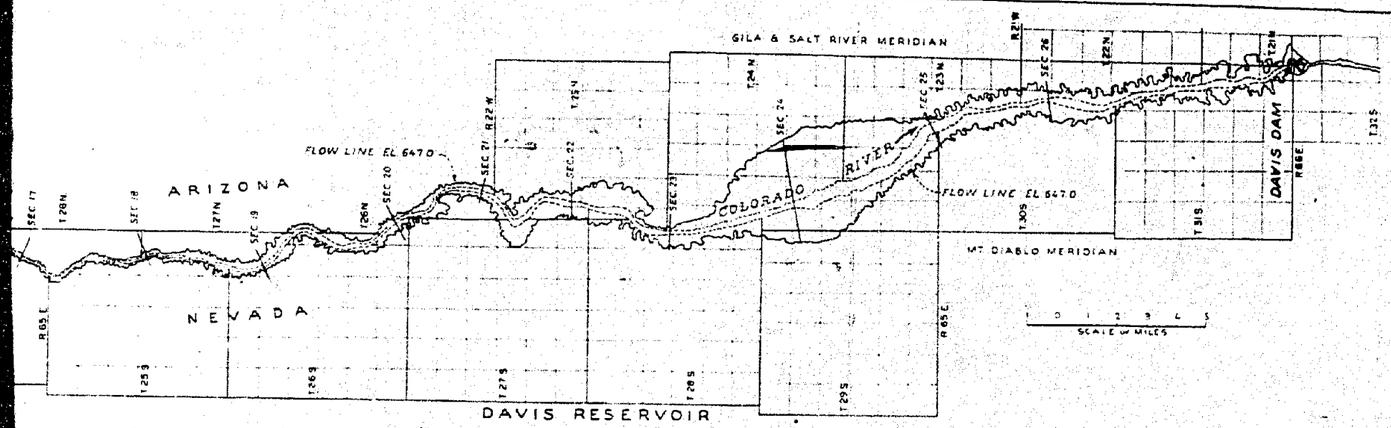
1. Outline of proposed work. Considerable success has resulted in the development of methods for correcting the adverse conditions which exist in the river channel downstream from Boulder Dam. This development has progressed through the aid of a 1:60 scale hydraulic model of the outlet structures, spillways, and related river channel downstream. Some of the preliminary studies were witnessed by Engineer Don S. Walter who presented ideas originating on the project as an approach to a solution.

As a result of the study the following repairs and alterations are recommended and are summarized in the order of their importance:

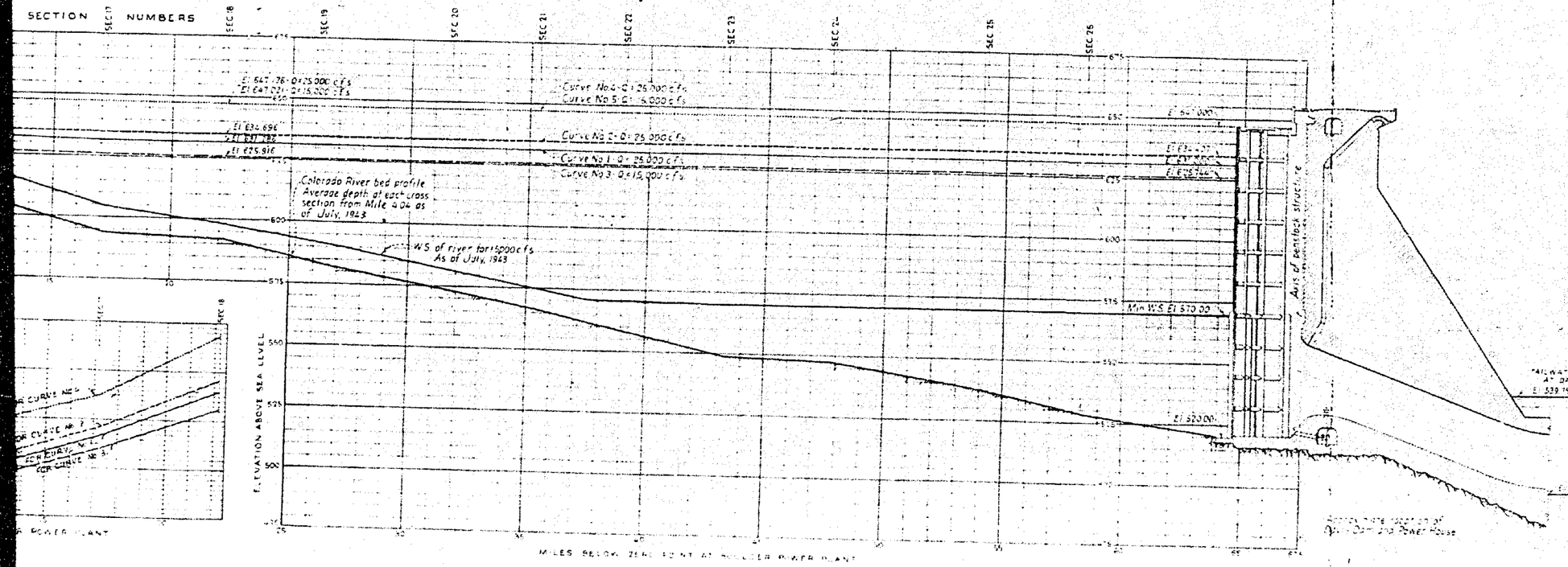
a. Extension of the Nevada Spillway Tunnel (Tunnel 1, Figure 1), a distance of 377 feet downstream on an 1,170-foot radius curve, to direct the flow downstream with minimum disturbance and to provide protection against slides from the canyon wall. The tunnel as it now exists guides the flow directly into a fault area in the canyon wall, in which large slides are active. Slides in this area can conceivably develop in magnitude sufficient to render the Nevada Spillway Tunnel inoperative. Should it become necessary to operate this spillway for any period of time, the slides, which are now a menace, would become a reality as undercutting of the fault area would be severe. For the above reasons, extension of Tunnel 1 is imperative and of first importance.

b. Major repairs to the foundation of the Arizona Tunnel plug outlet portal (Tunnel 3), repair of the tunnel invert, and modification of the portal transition to prevent further damage to the portal foundation and canyon wall. Slides and erosion from a fault area immediately downstream from the tunnel portal have progressed to such an extent that they threaten to expose a portion of the Arizona Spillway Tunnel. Erosion results as spray from the outlet tunnel collects in small streams and returns to the river. It will be necessary to protect this area against spray. Flow from the tunnel also impinges on a portion of the canyon wall which protrudes out into its path. This can be avoided by deflecting the jet toward the center of the river.


GILA & SALT RIVER MERIDIAN
MT. DIABLO MERIDIAN
ARIZONA
NEVADA
COLORADO RIVER
FLOW LINE EL 647.0
FLOW LINE EL 647.0
LAKE MEAD
BOULDER DAM & POWER PLANT
RINGBOLT RAPIDS
DAVIS DAM
DAVIS RESERVOIR
SCALE OF MILES
SECTION NUMBERS
BOULDER POWER PLANT
Ringbolt Rapids
Excavated portion
Colorado River bed profile. Average depth at each cross section from Mile 404 as of July, 1943
WS of river for 15,000 c.f.s. As of July, 1943
Min WS El 570.00
Axis of Davis Dam
ELEVATION ABOVE SEA LEVEL
MILES BELOW ZERO POINT AT BOULDER POWER PLANT
AREAS ARE TRANSVERSE AND TAKEN AT MILE 0 (RESPECTIVE SECTION NUMBER)
AREA - SQUARE FEET
FOR CURVE No 6
FOR CURVE No 7
FOR CURVE No 8
FOR CURVE No 9



CURVE No	FLOW C.F.S.	ELEVATION AT FEET BOULDER	ELEVATION AT FEET DAVIS	RISE FEET BOULDER TO DAVIS	CHANNEL EXCAVATION CUBIC YARDS	CHANNEL EXCAVATION LENGTH IN MILES
1	25,000	640.00	653.00	9.00	3,000,000	3.4
2	15,000	640.00	654.4	9.50	4,000,000	7.0
3	15,000	639.70	654.70	8.00	4,000,000	7.0
4	25,000	649.00	647.00	0.00	4,000,000	7.0
5	15,000	647.00	647.00	0.75	4,000,000	7.0



NOTES

CURVE No. 1

Curve of water surface for a flow of 25,000 c.f.s. assuming an elevation of 640.00 at a point 0.4 miles below Boulder Power Plant and excavation as shown in the channel from this point to a point 4.04 miles below the power plant.

CURVE No. 2

Water surface under the same conditions as for curve No. 1 except with an additional excavation as shown in dotted line to section 9A.

CURVE No. 3

Water surface under the same conditions of excavation as in curve No. 2 but with a flow of 15,000 c.f.s. With this flow the water surface at a point 0.4 miles below Boulder Power Plant will be at elevation 639.70.

CURVE No. 4

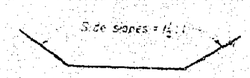
Water surface under the same conditions of flow and excavation as in curve No. 2 but with the water at Davis Dam held at elevation 647.00. The water surface at a point 0.4 miles below the Power Plant will be at approx. El 646.70.

CURVE No. 5

Water surface under the same conditions of excavation as in curve No. 3 but with a flow of 15,000 c.f.s. and with the water at Davis Dam held at elevation 647.00. The water surface at a point 0.4 miles below Boulder Power Plant will be at approx. El 646.70.

In determining the above curves the following values were used:

For excavated sections, S = .0001, Mannings N = .030; for unexcavated sections, Mannings N = .035.



EXCAVATED SECTION

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
DAVIS DAM PROJECT - ARIZONA-NEVADA

DAVIS RESERVOIR

BACKWATER CURVES

DENVER, COLORADO MAY 1948

351-D-260

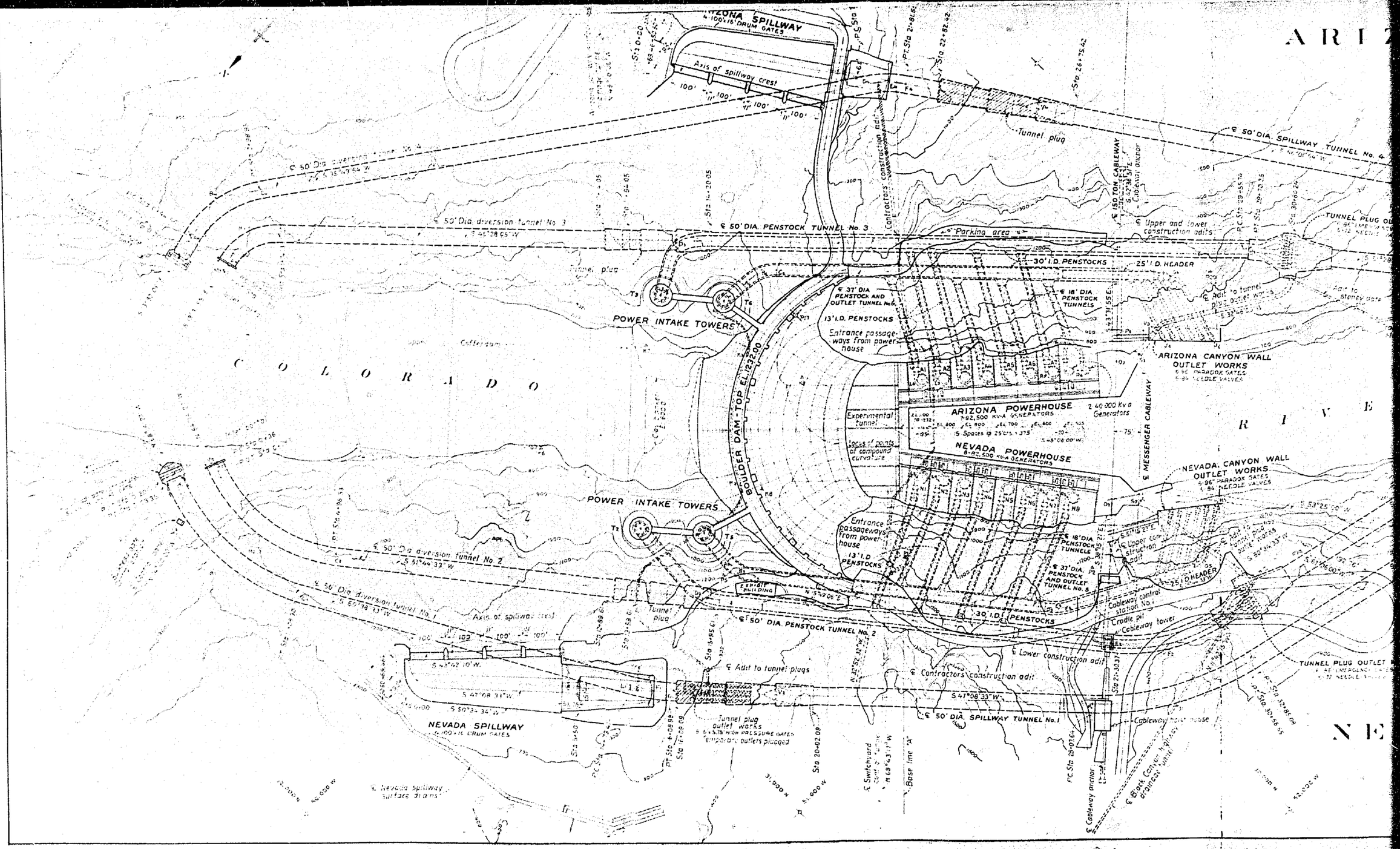
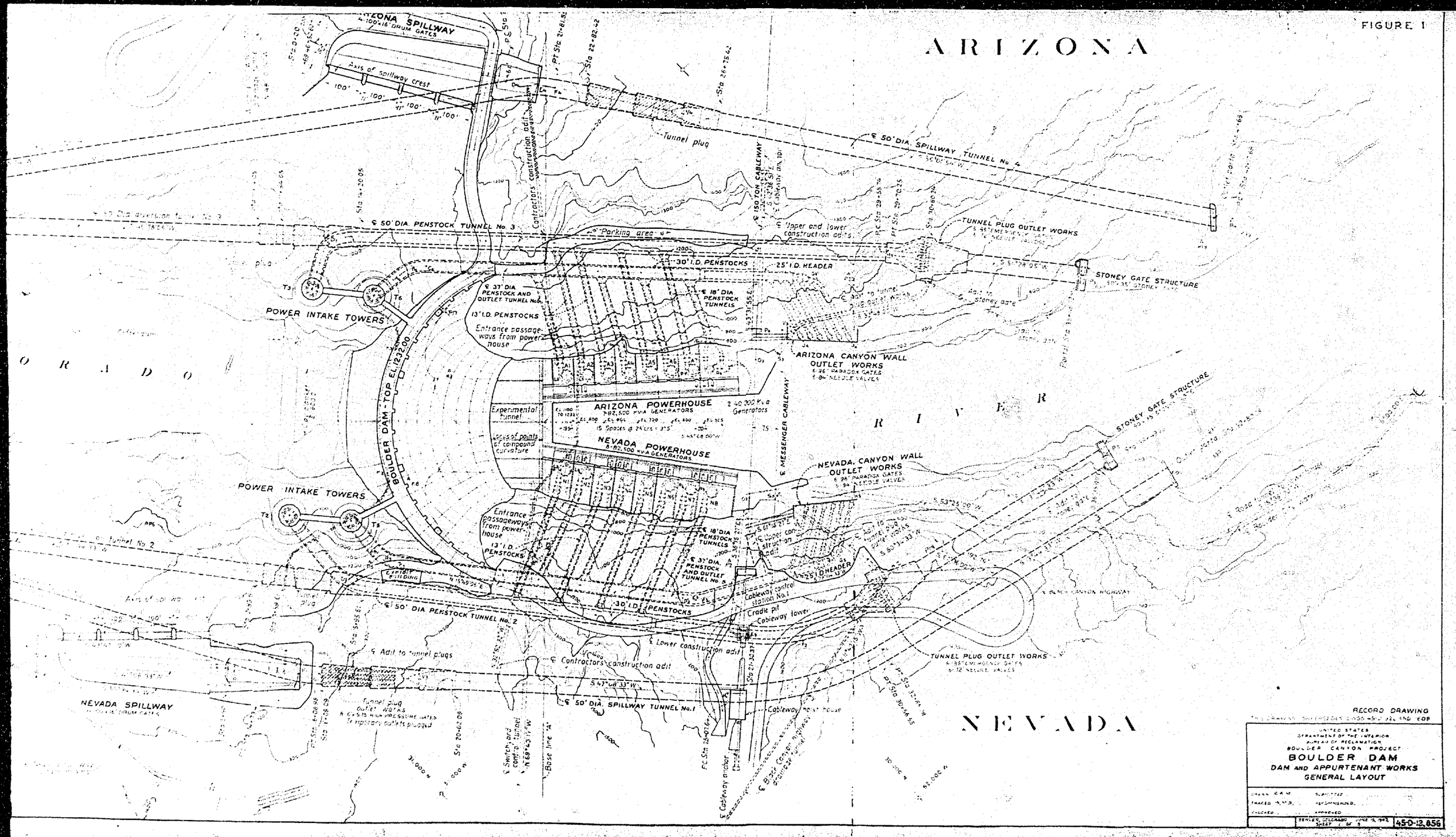

ARIZONA SPILLWAY
100'x16' DRUM GATES
Axis of spillway crest
℄ 50' Dia. diversion tunnel No. 4
℄ 50' Dia. diversion tunnel No. 3
℄ 50' DIA. PENSTOCK TUNNEL No. 3
Tunnel plug
Contractors construction adit
℄ 50' DIA. SPILLWAY TUNNEL No. 4
℄ 150 TON CABLEWAY
Cableway anchor
℄ Upper and lower construction adits
TUNNEL PLUG OUTLET
Parking area
30' I.D. PENSTOCKS
25' I.D. HEADER
℄ 37' DIA. PENSTOCK AND OUTLET TUNNEL No. 4
13' I.D. PENSTOCKS
℄ 18' DIA. PENSTOCK TUNNELS
℄ Adit to tunnel plug outlet works
POWER INTAKE TOWERS
Entrance passageways from power house
ARIZONA CANYON WALL OUTLET WORKS
6-96" PARADOX GATES
6-84" NEEDLE VALVES
BOULDER DAM TOP EL. 1232.00
ARIZONA POWERHOUSE
7-92,500 KVA GENERATORS
2 40,000 Kva Generators
Experimental tunnel
NEVADA POWERHOUSE
8-82,500 KVA GENERATORS
℄ MESSENGER CABLEWAY
NEVADA CANYON WALL OUTLET WORKS
6-96" PARADOX GATES
6-84" NEEDLE VALVES
℄ 50' Dia. diversion tunnel No. 2
℄ 50' Dia. diversion tunnel No. 1
Axis of spillway crest
Tunnel plug
℄ 50' DIA. PENSTOCK TUNNEL No. 2
℄ 33' DIA. PENSTOCK AND OUTLET TUNNEL No. 5
Cableway control station No. 1
Cradle pit
Cableway tower
℄ Lower construction adit
℄ Adit to tunnel plugs
℄ Contractors construction adit
℄ 50' DIA. SPILLWAY TUNNEL No. 1
Cableway hoist house
NEVADA SPILLWAY
Tunnel plug outlet works
Temporary outlets plugged
℄ Switchyard
Base line "A"
℄ Back Canyon hillside drainage tunnel
℄ Nevada spillway surface drains
COLORADO
ARIZONA
NEVADA

FIGURE 1


ARIZONA
NEVADA
RIVER
ARIZONA SPILLWAY
4-100'x16' DRUM GATES
Axis of spillway crest
Tunnel plug
℄ 50' DIA. SPILLWAY TUNNEL No. 4
℄ 50' DIA PENSTOCK TUNNEL No. 3
Parking area
30' I.D. PENSTOCKS
25' I.D. HEADER
TUNNEL PLUG OUTLET WORKS
STONEY GATE STRUCTURE
℄ 37' DIA PENSTOCK AND OUTLET TUNNEL No. 3
13' I.D. PENSTOCKS
℄ 18' DIA PENSTOCK TUNNELS
Entrance passageways from powerhouse
POWER INTAKE TOWERS
BOULDER DAM - TOP EL. 1232.00
ARIZONA CANYON WALL OUTLET WORKS
ARIZONA POWERHOUSE
NEVADA POWERHOUSE
℄ MESSENGER CABLEWAY
NEVADA CANYON WALL OUTLET WORKS
Experimental tunnel
Lines of points of compound curvature
℄ Upper construction adit
℄ Lower construction adit
℄ Contractors construction adit
℄ Adit to tunnel plugs
℄ 50' DIA PENSTOCK TUNNEL No. 2
℄ 50' DIA. SPILLWAY TUNNEL No. 1
Cableway control station No. 1
Cradle pit
Cableway tower
Cableway hoist house
Cableway anchor
℄ Base Canyon highway
℄ Base line "A"
℄ Switch and control tunnel
NEVADA SPILLWAY
Tunnel plug outlet works
Tunnel No. 2
Axis of dam
Capitol building
RECORD DRAWING
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
BOULDER CANYON PROJECT
BOULDER DAM
DAM AND APPURTENANT WORKS
GENERAL LAYOUT
DENVER, COLORADO
450-12,856

c. Repairs to the foundation of the Nevada Tunnel plug outlet portal (Tunnel 2), repairs to the tunnel invert, and modification of the portal transition to raise and deflect the issuing jet toward the center of the river.

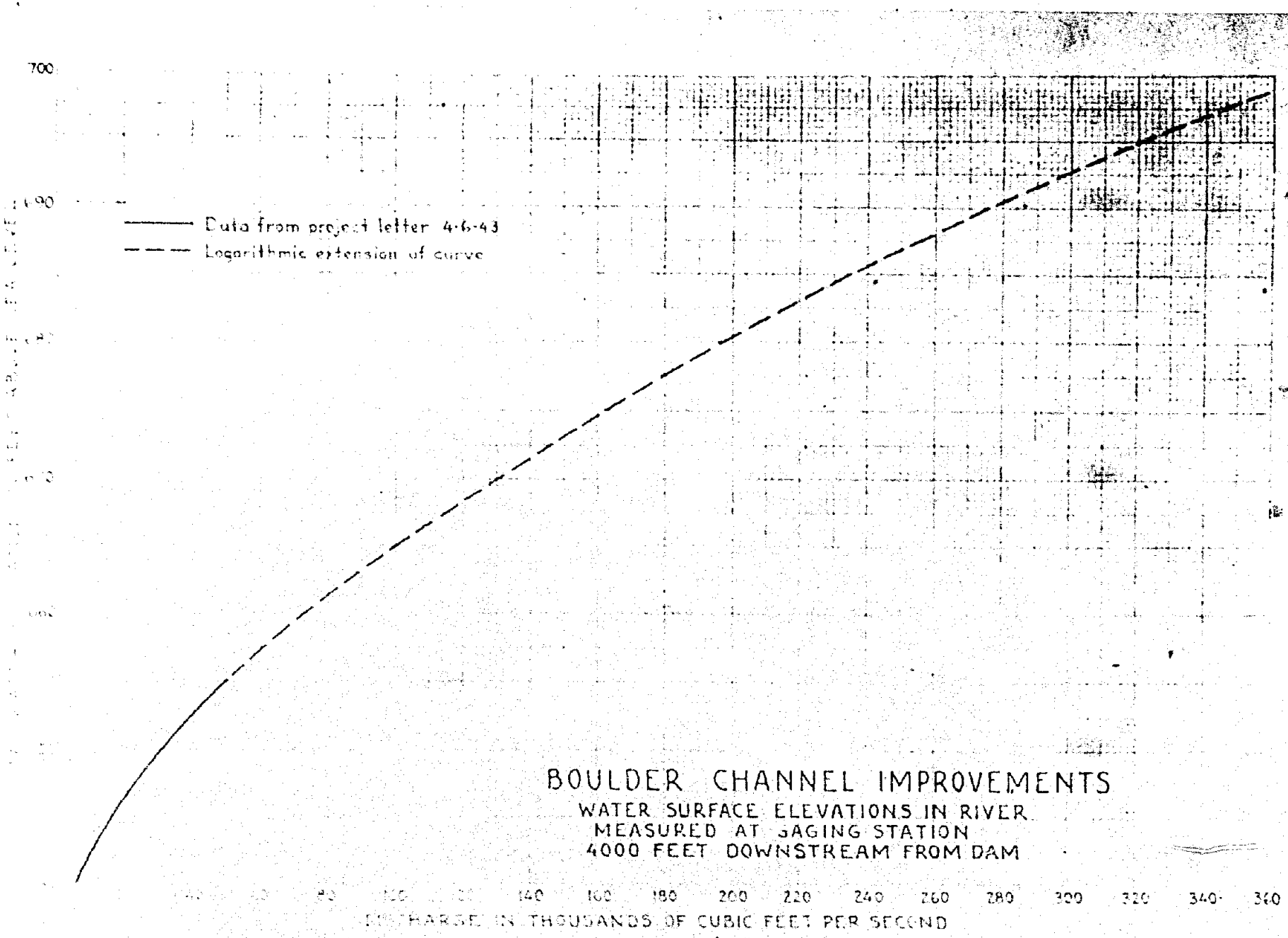
d. Repairs to the foundation of the Arizona Spillway portal (Tunnel 4) and modification of the portal transition to minimize further damage in that area. The greatest objection to the operation of this tunnel, and one which cannot be corrected without great expenditure, is the directness with which the high-velocity flow from the tunnel impinges on the opposite bank of the river.

e. Dredging of the river channel in the reach between the dam and river gaging station to lower the tailwater at the powerhouse and tunnel portals. This will increase the effective head on the turbines and improve flow conditions at the tunnel plug outlets.

The first four items are listed in the order of their urgency, the fifth is considered to parallel the first four and has not been necessarily listed in the order of importance.

2. Preliminary considerations. It was necessary to make certain assumptions in studying flow conditions in the model. The principal assumption concerned the present and future status of the tailwater at the river gaging station. Although the tailwater curve used in the model studies was obtained from recent hydrographic records, the proposed dredging of the river channel between the dam and the river gaging station can lower the water surface some five feet for a flow of 25,000 second-feet, which is approximately the ultimate flow expected from the powerhouse. However, a portion of the gain accomplished by dredging will be canceled by the proposal to maintain the future Davis Dam Reservoir at elevation 647 during a portion of the year. As it was necessary to test the model at much larger discharges than have been passed at the dam since its completion, the present tailwater curve was extended logarithmically for flows up to 360,000 second-feet. The accuracy of this procedure is questionable. The result is shown on Figure 2. To accommodate these variables, the tailwater in the model was varied over a range of 10 feet for each revision in design. Solutions extremely sensitive to tailwater fluctuations were immediately discarded.

Other assumptions necessary in the model studies concerned the probable discharges for which the modifications should be designed. It was early discovered that the higher the discharge to be provided for, the greater would be the expense of modification. Each spillway



BOULDER CHANNEL IMPROVEMENTS
WATER SURFACE ELEVATIONS IN RIVER
MEASURED AT GAGING STATION
4000 FEET DOWNSTREAM FROM DAM

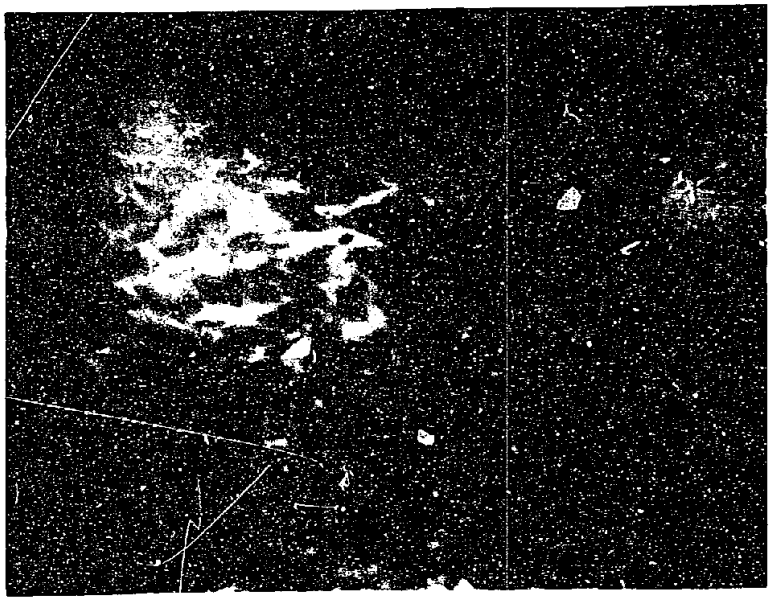
FIGURE 2

was originally designed for a discharge of 200,000 second-feet or a combined spillway capacity of 400,000 second-feet. A discharge of half this magnitude, under present conditions, however, would result in havoc downstream from the tunnel portals, as the Arizona Spillway is directed toward the opposite bank of the river which is composed of loose fill. This damage would be insignificant, however, to that which would occur to towns, bridges, and dams downstream. It is, therefore, imperative that the level of Lake Mead be regulated such that discharges of this magnitude will be avoided whenever possible. It is entirely probable that a discharge of 200,000 second-feet could occur for a short period of time should a drum gate drop or fail to function properly. For short duration, a discharge of this magnitude should be of little concern, as the modified tunnels, together with dredging and removal of the loose material on the Nevada side, will adequately handle the flow, and the reservoirs downstream will absorb the excessive river flow. It was decided to limit the modifications such that the performance of the spillways and outlet works would be satisfactory for a combined flow of 200,000 second-feet and reasonably satisfactory for larger flows. For flows above 200,000 second-feet there will undoubtedly be damage to the canyon walls across the river from each portal where the respective jets impinge.

3. The present design. A model of the spillways and tunnels, outlet tunnels, including one set of six needle valves and a portion of the river channel downstream was constructed to a 1:60 scale throughout for the purpose of visually observing the hydraulic conditions in the river below Boulder Dam. The flow conditions in the river below the spillway and outlet portals with the present design are shown in the 1:60 model, on Figures 3 to 6, inclusive. Figures 3A and B show the Nevada Spillway operating at 50,000 and 100,000 second-feet, respectively. The jet of water impinging against the Nevada canyon wall is clearly illustrated. This wall consists of a fault area immediately downstream from the tunnel portal and loose fill farther downstream. A closer examination shows water flowing into the area occupied by the high-velocity jet. This water was continually carried away by the jet while more poured in to replace that which had been removed. The result was a large swirling eddy which occupied the entire width of the river.

Figures 3C and D depict similar discharges from the Arizona Spillway Tunnel. This jet also threatened removal of the loose fill on the Nevada side of the river, while conditions on the Arizona side were favorable, except for a large eddy similar, but opposite in direction of rotation, to that described above. This is best shown in Figure 3D by the manner in which the inflowing water from the eddy forced the high-velocity jet toward the Arizona canyon wall. The photographs do not justly portray the eddies which would be tremendous in size and power in the prototype. It is these eddies which are responsible for the present damage of the portal structures.

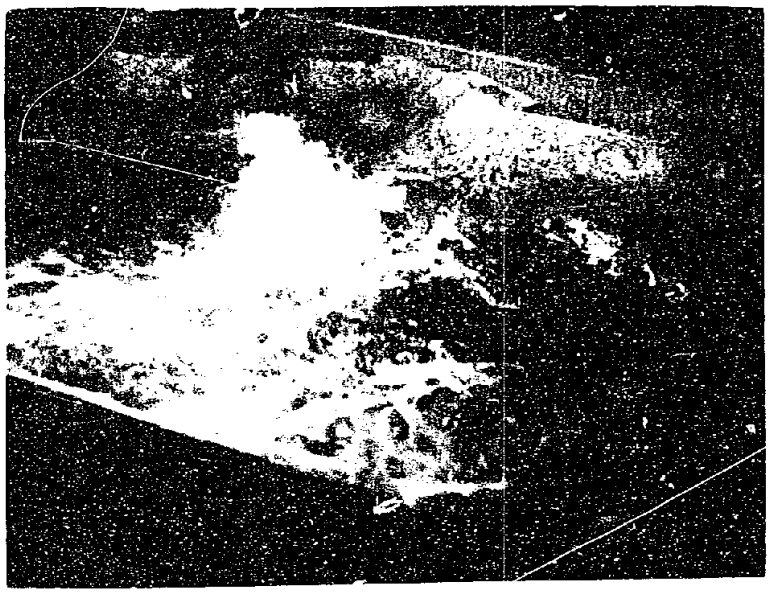
A-50,000 Second-Feet



B-100,000 Second-Feet

Flow through Tunnel 1

C-50,000 Second-Feet



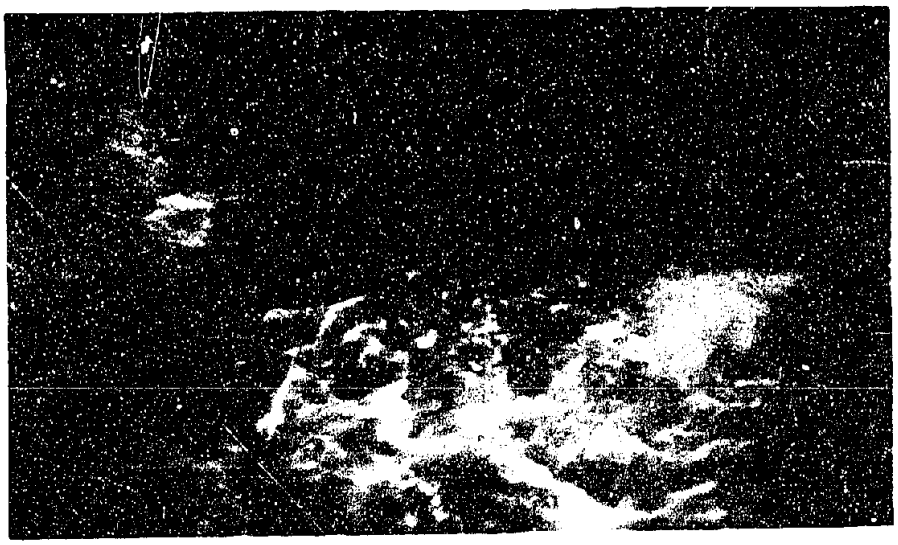
D-100,000 Second-Feet

Flow through Tunnel 4

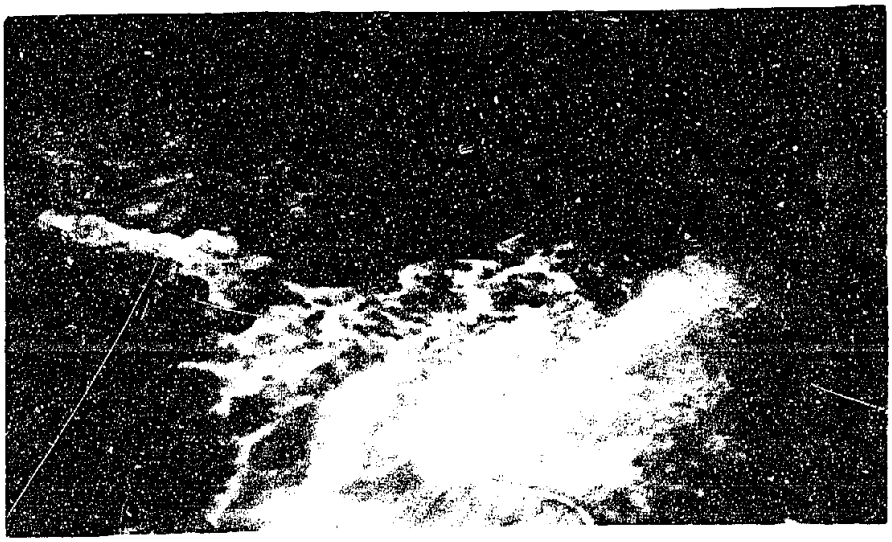
PRESENT DESIGN - SPILLWAY TUNNELS 1 AND 4 OPERATING SEPARATELY

FIGURE 5

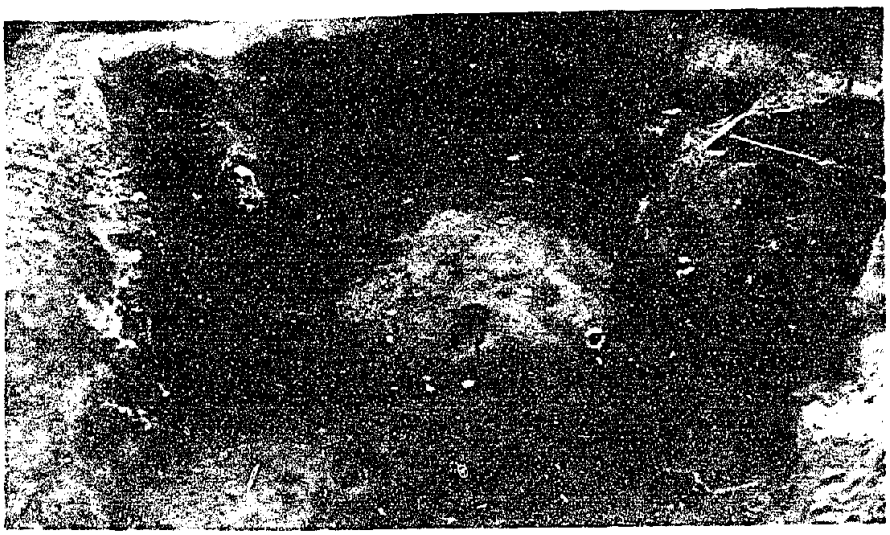
FIGURE 4



A-50,000 Sec.-Ft. through Tunnel 1 and 50,000 Sec.-Ft. through Tunnel 4

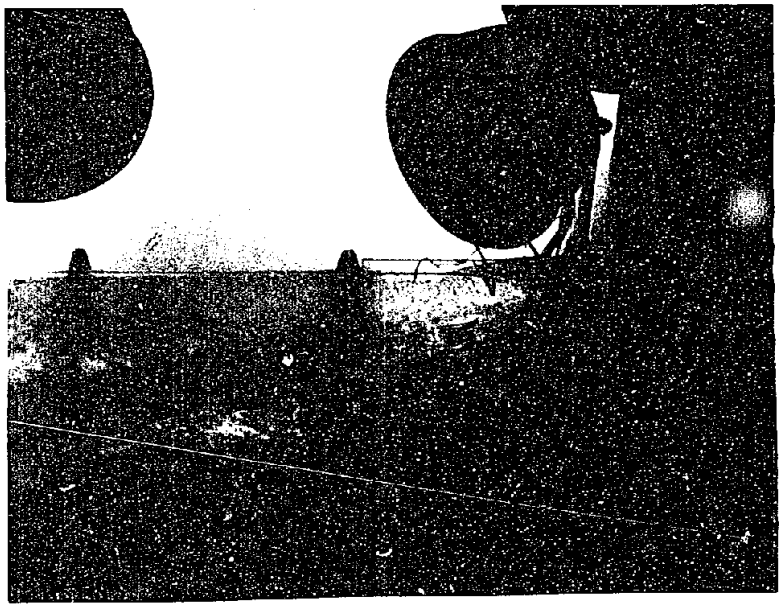


B-100,000 Sec.-Ft. through Tunnel 1 and 100,000 Sec.-Ft. through Tunnel 4

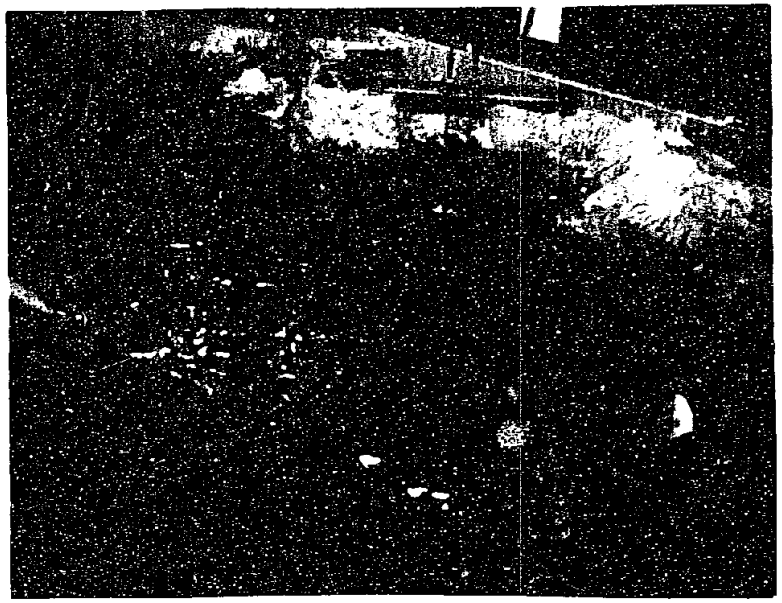


C-Scour in River Channel after above Operation

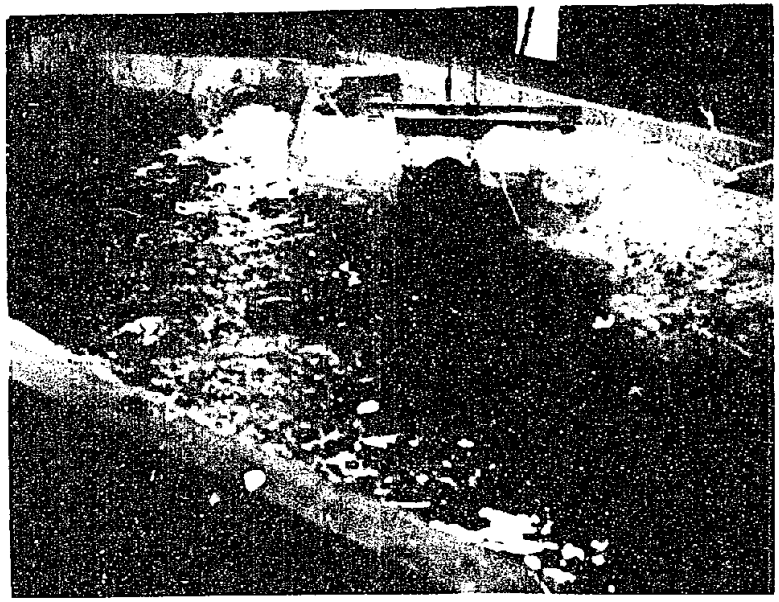
PRESENT DESIGN - SPILLWAY TUNNELS 1 AND 4 IN SIMULTANEOUS OPERATION



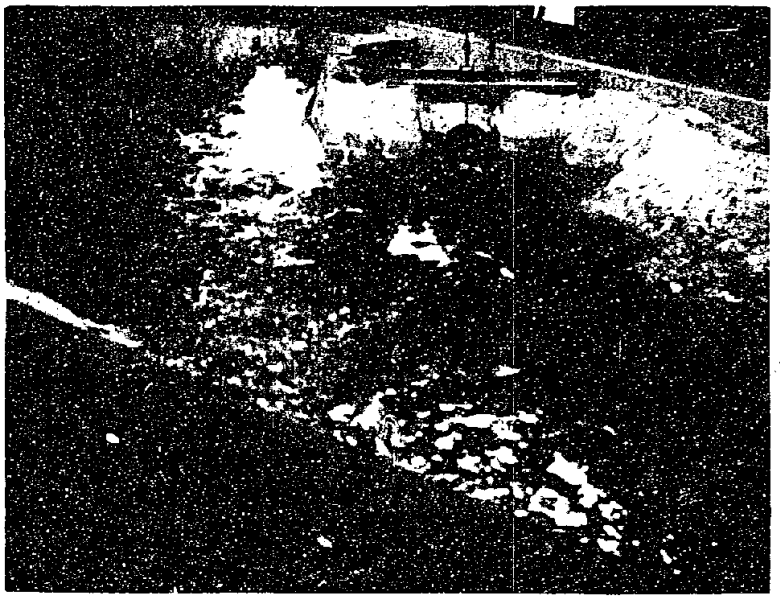
A-Model Sewing Needle Valves in Operation



B-Two Valves Discharging [illegible] Sec.-Ft.



C-Four Valves Discharging [illegible] Sec.-Ft.



D-Six Valves Discharging 34,000 Sec.-ft.

FIGURE 5

PRESENT DESIGN - OUTLET TUNNEL 3 IN OPERATION

Figures 4A and B show the two spillways operating simultaneously at discharges of 50,000 and 100,000 second-feet each. The Arizona Spillway with less length of horizontal tunnel and consequently higher velocity, predominates. Eddies, present for separate operation, were practically absent when the spillways were operated together. Scour in the river was severe, as can be seen in Figure 4C.

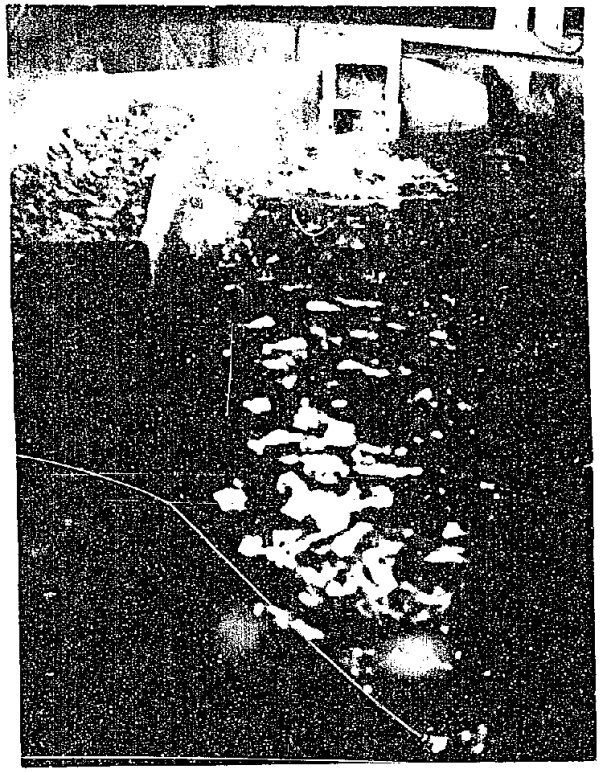
Operation of the model of the present Arizona Tunnel plug outlet is shown for two, four, and six valves, at a head equivalent to a reservoir water surface of elevation 1205 in Figures 5B, C, and D. The photographs show the jet of water impinging on the Arizona canyon wall, which in this case projects out to approximately the centerline of the tunnel. Although not clearly visible in the picture, an eddy was present which tended to force the high-velocity jet toward the canyon wall.

The tunnel plug valve assembly on a 1:60 scale as used for the model is shown on Figure 5A. The valve passages could not be regulated, but flow through individual valves could be completely stopped by slide gates unstream. The same valve assembly was used for both the Arizona and Nevada outlets so these were not operated simultaneously.

Views of the model showing the present Nevada Tunnel plug outlet in operation with two, four, and six valves are shown on Figure 6. Flow for any valve combination was a series of eructations difficult to depict by photographs. In fact, its resemblance to the prototype in operation was very similar except for spray. The belching effect was found to be entirely a tailwater problem. Pressure in the tunnel showed a steady negative two feet of water (prototype) for six valve operation. Belching occurred only near the end of the tunnel. The Nevada outlet tunnel is over twice the length of the Arizona outlet tunnel. The extra length produced a decrease in velocity sufficient to allow the tailwater to intermittently play back and forth in the end of the tunnel. This did not occur in the shorter Arizona Tunnel. Figure 6 shows the Nevada Spillway Tunnel extension rather than the original portal.

4. Preliminary alterations to outlet tunnels. A brief description of the model studies leading up to the recommended modified design will be presented to indicate the extent of the investigation. It was decided to commence with the outlets as these were subject to much less flow than the spillways.

The cheapest solution appeared to involve repair of the Arizona portal foundation and construction of a short wall on the river side of the structure to block the side inflow to the high velocity stream, as shown on Figure 7A. It was intended that the concrete be placed by underwater methods. The short wall on the river side proved to be of little value. The same eroding action occurred at the end of the wall that prevailed previously at the corner of the gate structure, as the eddy merely moved downstream the length of the wall.



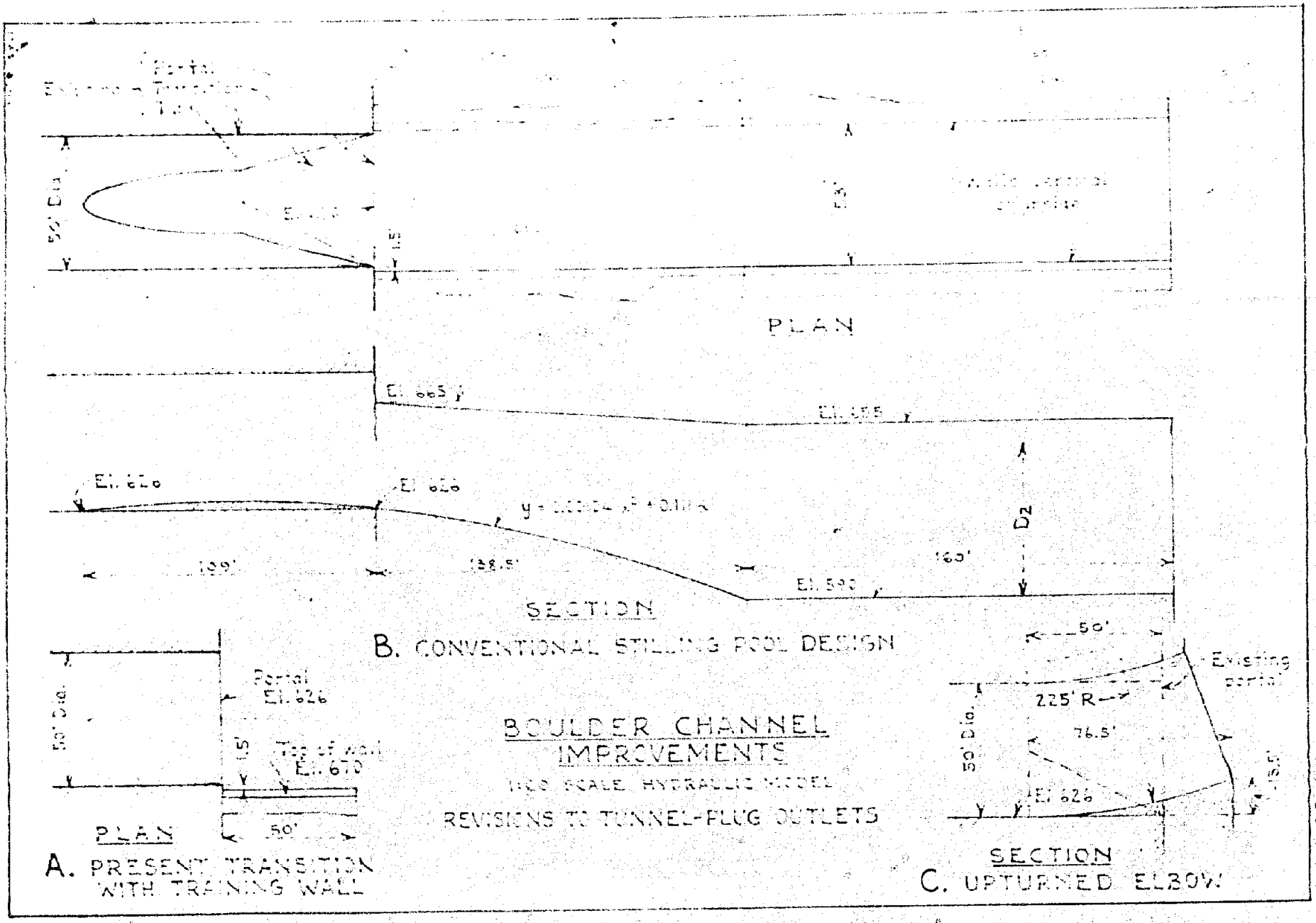
A-Two Valves Discharging 8,000 Sec.-Ft.

B-Four Valves Discharging 16,000 Sec.-Ft.

C-Six Valves Discharging 24,000 Sec.-Ft.

PRESENT DESIGN - OUTLET TUNNEL 2 IN OPERATION

FIGURE 6



BOULDER CHANNEL IMPROVEMENTS

1:60 SCALE HYDRAULIC MODEL

REVISIONS TO TUNNEL-PLUG OUTLETS

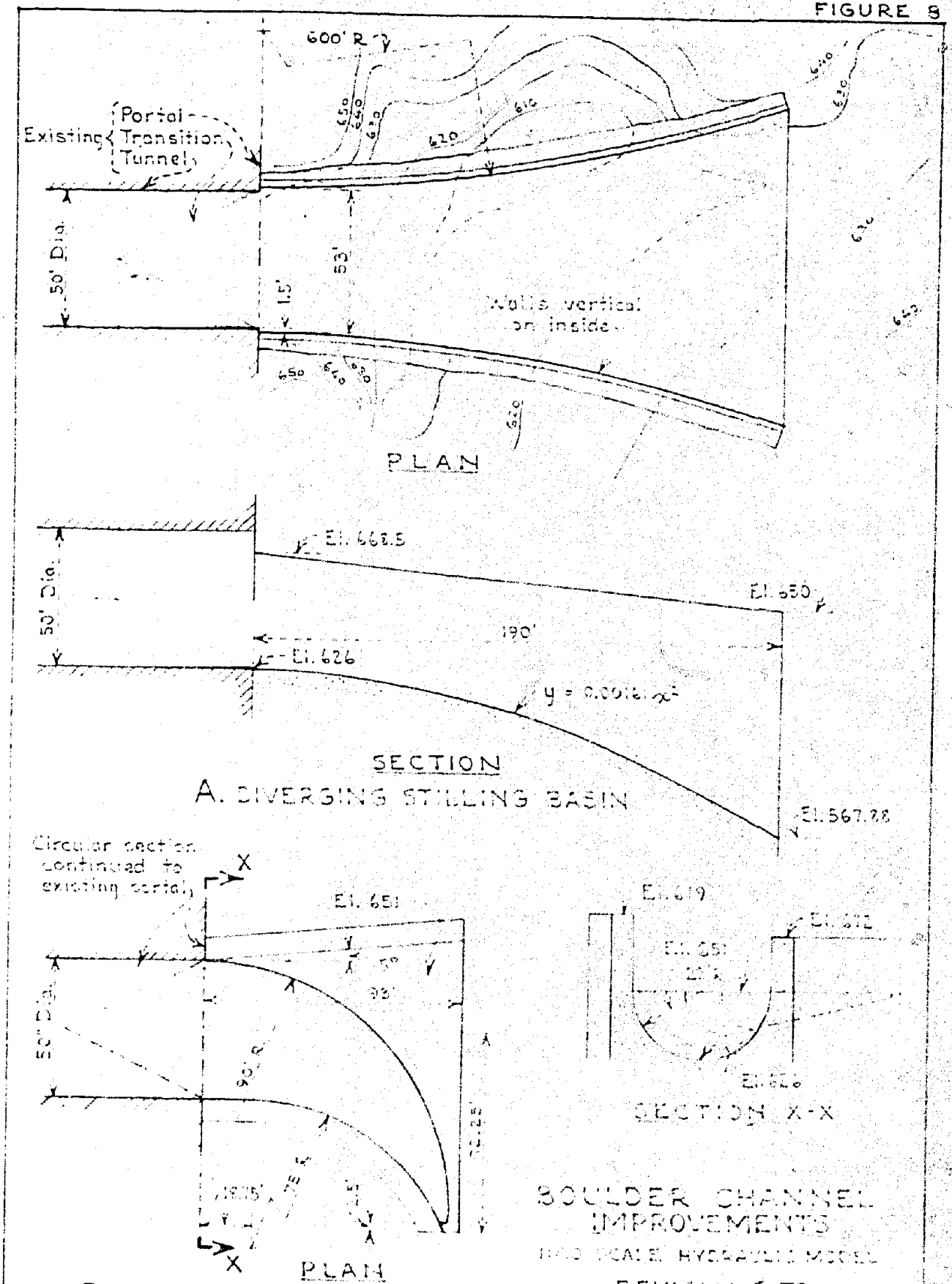
FIGURE 7

A second trial (Figure 7B) consisted of a conventional rectangular stilling-basin, 53 feet in width, designed for a maximum discharge of 24,000 second-feet. The basin consisted of a trajectory floor, designed for a velocity of 125 feet per second, which intersected a horizontal floor at the proper depth to obtain a good hydraulic jump at the maximum discharge. The original length of the horizontal floor was 4D2, but it was found that the basin operated satisfactorily with the floor cut back to half this length. It was necessary to excavate a sizable area from the canyon wall which interfered with construction of this structure. Excellent operation resulted for all but the very small discharges, in which case the tailwater was excessive. This difficulty could have been overcome by increasing the height of the rise in the tunnel (Figure 7B) but would have required a longer trajectory floor and consequently a longer structure. The main objection to this design was its cost. Portions of the stilling-basin walls were 65 feet high; consequently, a cofferdam would have been required to pour them.

A third trial, which was suggested by Engineer E. S. Walter, consisted of constructing a circular upward deflecting elbow beginning at the end of the present transition (Figure 7C). The elbow was on a radius of 225 feet with downstream lip at elevation 639.5. The purpose of the deflector was to discharge the high-velocity jet on the surface of the river. In all previous trials, the plan had been to force the high-velocity jet to dive quickly to eliminate as much spray and surface disturbance as possible. The upturned elbow was therefore a contradiction to the previous considerations; however, its ease of construction and low cost were much in its favor. Spray was excessive, but it was felt that this was offset by the more favorable factors. The former eddy in the river was eliminated. Beginning with this trial, some of the objectionable features of the deflector elbow were systematically corrected; thus, the final modified design was developed.

5. Preliminary alterations to spillway tunnels. Because of the greater flows involved, it still did not appear advisable to discharge the high-velocity jet from the Arizona Spillway Tunnel on the surface of the river, especially when it was considered that a large loose fill existed on the opposite bank. It was again thought advisable to plunge the jet into the river as quickly as possible. To accomplish this, a stilling-basin, diverging in plan, designed for a discharge of 60,000 second-feet, was installed in the model, Figure 8A. The structure was 190 feet long and the floor extended on a trajectory from elevation 626 at the tunnel portal to 567.9 in the riverbed. The diverging walls and sloping floor provided a gradual increase in area which decelerated the velocity of the jet producing a modified form of hydraulic jump. The walls extended only to the end of the trajectory floor in this case. Operation was very satisfactory up to flows of 60,000 second-feet. Beyond this discharge, undermining of the fill on the opposite bank would occur. Computations showed that a conventional stilling-basin for a flow of 100,000 second-feet would require a length equivalent to the width of the river at this point and a depth extending to elevation 540. This should give some idea as to

FIGURE 9


600' R
Existing
Portal
Transition
Tunnel
50' Dia.
53'
15'
Walls vertical on inside
650
640
630
620
610
PLAN
El. 663.5
El. 650
190'
El. 626
y = 0.0016 x²
SECTION
A. DIVERGING STILLING BASIN
El. 567.28
Circular section continued to existing portal
X
El. 651
5°
93'
50' Dia.
90' R
El. 619
El. 612
El. 651
El. 626
SECTION X-X
PLAN
B. FONTANA DEFLECTOR
BOULDER CHANNEL IMPROVEMENTS
REVISIONS TO SPILLWAY TUNNELS

the complexity of the spillway problem, especially on the Arizona side. The 100,000 second-feet is just one-half the capacity for which each spillway was originally designed. In other words, the portion of the river available is neither sufficient in area nor depth to properly dissipate the energy involved. The above design performed the best of any tried; however, the disadvantages were numerous. The structure would be very expensive as it would be necessary to place the concrete in the dry, requiring a large cofferdam; the wall on the river side would necessarily be massive to withstand full hydrostatic head; and future inspection and maintenance would be difficult as a portion of the basin would be under approximately 80 feet of water. Therefore, less expensive measures were sought.

A second scheme investigated was the installation of a deflector cone to the Arizona Spillway Tunnel similar to those used at Fontana Dam. The device is shown on Figure 8P. Numerous variations of the design were tested. The purpose of the cone reflector was to spread the high-velocity jet on the surface of a large area of the river. The device performed as expected but, with the area of the river limited, the surface disturbance was intense at the base of the fill on the Nevada side for discharges greater than 50,000 second-feet. The deflector cone has merit but requires a large body of water to operate properly.

A third trial consisted of installation of a circular deflector elbow similar to that used previously on the Arizona outlet tunnel (Figure 7C). The elbow performed well for discharges up to 50,000 second-feet, but undercut the opposite bank for flows greater than this amount. After balancing advantages and disadvantages against cost of construction, the deflector elbow for the spillway tunnels was favored over previous designs. The side flow to the high-velocity jet was eliminated. For discharges greater than 50,000 second-feet, however, the stream from the deflector elbow impinged on the Nevada bank of the river causing a portion of the jet to flow downstream and the remainder upstream, the latter forming a large back eddy. This was characteristic of all devices used on the Arizona Spillway Tunnel, as the area of the river at this point limited the effectiveness of any means of energy dissipation. A modification of the circular deflector elbow, Figure 7C, was utilized in the recommended design for the spillway tunnels.

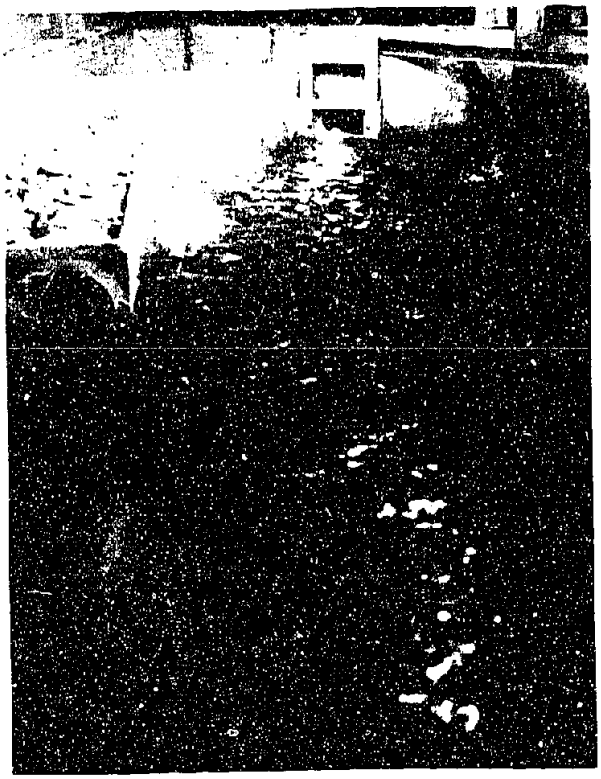
The above tests represent only the more important phases of the model study. Many variations of the above designs were tested, together with less successful devices not mentioned. The results have not been reported in any particular chronological order, as testing on both the outlet and spillway tunnels proceeded intermittently.

6. Recommended modified design of outlet tunnels. As stated previously, the recommended modified outlet tunnel design resembles the simple upturned elbow in Figure 7C. It was necessary to deflect the jets from both Tunnels 2 and 3 toward the center of the river, as well as upward, to avoid impingement on the Arizona canyon wall and reduce scour on the Nevada side. The design, therefore, resembles an upturned elbow tilted at an angle of approximately 45 degrees. The effectiveness of the elbows to perform as desired is illustrated on Figures 9 and 10, which show the outlet tunnels operating for one, two, four, and six valves on the Arizona and Nevada sides, respectively. A comparison of these photographs with those of the present design, Figures 5 and 6, show the improvement. The greatest advantage of the deflector elbow is that it can be located entirely within the present outlet tunnel, Figure 11A. Unwatering can be accomplished with the present wooden trussed bulkhead which has been used to unwater the spillway tunnels. It is planned to repair the foundation of the present gate structures by underwater methods, at which time a fairly smooth base should be poured at each structure to support the bulkhead, as shown in Figure 11B. Figures 11C and D show the deflector elbows, which are exactly opposite in plan, for both outlet tunnels. The same photographs show the scour after six-valve operation. No scour was apparent on the Arizona side; however, there was a tendency for the jet from the Nevada outlet to dig near the downstream end of Tunnel 1 extension. An attempt was made to further deflect this jet toward the center of the river to decrease scour, but the trial was unsuccessful. To accomplish greater deflection of the jet would require a major change in the alinement of the tunnel. A remedy found effective in lessening the scour from Tunnel 2 was to place large boulders, at least 6 feet in diameter, along the downstream end of the extension wall, as shown in Figure 11C. The extent to which the protection is necessary depends on the condition and location of bedrock in this area.

Figure 12 is a working drawing showing plan and sections of the deflector elbows for Tunnels 2 and 3. Repairs to the floor of the tunnel will consist of pouring concrete in the invert to a finished radius of 85 feet. Care should be taken to see that the finished surface is smooth and free from irregularities. This method of repair was suggested by Engineer D. S. Walter and has three distinct advantages. First, a greater depth of concrete is provided for wear; secondly, the resulting surface can be made smoother and more substantial than that which would result after patching the old lining; and thirdly, the hydraulic performance of the outlet tunnels will be improved with the raised inverts. The latter is especially true in the case of Tunnel 2, which is about twice the length of Tunnel 3. The smaller the depth of water in the tunnels during the starting operation the less difficulty will be experienced in sweeping the hydraulic jump out of the tunnels. It is not recommended that either the outlets or spillways be operated with a hydraulic jump in the tunnels. For present tailwater conditions, the curves on Figure 13A show the reservoir elevations required in the model to move the jump out of Tunnels 2 and 3 for one, two, four and six valves operating fully open. The model valves were not adjustable.

FIGURE 9

MONTICELLO DESIGN - OUTLET TUNNEL 3 IN OPERATION



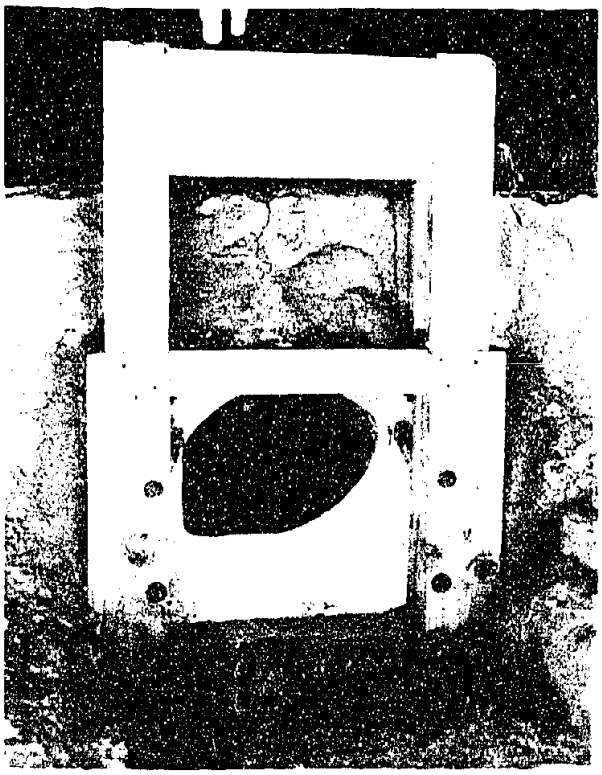
A-One Valve Discharging 4,000 Sec.-Ft.

B-Two Valves Discharging 8,000 Sec.-Ft.

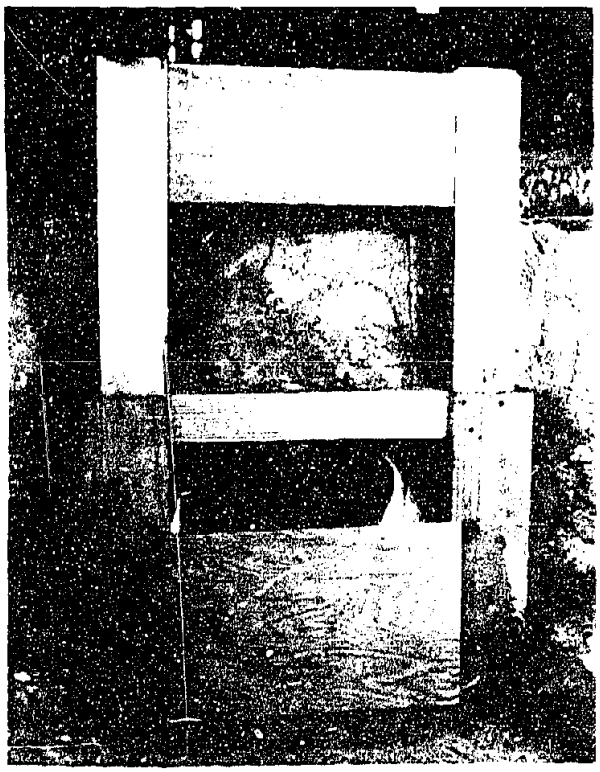
C-[illegible] Valves Discharging 16,000 Sec.-Ft.

D-[illegible] Valves Discharging [illegible] Sec.-Ft.

MODEL DESIGN - OUTLET TUNNEL : IN OPERATION



A-Deflector Transition at End of Outlet



B-Illustration of Proposed Method of Unwatering Tunnel 2 with Present

C-Scour Resulting from Operation of

D-Scour Resulting from Operation of Six Valves in Outlet Tunnel 2

MODIFIED DESIGN - OUTLET TUNNELS 1 AND 2

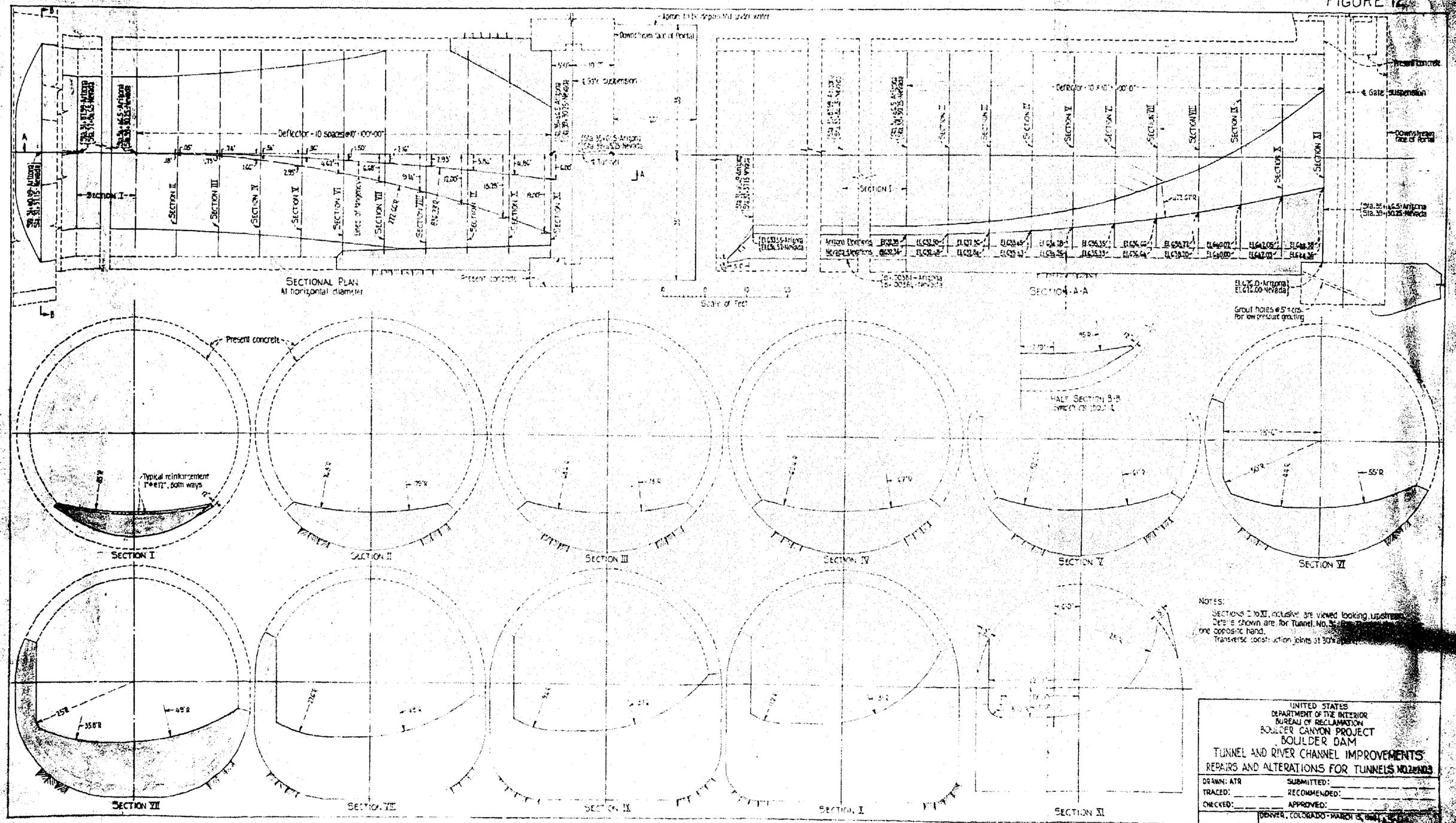
Prototype operation is directly the opposite: the valves are adjustable while the reservoir elevation is more or less fixed. Nevertheless, the study demonstrated that the valves should be opened one at a time on starting, leaving the two outer ones until last. From Figure 13A, it is shown that higher heads were required to sweep the jump out of the tunnels with six valves operating than four. In fact, it was very difficult to move the jump out of either tunnel when all six valves were opened simultaneously as the two outer valves hindered rather than aided in the starting process.

The sweep-out characteristics for Tunnel 3 with the present circular invert are shown by the dotted line on Figure 13A. In this case, it was not possible to move the hydraulic jump out of the tunnel when six valves were opened simultaneously. A comparison of the two curves for Tunnel 3 on Figure 13A indicates the hydraulic improvement gained by raising the tunnel invert.

7. Recommended modified design for Arizona Spillway Tunnel. The recommended design for the Arizona Spillway Tunnel consists of another modification of the upturned deflector elbow, which is again confined to the present tunnel section, as shown on Figures 14A and 15. The latter figure consists of a working drawing for modification of this tunnel. The deflector was designed to lift and spread the jet as it emerged from the tunnel to eliminate the undesirable eddy in the river. For discharges greater than 50,000 second-feet, the jet from the Arizona Spillway impinged on the opposite bank of the river. For discharges above 70,000 second-feet, this action was severe; however, without a change in the present alinement of the tunnel, this was unavoidable. For discharges less than 10,000 second-feet, the hydraulic jump formed in the tunnel, which is to be avoided. Figure 16A shows the jump forming in the end of the tunnel for a discharge of 9,000 second-feet. Figures 16B, C, and D show the flow conditions for discharges of 25,000, 50,000, and 75,000 second-feet, respectively. Figures 17A and B depict the same tunnel discharging at 100,000 and 150,000 second-feet. A comparison of the above photographs with those of the present design, Figure 3 indicates the absence of the large river eddies in the modified design. Scour of the riverbed is shown to be negligible after a discharge of 150,000 second-feet, Figure 17C.

Naturally, the addition of the deflector elbow decreased the capacity of the Arizona Spillway Tunnel. Tests made to investigate this effect showed that the downstream end of the tunnel commenced to flow full at a discharge of 17,000 second-feet. The capacity of the Arizona Spillway with both the horizontal and inclined tunnels flowing full, which is a possible condition of operation, was found to be approximately 210,000 second-feet, which is slightly more than that for which the spillway was originally designed.

FIGURE 12


SECTIONAL PLAN
At horizontal diameter
SECTION A-A
Deflector - 10 spaces @ 10' - 100'-00"
Present concrete
Downstream face of portal
℄ Gate suspension
Grout holes @ 5' c/c
For low pressure grouting
Scale of feet
HALF SECTION B-B
Typical reinforcement
1"@11", both ways
SECTION I
SECTION II
SECTION III
SECTION IV
SECTION V
SECTION VI
SECTION VII
SECTION VIII
SECTION IX
SECTION X
SECTION XI
NOTES:
Sections I to XI, inclusive are viewed looking upstream.
Details shown are for Tunnel No.
one opposite hand.
Transverse construction joints at 30'
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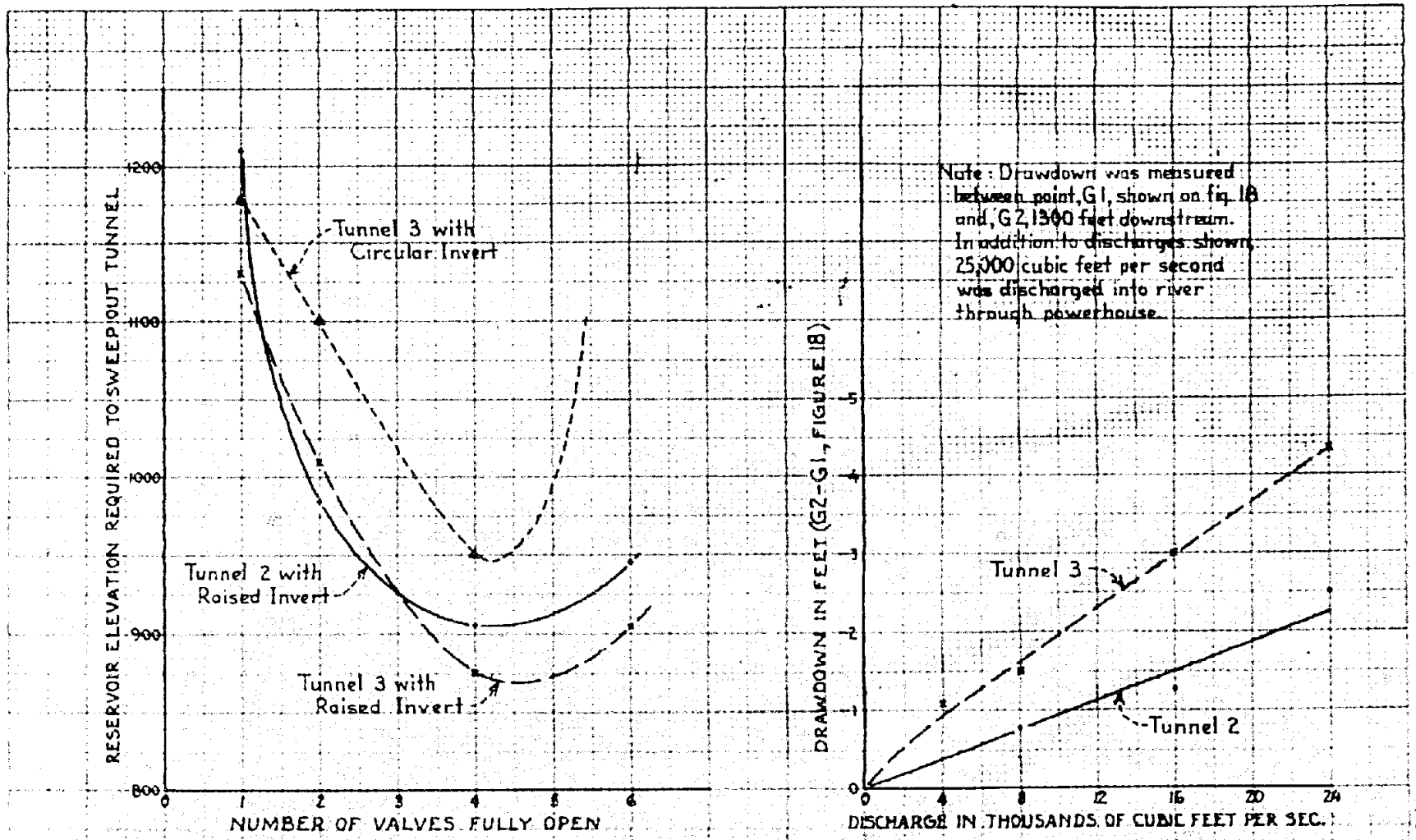
BOULDER CANYON PROJECT
BOULDER DAM
TUNNEL AND RIVER CHANNEL IMPROVEMENTS
REPAIRS AND ALTERATIONS FOR TUNNELS NO. 2 AND 3
DRAWN: ATR
SUBMITTED:
TRACED:
RECOMMENDED:
CHECKED:
APPROVED:
DENVER, COLORADO - MARCH 15,



A. RESERVOIR ELEVATION REQUIRED TO MOVE HYDRAULIC JUMP OUT OF OUTLET TUNNELS

B. DRAWDOWN AT POWERHOUSE PRODUCED BY DISCHARGE FROM OUTLETS

FIGURE 13

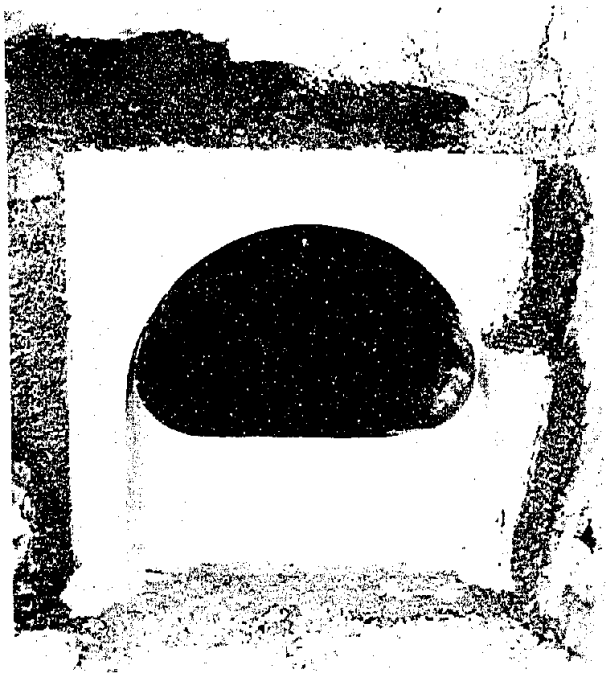
BOULDER CHANNEL IMPROVEMENTS

A suggestion for unwatering of Tunnel 4 for inspection and repair is illustrated in Figures 14A and B. Repair of the portal foundation and pouring of a short base on which the bulkhead can rest, Figure 14B, can be accomplished by underwater methods. As the portal is not normal with the centerline of Tunnel 4, it is suggested that a short wall be poured, also by underwater methods, on the canyon wall side against which the end of the bulkhead can bear. This wall can be seen in Figures 14A, B, and C. In this way, the lip of the deflector transition can be made normal to the centerline of the tunnel, thus establishing it approximately 10 feet farther downstream, which is very desirable. Figure 14B shows the bulkhead in place as suggested. Photographs C and D illustrate a possible method of bulkheading the spillway and outlet tunnels for inspection, after the present contemplated repairs and modifications have been completed. This bulkhead, which can be of steel or wood, needs be only 15 feet in height.

8. Recommended modified design for Nevada Spillway Tunnel. As the present Nevada Spillway Tunnel is directed such that the jet of water issuing from it impinges on the adjacent canyon wall, there appears to be but one solution, regardless of expense. This consists of a curved tunnel extension approximately 400 feet in length as shown on Figures 18 and 20. A shorter section may have been satisfactory from a hydraulic standpoint, but the length in this case is dictated by structural considerations. Due to the instability of foundation material in this region, an extension approximating 400 feet will be necessary to reach solid rock. At the same time, a retaining-wall, such as shown on Figure 21, will help to eventually stabilize loose material which slides down the canyon wall from the fault area. Figure 18 shows a general plan of the proposed river channel improvements embodying the most recent information on canyon wall topography and soundings in the river. Figure 19 is a downstream continuation of topography and soundings showing recommended channel improvements.

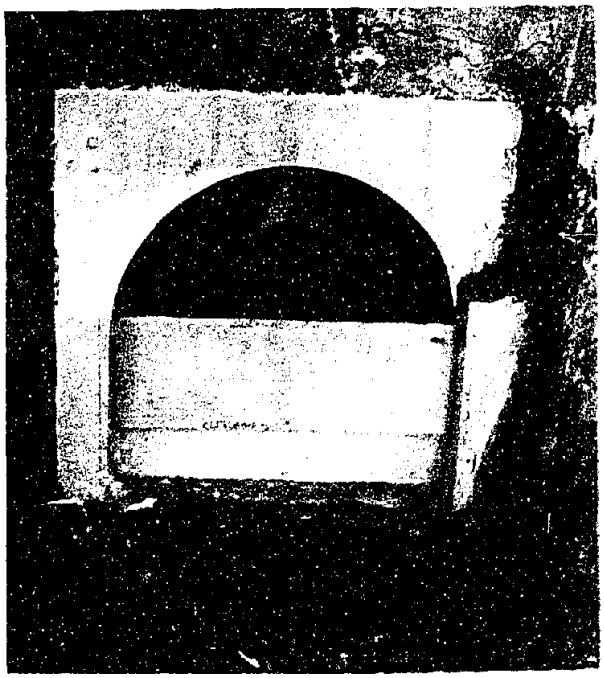
Figure 20A shows the actual tunnel extension on the model and Figure 20B indicates how the tunnel will appear with retention and protective walls as proposed. Figure 20C shows a view of the deflector transition at the downstream end of the tunnel extension. This deflector is similar to the one for Tunnel 4, except that the lip is at elevation 642.16 for Tunnel 1, instead of elevation 644.36 as for Tunnel 4. Due to the longer length of tunnel on the Nevada side, the velocity was less than that from the Arizona Spillway. The deflector lip on Tunnel 1 was lowered approximately two feet to partially compensate for this difference. A working drawing for the construction of Tunnel 1 extension is included as Figure 21. The construction of this extension will require unwatering by cofferdams; thus, the deflector lip has been placed to coincide with the tunnel portal.

FIGURE 14



A-View of Symmetrical Transition at End of Tunnel 4

B-Proposed Method of Unwatering Tunnel 4 with Present Bulkhead

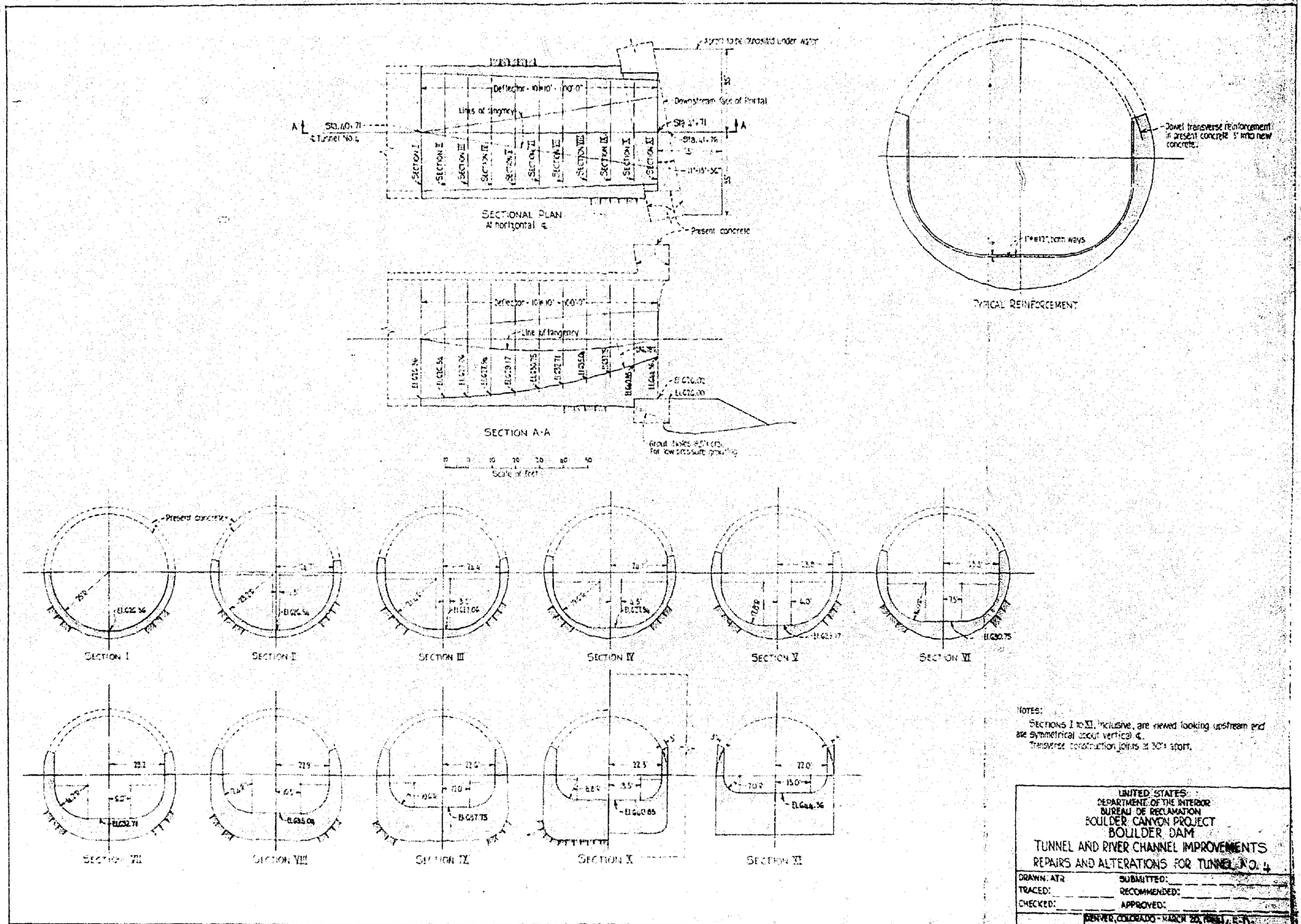


C-Illustration Showing Future Inspection Bulkhead, Approximately 15 Feet in Height, which can be used after Tunnel 4 Repairs have been Completed

D-Illustration Showing how Future Inspection Bulkhead will be Adaptable to Outlet Tunnels 2 and 3 after Repairs have been Completed

MODIFIED DESIGN - CONSTRUCTION DETAILS OF TUNNELS 2, 3, AND 4

FIGURE 15



Notes:

Sections I to XI, inclusive, are viewed looking upstream and are symmetrical about vertical ℄.

Transverse construction joints at 30' apart.

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BOULDER CANYON PROJECT
BOULDER DAM
TUNNEL AND RIVER CHANNEL IMPROVEMENTS
REPAIRS AND ALTERATIONS FOR TUNNEL NO. 4

DRAWN: ATR	SUBMITTED:
TRACED:	RECOMMENDED:
CHECKED:	APPROVED:

DENVER, COLORADO - MARCH 22, 1945-D

FIGURE 16

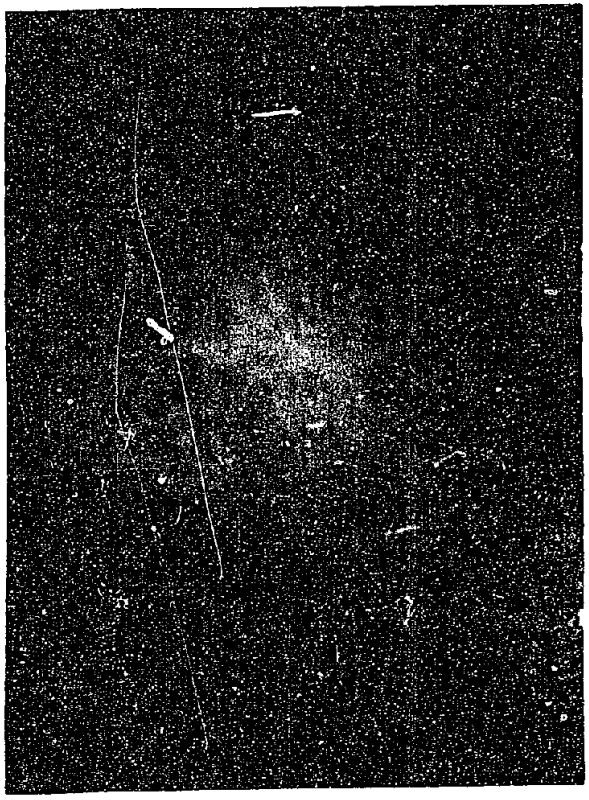
A-9,000 Second-Feet
Jump Forms in End of Tunnel

B-25,000 Second-Feet

C-50,000 Second-Feet

D-75,000 Second-Feet

MODIFIED DESIGN - SPILLWAY TUNNEL 4 IN OPERATION



A-100,000 Second-Feet

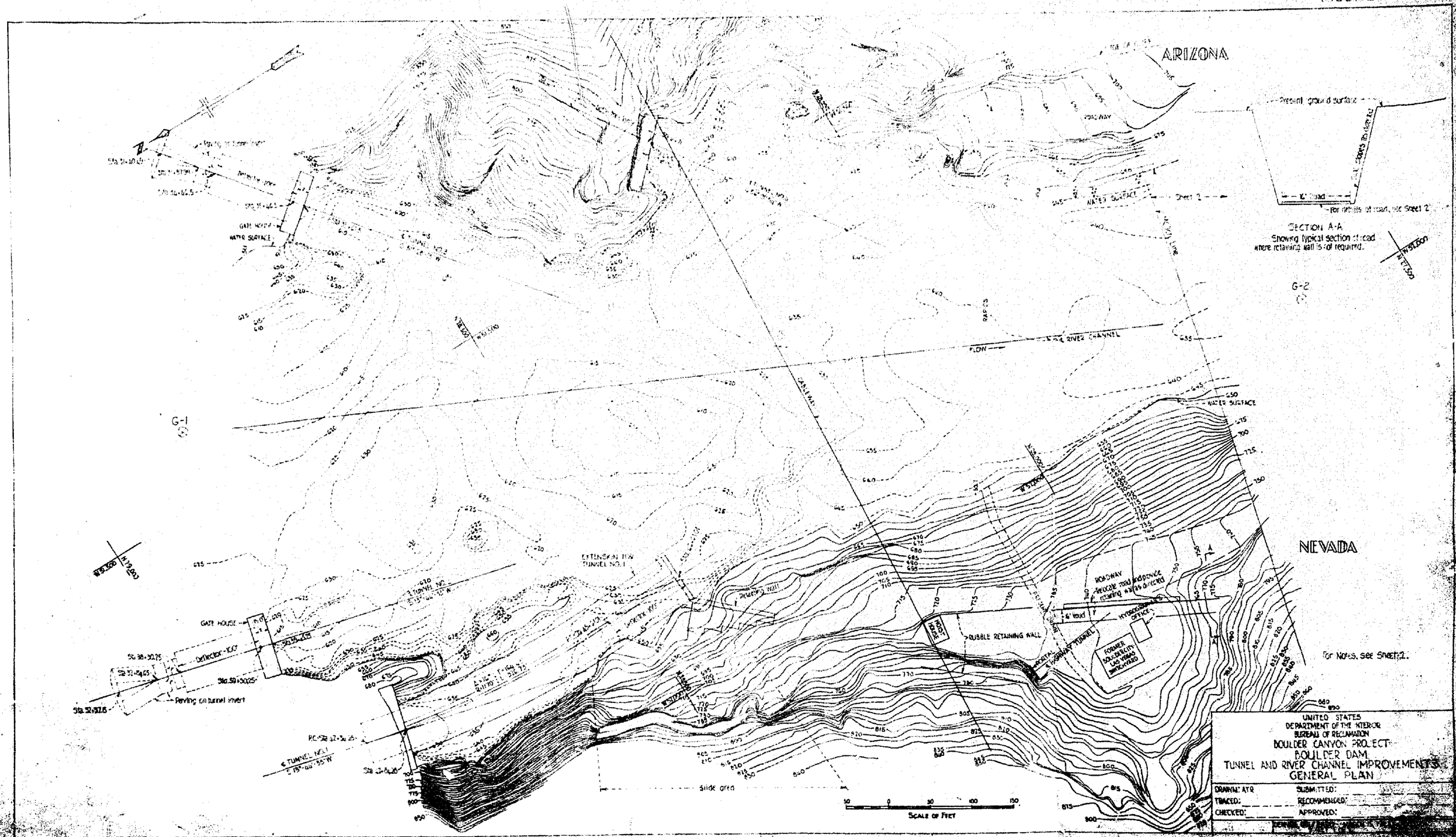
B-150,000 Second-Feet

C-Scour in River Channel after Flow of 150,000 Second-Feet

MODIFIED DESIGN - SPILLWAY TUNNEL 4 IN OPERATION

FIGURE 17

FIGURE 18


ARIZONA
NEVADA
Present ground surface
SECTION A-A
Showing typical section of road where retaining wall is not required.
For details of road, see Sheet 2
G-1
G-2
GATE HOUSE
WATER SURFACE
FLOW
RIVER CHANNEL
RAPIDS
Deflector-100'
Paving on tunnel invert
Slide area
RUBBLE RETAINING WALL
ROADWAY
HYDROGRAPHIC OFFICE
FORMER SOUTH UTILITY LAS VEGAS SHIPYARD
For Notes, see Sheet 2.
SCALE OF FEET
UNITED STATES
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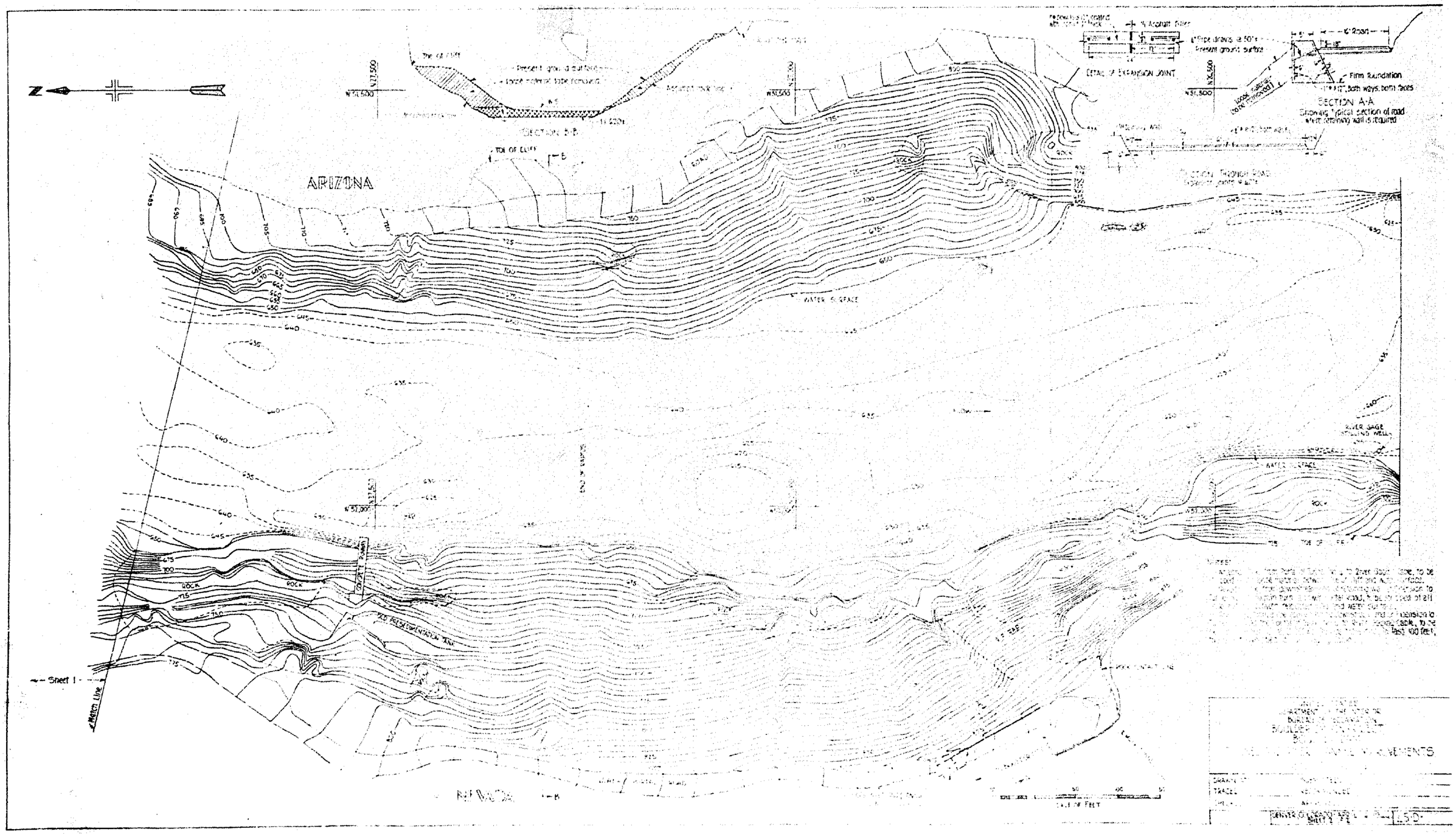
BOULDER DAM
TUNNEL AND RIVER CHANNEL IMPROVEMENTS
GENERAL PLAN
DRAWN: ATR
SUBMITTED:
TRACED:
RECOMMENDED:
CHECKED:
APPROVED:

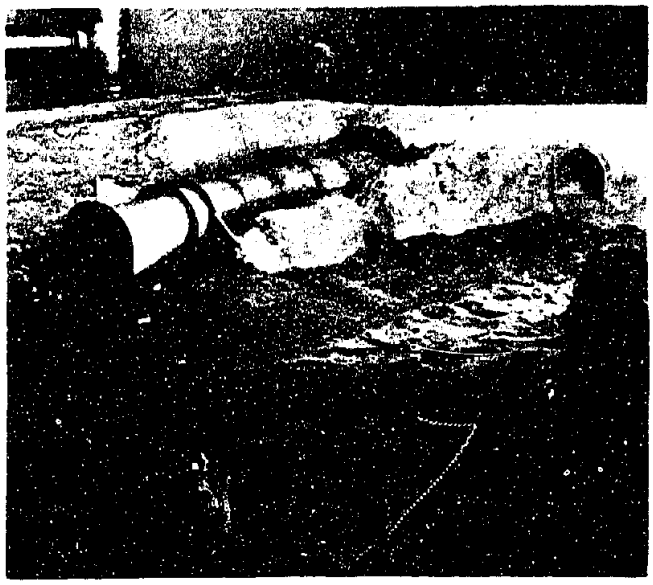
FIGURE 19


ARIZONA
NEVADA
SECTION B-B
TOE OF CLIFF
WATER SURFACE
ROCK
SECTION A-A
Firm Foundation
DETAIL OF EXPANSION JOINT
RIVER GAGE
Sheet 1
Match Line
SCALE OF FEET

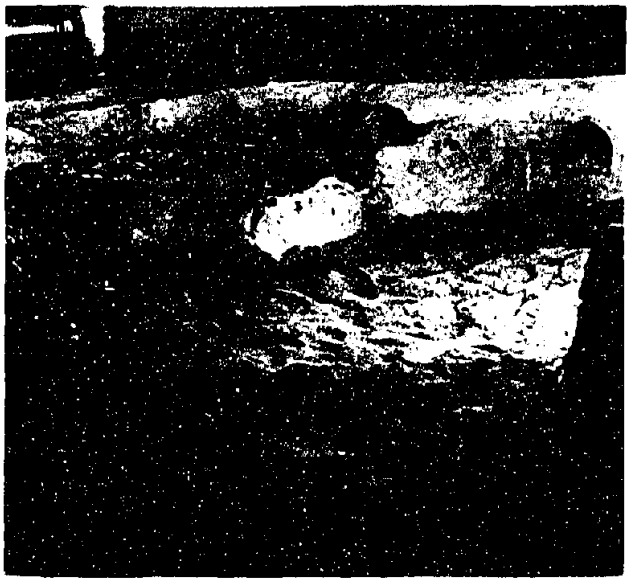
Figures 22 and 23 show the modified Tunnel 1 in operation. It is interesting to compare these photographs with those of the present design, shown on Figure 3. Figure 22A shows the Nevada Spillway Tunnel operating at a discharge of 15,000 second-feet. The outflow is quiet, but the hydraulic jump is in the tunnel. Figure 22B shows the jump forming in the end of the tunnel for a flow of 20,000 second-feet. For present tailwater conditions, the jump moved out of the tunnel at 23,000 second-feet. Figures 22C and D show operation of the tunnel for flows of 25,000 and 50,000 second-feet. Figures 23A, B and C show flows of 75,000 100,000, and 130,000 second-feet. The end of the Nevada Spillway Tunnel commenced to flow full at a discharge of 125,000 second-feet. The tunnel will pass 200,000 second-feet, however, with both horizontal and inclined sections flowing full. Figure 23D shows the scour pattern in the river after a discharge of 130,000 second-feet. A careful examination shows the floor of the model box exposed in the lower left-hand corner. Regardless of whether the Nevada or Arizona Spillway was operating, there was a tendency for the flow to cut a channel along the base of the Nevada bank. It is suggested, therefore, that the loose fill on the Nevada side be removed, as it will slough into the river during the first moderate flood.

Figures 24A, B, and C show the two spillways operating simultaneously for the best possible flow conditions. In each case, the flow through the Nevada Spillway was twice that through the Arizona Spillway. By distributing the flow in this proportion the resulting jet flowed down the center of the river as shown, regardless of the total magnitude of the discharge. A small variation either way in the above proportion, however, caused the resultant flow to swing to one bank or the other. Upstream eddies were entirely absent when the spillways were operated in this manner, and the resulting scour was minor, except for a channel which was persistently present along the Nevada bank, Figure 24D.

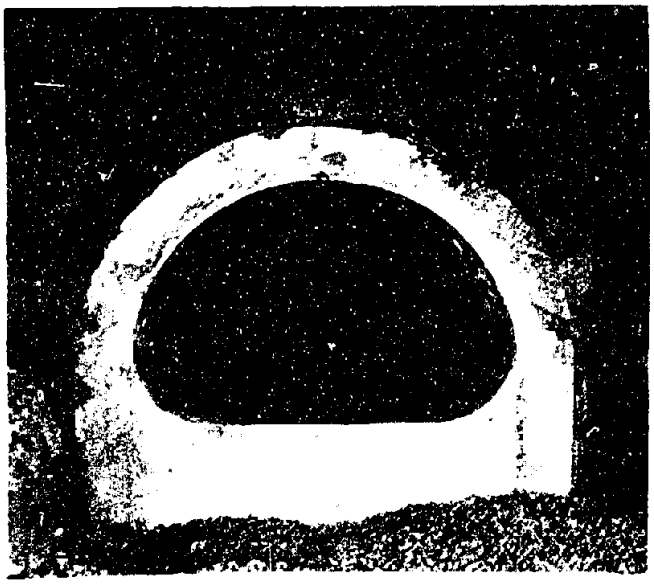
9. Drawdown produced at power house by outlet and spillway discharge. The following information may be of some value, and is presented here as a record. A gage was installed in the model immediately upstream from the outlet portals (Point G-1, Figure 18), and a second gage installed 1,300 feet prototype, downstream (Point G-2) for the purpose of measuring the drawdown between these two stations, produced by flow from the outlet and spillway tunnels. It was desired to place the gages farther apart, but the size of the model limited this distance. During the following tests, 25,000 second-feet entered the river continuously from the powerhouse. With any appreciable flow from the outlets or spillways, a pumping or ejector action occurred which dropped the water surface at Gage 1 below that at Gage 2. The extent of this drawdown is shown



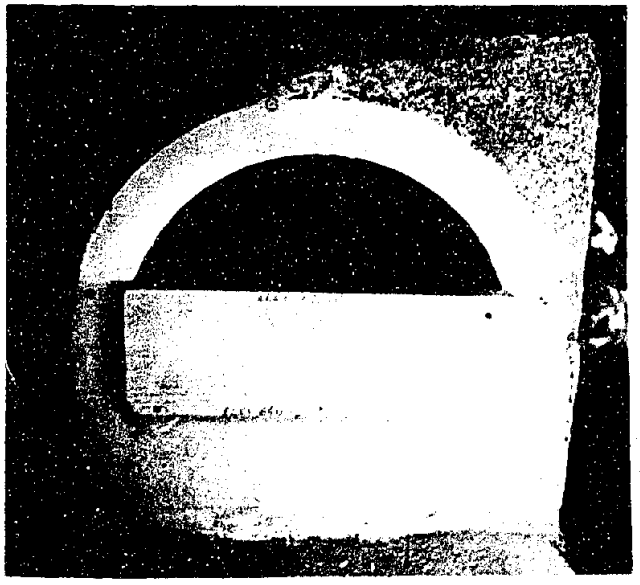
A-Downstream Portion of Tunnel 1 Showing 400-Foot Extension on 1170-Foot Radius



B-Spillway Tunnel 1 Showing Proposed Extension with Retaining Walls



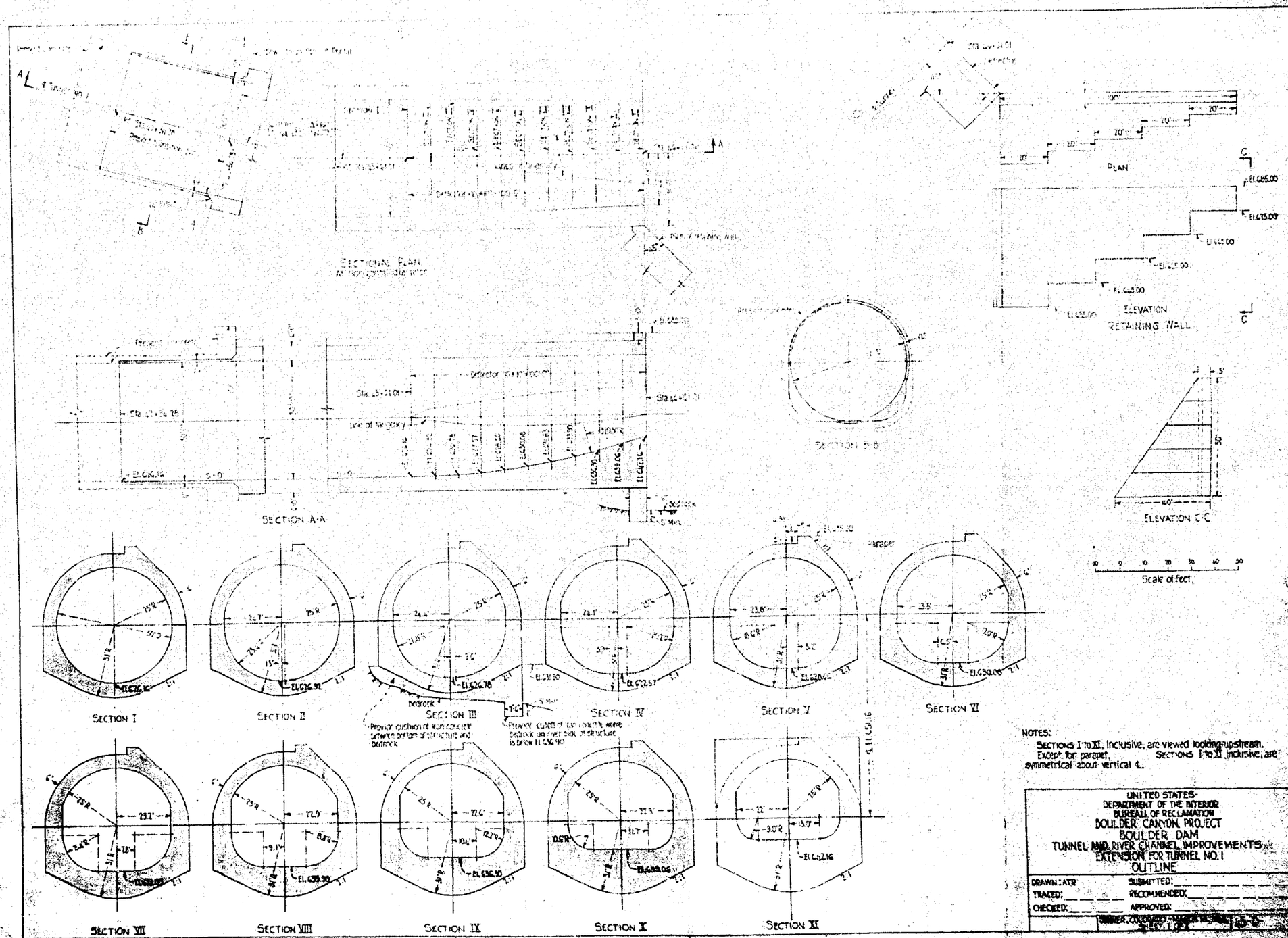
C-View of Symmetrical Transition at End of Tunnel 1



D-Illustration Showing Future Inspection Bulkhead, Approximately 10 Feet in Height, which can be used after Tunnel Extension has been Completed

MODIFIED DESIGN - CONSTRUCTION FEATURES OF TUNNEL 1

FIGURE 21



NOTES:

Sections I to XI, inclusive, are viewed looking upstream. Except for parapet, Sections I to XI inclusive, are symmetrical about vertical ℄.

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
BOULDER CANYON PROJECT
BOULDER DAM
TUNNEL AND RIVER CHANNEL IMPROVEMENTS
EXTENSION FOR TUNNEL NO. 1
OUTLINE

DRAWN: ATR
TRACED:
CHECKED:
SUBMITTED:
RECOMMENDED:
APPROVED:

FIGURE 22

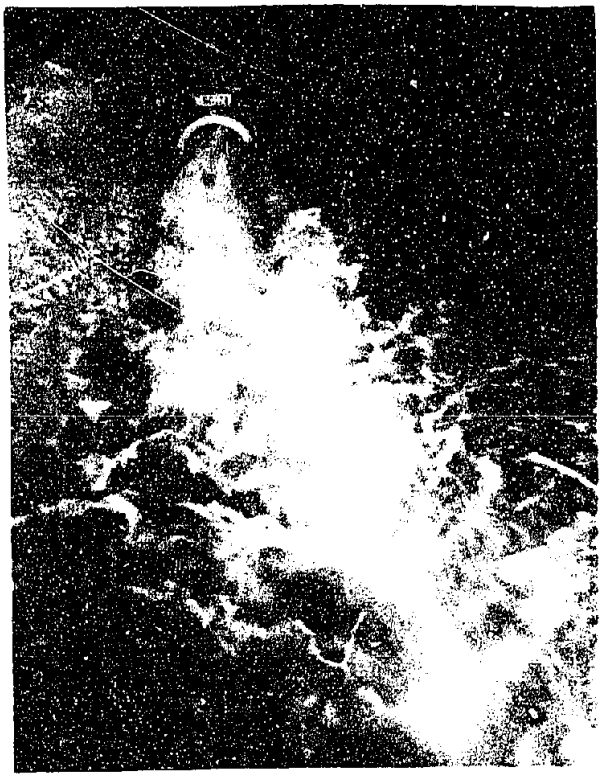
A-15,000 Second-Feet
Jump Forms in Tunnel

B-20,000 Second-Feet
Jump Forms in End of Tunnel

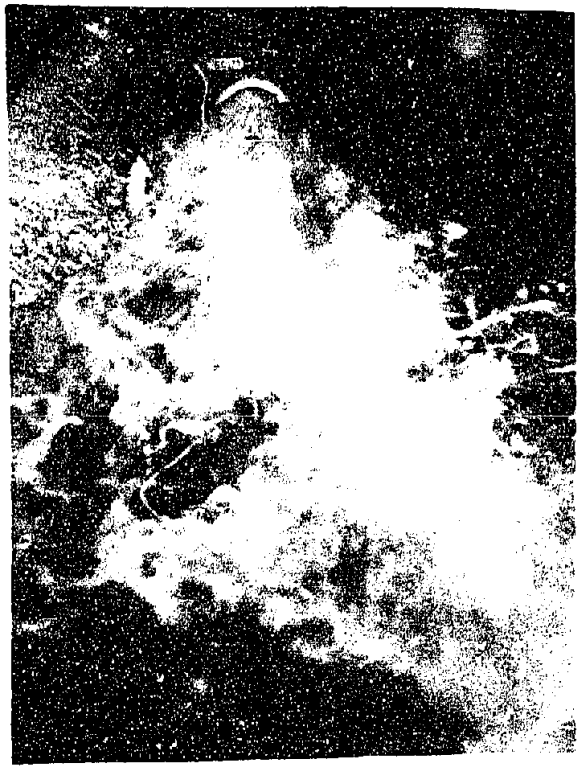
C-25,000 Second-Feet
Jump Free of Tunnel

D-50,000 Second-Feet

MODIFIED DESIGN - SPILLWAY TUNNEL 1 IN OPERATION

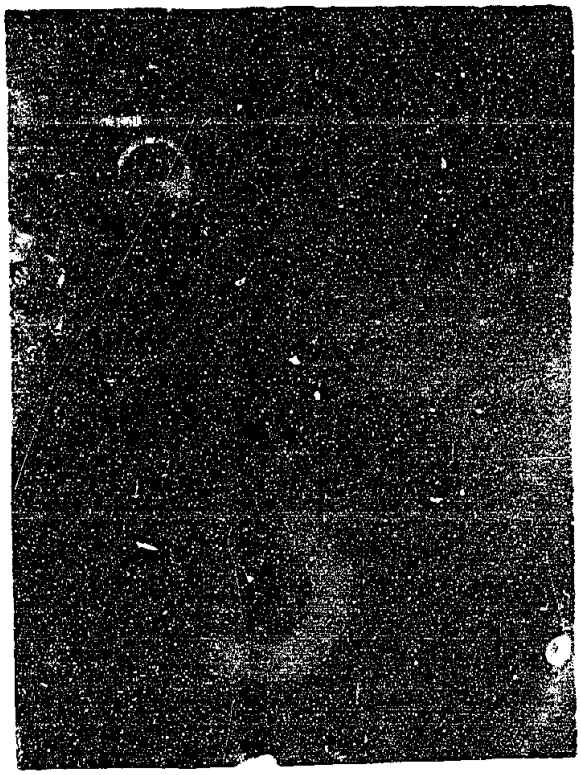


A-75,000 Second-Feet



B-100,000 Second-Feet

C-130,000 Second-Feet



D-Scour in River after Flow of 130,000 Second-Feet

MODIFIED DESIGN - SPILLWAY TUNNEL 1 IN OPERATION

on Figure 13B for either outlet tunnel discharging. The curves show a drawdown of -2.25 feet for Tunnel 2 and -4.3 feet for Tunnel 3, when operating at full capacity. The drawdown would undoubtedly be larger for the two tunnels operating simultaneously, but the two outlets were never operated together in the model as only one model needle valve structure was constructed.

Similar drawdown curves obtained for spillway operation are plotted on Figure 25. The curve for the Nevada Spillway operating alone shows a steady increase in drawdown, with increase in discharge amounting to a -11 feet for a flow of 130,000 second-feet. The curve for the Arizona Spillway operating alone, however, shows an increase in drawdown with increase in discharge up to a -4 feet at 100,000 second-feet. For further increases in discharge, the drawdown diminishes. The difference in the above two curves is chargeable to the angle at which the jets from the spillway tunnels enter the river. The Nevada Tunnel practically parallels the river, while the Arizona Tunnel discharges at an angle across the river. In the latter case, the jet is divided as it strikes the opposite bank, a portion turning upstream and the remainder swinging downstream. The upstream flow has a tendency to counteract the drawdown effect.

The third curve on Figure 25 shows the drawdown with simultaneous operation of the spillways. The flow throughout these tests was proportioned as one third of the total through the Arizona Spillway and two-thirds through the Nevada Spillway. The drawdown in this case amounted to a -17.5 feet for a combined discharge of 180,000 second-feet. The 25,000 additional second-feet from the powerhouse appeared to have little effect on the drawdown.

10. Dredging of river channel. In addition to the alterations and repairs outlined for the tunnel portals, it is proposed that a certain amount of dredging be performed in the river channel. The model tests indicate a satisfactory correction of the present difficulties at the tunnel portals independent of the present range of tailwater elevation. Any lowering of the tailwater by dredging would have little effect on the flow from the modified tunnel portals. The value of dredging should be judged according to possible increase in power production by an increase of head. It is therefore recommended, for the present, to limit the dredging operations to the reach of the river from the tunnel portals downstream to a point slightly beyond the river gaging station. This should increase the operating head on the powerplant by approximately 5 feet and reduce the height of necessary cofferdams for the extension of Tunnel 1 by a like amount, providing dredging is done first. The benefits to be derived in the maintenance of the tunnel outlet structures by further reduction in tailwater elevation appear to be negligible.

FIGURE 24

A-50,000 Sec.-Ft. through Tunnel 1
28,000 Sec.-Ft. through Tunnel 4

B-75,000 Sec.-Ft. through Tunnel 1
37,500 Sec.-Ft. through Tunnel 2

C-[illegible] Sec.-Ft. through Tunnel 1
50,000 Sec.-Ft. through Tunnel 4

D-Scour in River Channel after Flow of
100,000 Sec.-Ft. through Tunnel 1 and
50,000 Sec.-Ft. through Tunnel 4

MODIFIED DESIGN - SPILLWAY TUNNELS 1 AND 4 IN OPERATION

It is proposed to divide the dredging into two operations:

a. Continuation of operation of the cableway dredge immediately downstream from the spillway tunnel portals to a point about 400 feet downstream from the portal Tunnel 4, until a contract can be executed. No effort should be made to excavate a channel of any specific cross section or dimension in this reach of the river, but rather remove all loose material that might, in the future, be swept out by the action of the jets from the tunnels and piled in bars further downstream.

b. A contract be let for the removal of the remainder of the upstream bar and for material downstream to a point slightly beyond the gaging station. A second item of the contract would be removal of the waste materials above waterline which have been deposited along both banks down to the hairpin turn in the lower portal road. This will involve relocation of the principal portion of the road from the hairpin turn to the highway tunnel portal such that it will be founded on natural rock instead of fill. The work can be advertised and awarded on a yardage basis or, if deemed advisable, as a fixed-fee negotiated contract. For further information concerning contract details, reference is made to a letter of February 14, 1944, from Chief Engineer to Director of Power, Boulder City, Nevada, subject, "Improvements in river channel below Boulder Dam, Boulder Canyon Project."

In addition to dredging of the river, removal of slide material and road relocation, some retaining walls and other bank protective works will be required. The extent and nature of the protection can best be determined in the field. Construction can be done by either Government forces or included as a part of the contract for extension of Tunnel 1.

11. Instructions to watermaster. It was felt advisable to summarize the operating characteristics inherent in the modified structures as they differ from those of the present design. Due to the deflector elbows on the outlet and spillway tunnels, more care will be necessary to sweep the hydraulic jump out of the tunnels than heretofore. It cannot be proven that a jump in a tunnel will be detrimental to that structure. However, when it is considered that at least 10 percent of the total energy of flow is dissipated in the jump, and the tunnel and water in the tunnel must absorb this energy, it is felt advisable to avoid dissipating any more energy in a tunnel than absolutely necessary. For example, the energy lost to the tunnel and water in the tunnel for a discharge of 10,000 second-feet would be approximately 55,000 horsepower. The following suggestions on operation are therefore offered concerning the modified tunnel designs:

a. When starting flow through the tunnel plug outlet valves, it is advisable to first open the four inside valves, singly or in pairs. Best results will be obtained by operating Valves 3 and 4, and 2 and 5 in pairs, leaving Valves 1 and 6 until last. Valves 2, 3, 4, and 5 will sweep the jump out of the tunnel when operated individually or in pairs. It is doubtful, however, whether Valves 1 and 6 will move the jump out of the tunnel, or even hold it out, when operated singly or together. This is a point to be determined in the field. If Valves 1 and 6 will not operate properly alone, it means that these two valves will not experience as much service as the other four. The above applies for both outlet tunnels.

b. In the case of the spillways, the Arizona should not be operated at less than 10,000 second-feet, nor the Nevada at less than 23,000 second-feet, as these discharges are required to sweep the jumps out of the tunnels.

c. For spillway discharges greater than 40,000 second-feet, it is advisable to operate both spillways, when possible, routing two-thirds of the total discharge through the Nevada and one-third through the Arizona spillway. In this way the jets from the two spillway tunnels combine and flow down the center of the river. Any appreciable deviation from this proportion, which applies to all flows, will force the combined jet to either one bank or the other. It may be possible to observe the combining of the jets from the watermaster's office. If so, this will probably be the most satisfactory means of proportioning the flow.

d. The outlet tunnels will operate over a wide range of tailwater conditions for the modified design. It may be valuable to remember that the tunnel plug outlets will operate satisfactorily along with the spillways up to a total flow approximating 200,000 second-feet.

12. Experience with 1:100 scale model. For the benefit of those who work with hydraulic models, the following experience is related. When the channel improvement problem was first assigned to the laboratory, space was very limited. Because of this limitation, certain liberties were taken to expedite the work. A 1:100 model was constructed using standard 6-inch pipe and fittings for the outlet and spillway tunnels. Although the heads, tunnel diameters, and river channel were to scale, the tunnel alinement was not. On operation of the model, the performance of both the tunnel plug outlets and spillways was questionable. It so happened that both of the prototype outlets were operated to capacity in 1938 and their performance recorded on motion picture film. A comparison showed dissimilarites in the flow between model and prototype. With the space available, rearrangement of the piping could not remedy the situation.

From the beginning, it was planned to construct a 1:60 scale model of the Arizona Spillway. With failure of the 1:100 scale model to perform properly, the 1:60 model was enlarged to include both spillways, both outlet tunnels, and a portion of the river channel downstream, the whole to be constructed as soon as space was available in the laboratory. For a complete picture, the outlet tunnels were provided with one set of six needle valves which was used previously in related tests in 1932. It was necessary to shift the set from one outlet tunnel to the other depending on the condition of operation desired.

The performance of the tunnel plug outlets on the 1:60 model matched that shown by the motion pictures. All testing was thereafter done on the 1:60 model and the 1:100 scale model was abandoned. This again shows that with certain types of models, in this case circular conduits flowing partially full, complete similarity between a model and prototype is essential.

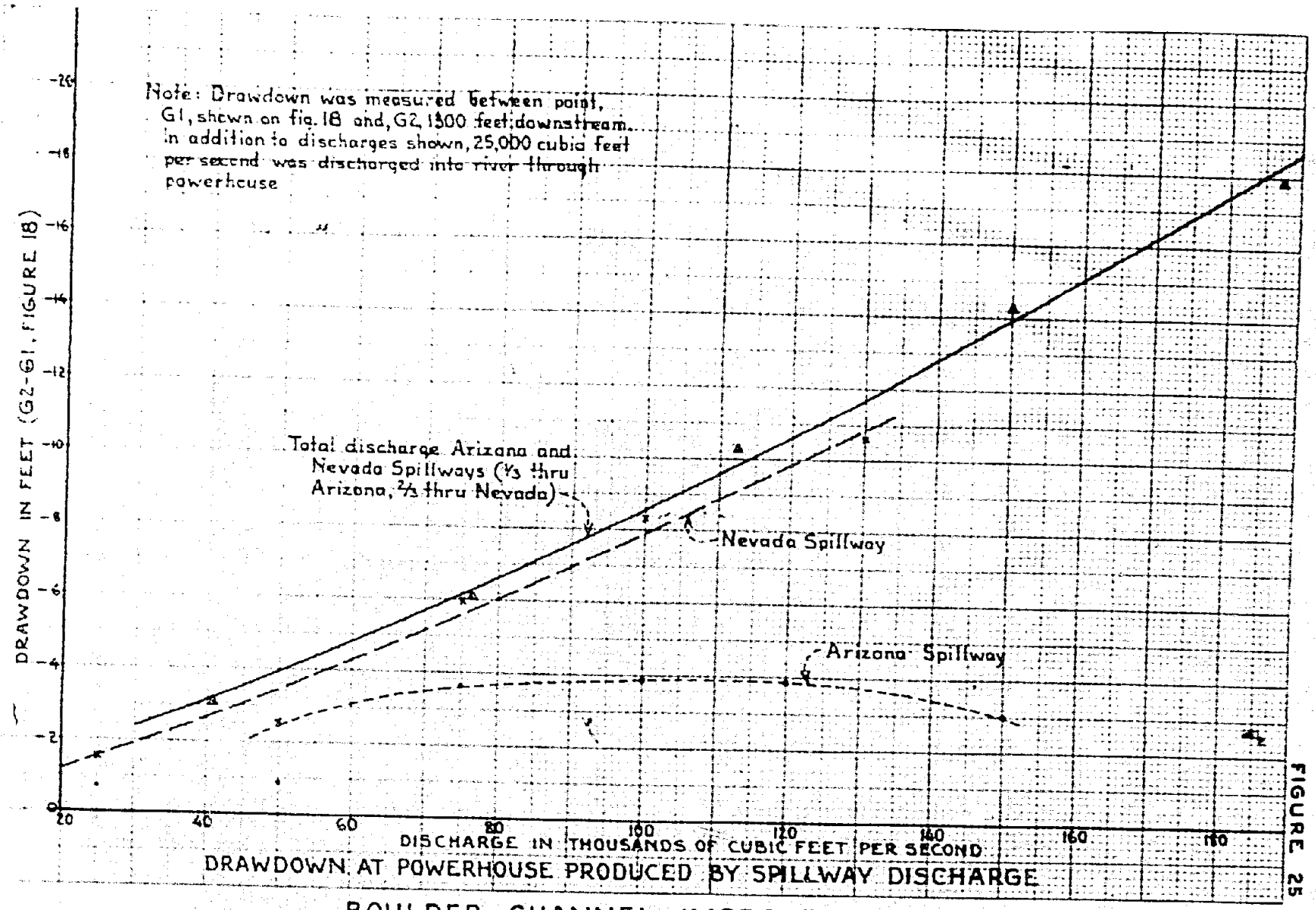


FIGURE 25

DRAWDOWN AT POWERHOUSE PRODUCED BY SPILLWAY DISCHARGE

BOULDER CHANNEL IMPROVEMENTS

RECORD OF CORRESPONDENCE

June 11, 1942 - Memorandum from Chief Designing Engineer to Design Section authorizing Senior Engineer S. E. Rockwell with direct charge of design work on Boulder channel improvements.

July 10, 1942 - Memorandum from Senior Engineer S. E. Rockwell to Chief Engineer--Report on Inspection at site.

July 28, 1942 - Memorandum from S. E. Rockwell to K. B. Keener--Request for authority to study problem by means of hydraulic model.

Nov. 4, 1942 - Memorandum from Supervisor of Equipment to Chief Engineer--Report on inspection of river channel, structures, and equipment.

Feb. 13, 1943 - Letter from Assistant Chief Designing Engineer to Director of Power--Transmittal of drawings for suggested schemes to protect canyon walls and to improve flow conditions at portals of outlet and spillway tunnels.

April 1, 1943 - Letter from Assistant Chief Designing Engineer to Director of Power--Requesting information on exact location of gaging station.

April 6, 1943 - Letter from Director of Power to Chief Engineer confirming position of river gaging station and enclosing water surface elevations measured at gaging stations.

April 16,1943 - Letter from Director of Power to Chief Engineer transmitting prints of topography of river channel below tunnel outlets as of December 1942 and as of October 1941.

April 27,1943 - Letter from Director of Power to Chief Engineer transmitting topographic sheet of river between gaging station and Ring Bolt Rapids, also photographs of available areas for disposal of excavated materials.

May 20, 1943 - Letter from Director of Power to Chief Engineer--Transmittal of topography of river channel below tunnel outlets as of May 1943. Also additional topography of river in vicinity of U. S. G. S. gaging station.

May 20, 1943 - Letter from Director of Power to Chief Engineer--Information on topographic features of river channel.

RECORD OF CORRESPONDENCE (Continued)

May 2[illegible], 1943 - Letter from Director of Power to Chief Engineer--Transmittal of additional information on river topography in vicinity of retrogression section 1.

June 14, 1943 - Letter from Director of Power to Chief Engineer--Transmittal of photographs and topographic sheets showing space available for disposal of excavated materials.

July 24, 1943 - Letter from Director of Power to Chief Engineer--Transmittal of river channel topography between retrogression sections 2 and 3.

Aug. 3, 1943 - Letter from Director of Power to Chief Engineer--Transmittal of revised drawings of topography of river banks at wider portions of channel.

Aug. 7, 1943 - Memorandum from Senior Engineer S. H. Rockwell to Chief Designing Engineer--Requesting information on future tailwater conditions at Boulder Dam which will be produced by backwater from Davis Dam.

Sept. 25, 1943 - Memorandum from Hydraulic Engineer H. F. Dehler to Chief Designing Engineer--Report on proposed operation of Davis Dam Reservoir.

Oct. 7, 1943 - Letter from Acting Chief Engineer to Director of Power--Transmittal of drawings for inclusion in specifications for dredging in river between Boulder Dam and Nine Bolt Rapids.

Oct. 14, 1943 - Letter from Director of Power to Chief Engineer--Comments and recommendations on river channel dredging and preparation of specifications.

Jan. 27, 1944 - Letter from Assistant Chief Designing Engineer to Director of Power--Transmittal of drawings of riverbed and canyon wall topography from tunnel outlet portals to point below river gaging station.

Feb. 14, 1944 - Letter from Chief Engineer to Director of Power--Recommendations for improvements at tunnel portals and dredging in river channel. Also suggestions for contracting work.

Feb. 25, 1944 - Letter from Director of Power to Denver office--Discussion of letter dated February 14, 1944, and transmittal of topographic sheets.

RECORD OF CORRESPONDENCE (Continued)

March 11, 1944 - Letter from Director of Power to Denver office--Relocation of lower portal road and exposed rock contacts required for road relocation purposes.

April 6, 1944 - Letter from Director of Power to Denver office--Transmittal of corrected prints of topography along lower portal road.

April 15, 1944 - Letter from Director of Power to Denver office--Transmittal of corrected prints relative to proposed tunnel modifications.

April 19, 1944 - Memorandum from J. N. Bradley to Chief Designing Engineer--Report on hydraulic model studies for improvements in river channel downstream from Boulder Dam.

April 18, 1944 - Letter from Director of Power to Denver office--Information concerning exploratory drilling along Tunnel 1 extension.

April 28, 1944 - Letter from Assistant Chief Designing Engineer to Director of Power--Request for additional drill holes along Tunnel 1 extension.

May 17, 1944 - Memorandum from I. A. Winter to Chief Electrical and Mechanical Engineer--Report on backwater study relative to dredging of the river between the outlet tunnels and Ring Bolt Rapids.

May 26, 1944 - Letter from Director of Power to Denver office--Transmittal of logs relative to exploratory drill holes along Tunnel 1 extension.

May 30, 1944 - Letter from Chief Engineer to Director of Power--Methods for grouping schedules for dredging and tunnel modification work.