UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

HYDRAULIC MODEL STUDIES FOR THE DESIGN OF BHAKRA DAM

PUNJAB PROVINCE, INDIA [redacted]

Hydraulic Laboratory Report No. Hyd. 210

[redacted]

BRANCH OF DESIGN AND CONSTRUCTION
DENVER, COLORADO

OCTOBER 15, 1946

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UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

Branch of Design and Construction
Engineering and Geological Control
and Research Division
Denver, Colorado
October 15, 1946

Laboratory Report No. 210
Hydraulic Laboratory
Compiled by: E. J. Rusho
Reviewed by: J. E. Warnock
and J. N. Bradley

Subject: Hydraulic model studies for the design of the Bhakra Dam--Province of Punjab, India.

INTRODUCTION

The Problem

On October 2, 1945, an agreement (Contract No. 12r-15491) was made between the United States of America, represented by the Chief Engineer, Bureau of Reclamation, and the Morrison-Knudsen Company, Inc., of Boise, Idaho, through the International Engineering Company, Inc., Denver, Colorado, whereby the Bureau would conduct model studies of the various hydraulic features of Bhakra Dam, being designed for construction in the Sutlej River in the Province of Punjab, India.

In this investigation the problem consisted of 3 features:

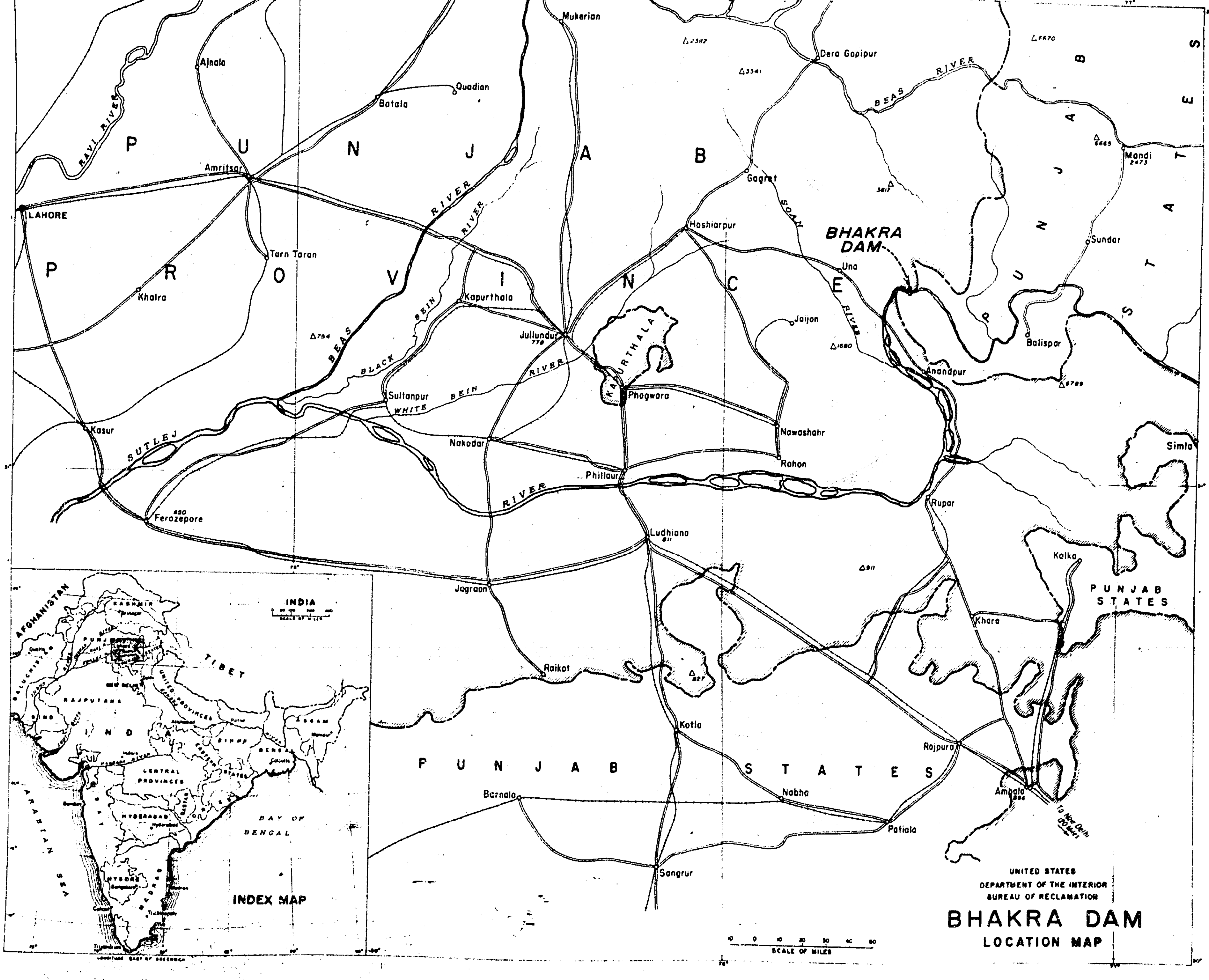
1. The drum-gate spillway section, which included the stilling basin and river outlets through the dam.
2. The tunnel spillway with the left diversion tunnel and deflector at the tunnel portal.
3. The tunnel outlet works in the right diversion tunnel.

In addition to a composite model of the dam, 5 additional models of various sections of the structure were used in these studies.

Prototype Structure

The Bhakra Dam is to be constructed on the Sutlej River in Northern India (Figure 1) for the Public Works Department of the Province of Punjab. It will provide flood control, additional water for irrigation,

FIGURE I


PUNJAB PROVINCE
PUNJAB STATES
BHAKRA DAM
RAVI RIVER
BEAS RIVER
SUTLEJ RIVER
BLACK BEIN RIVER
WHITE BEIN RIVER
SOAN RIVER
KAPURTHALA
LAHORE
Amritsar
Ajnala
Batala
Quadian
Mukerian
Dera Gopipur
Tarn Taran
Khalra
Kapurthala
Jullundur
Sultanpur
Kasur
Nakodar
Phagwara
Phillaur
Ferozepore
Ludhiana
Jagraon
Raikot
Hoshiarpur
Gagret
Una
Jaijon
Nawashahr
Rahon
Anandpur
Rupar
Mandi
Sundar
Balispar
Simla
Kalka
Khara
Kotla
Rajpura
Ambala
Nabha
Patiala
Barnala
Sangrur
To New Delhi
INDEX MAP
INDIA
AFGHANISTAN
TIBET
BAY OF BENGAL
ARABIAN SEA
SCALE OF MILES
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
BHAKRA DAM
LOCATION MAP

and hydroelectric power for the province. The general design is being made by the International Engineering Company, Inc., Denver, Colorado, with Mr. J. L. Savage as consulting engineer.

The Sutlej River drains an area of 21,960 square miles above the damsite. The design flood is 375,000 second-feet. The dam will be of the concrete gravity type with an overall height of 500 feet and a length of 1,400 feet. Maximum storage of the reservoir will be 4,240,000 acre-feet. Two spillways will be provided, the drum-gate spillway located in the center of the dam, Figures 2 and 3, and the tunnel spillway at the left abutment, Figures 2 and 4. The downstream section of the left diversion tunnel will be used for the outlet of the tunnel spillway. The crest control will be provided by two 135- by 28-foot drum gates for the drum-gate spillway and two 50- by 70-foot high radial gates for the tunnel spillway.

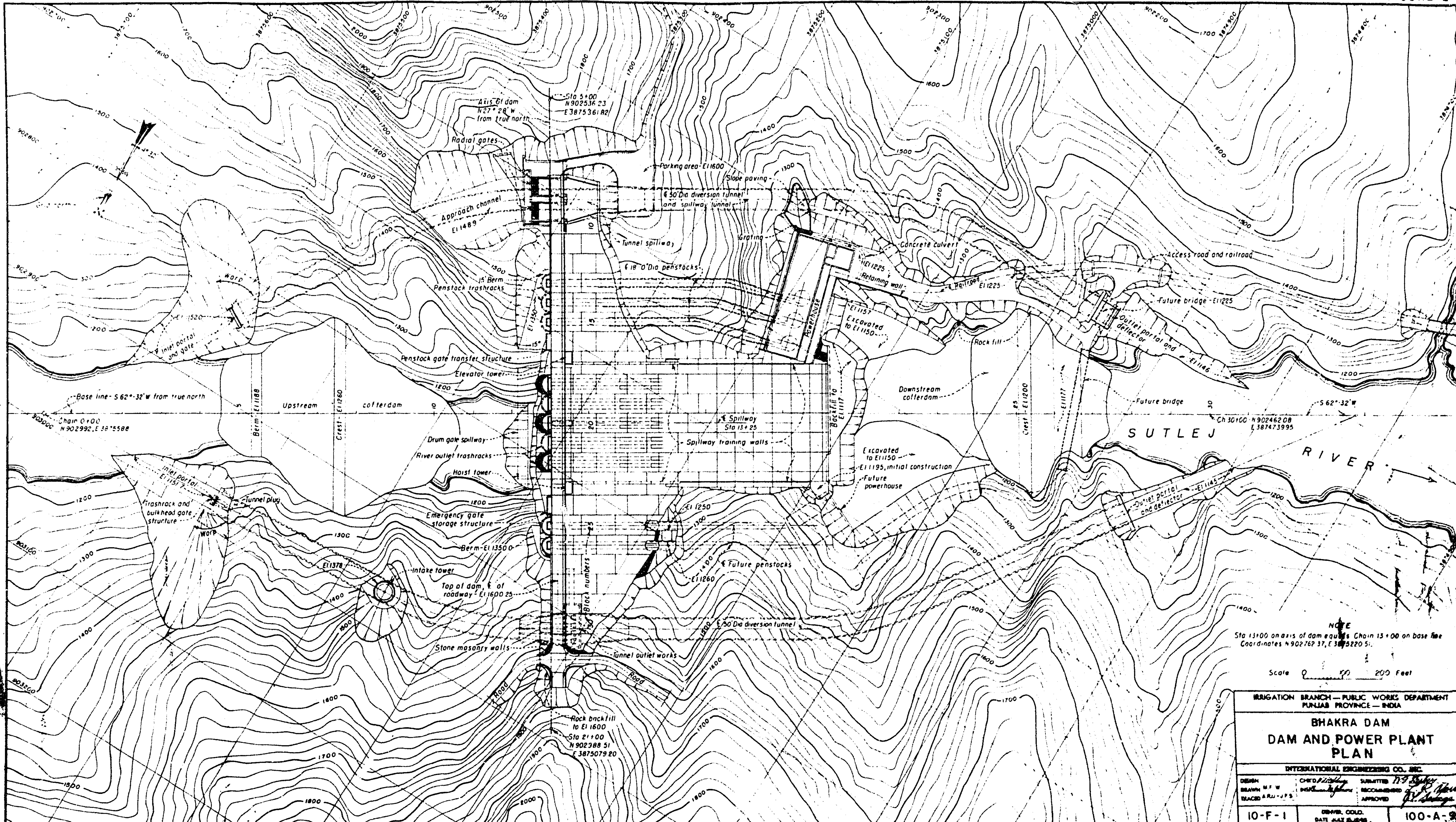
Two outlet systems are planned. The tunnel outlet works, located in the right diversion tunnel (Figure 5) will be regulated by four 96-inch hollow-jet valves. The river outlets in the dam will consist of 20 conduits, each regulated by a 96-inch jet-flow gate, Figures 2 and 3, which discharge into the spillway section on the downstream face of the dam.

Two powerplants will be installed ultimately, one on each bank adjacent to the spillway apron. In the initial development only the powerplant on the left bank will be constructed. Maximum flow requirements for both plants will be 15,000 second-feet.

Maximum discharge capacities for the spillways and outlets are as follows:

Drum-gate spillway	93,600 second-feet
Tunnel spillway	166,600 second-feet
River outlets	96,000 second-feet
Tunnel outlet works	21,300 second-feet

FIGURE 2



Axis of dam N27° 28' W from true north
Sta 5+00 N902536.23 E3875361.82
Radial gates
Parking area - El 1600
Slope paving
℄ 50' Dia diversion tunnel and spillway tunnel
Approach channel El 1489
Tunnel spillway
Grating
Concrete culvert
Access road and railroad
℄ 18' 0" Dia penstocks
15' Berm
Penstock trashracks
Retaining wall
Railroad El 1225
Future bridge - El 1225
Powerhouse
Excavated to El 1150
Rock fill
Outlet portal and deflector El 1146
Inlet portal and gate
Penstock gate transfer structure
Elevator tower
Base line - S 62°-32' W from true north
Chain 0+00 N902992, E38*5588
Upstream cofferdam
Berm - El 1188
Crest - El 1260
Downstream cofferdam
Crest - El 1200
Future bridge
S 62°-32' W
Ch 30+00 N90246208 E387473995
℄ Spillway Sta 13+25
Drum gate spillway
Spillway training walls
River outlet trashracks
Backfill to El 1117
SUTLEJ RIVER
Excavated to El 1150
El 1195, initial construction
Future powerhouse
Hoist tower
Inlet portal El 1151
Trashrack and bulkhead gate structure
Tunnel plug
Warp
Outlet portal and deflector El 1145
Emergency gate storage structure
El 1250
Berm - El 1350
Future penstocks
El 1260
Intake tower
Top of dam ℄ of roadway - El 1600.25
Block numbers
℄ 50' Dia diversion tunnel
Stone masonry walls
Tunnel outlet works
Road
Rock backfill to El 1600
Sta 21+00 N902388.51 E3875079.20
NOTE
Sta 13+00 on axis of dam equals Chain 13+00 on base line
Coordinates N902762.37, E3875220.51
Scale 0 100 200 Feet
IRRIGATION BRANCH — PUBLIC WORKS DEPARTMENT
PUNJAB PROVINCE — INDIA
BHAKRA DAM
DAM AND POWER PLANT
PLAN
INTERNATIONAL ENGINEERING CO. INC.
DESIGN
DRAWN M.F.W.
TRACED
SUBMITTED
RECOMMENDED
APPROVED
10-F-1
DENVER, COLO.
100-A-

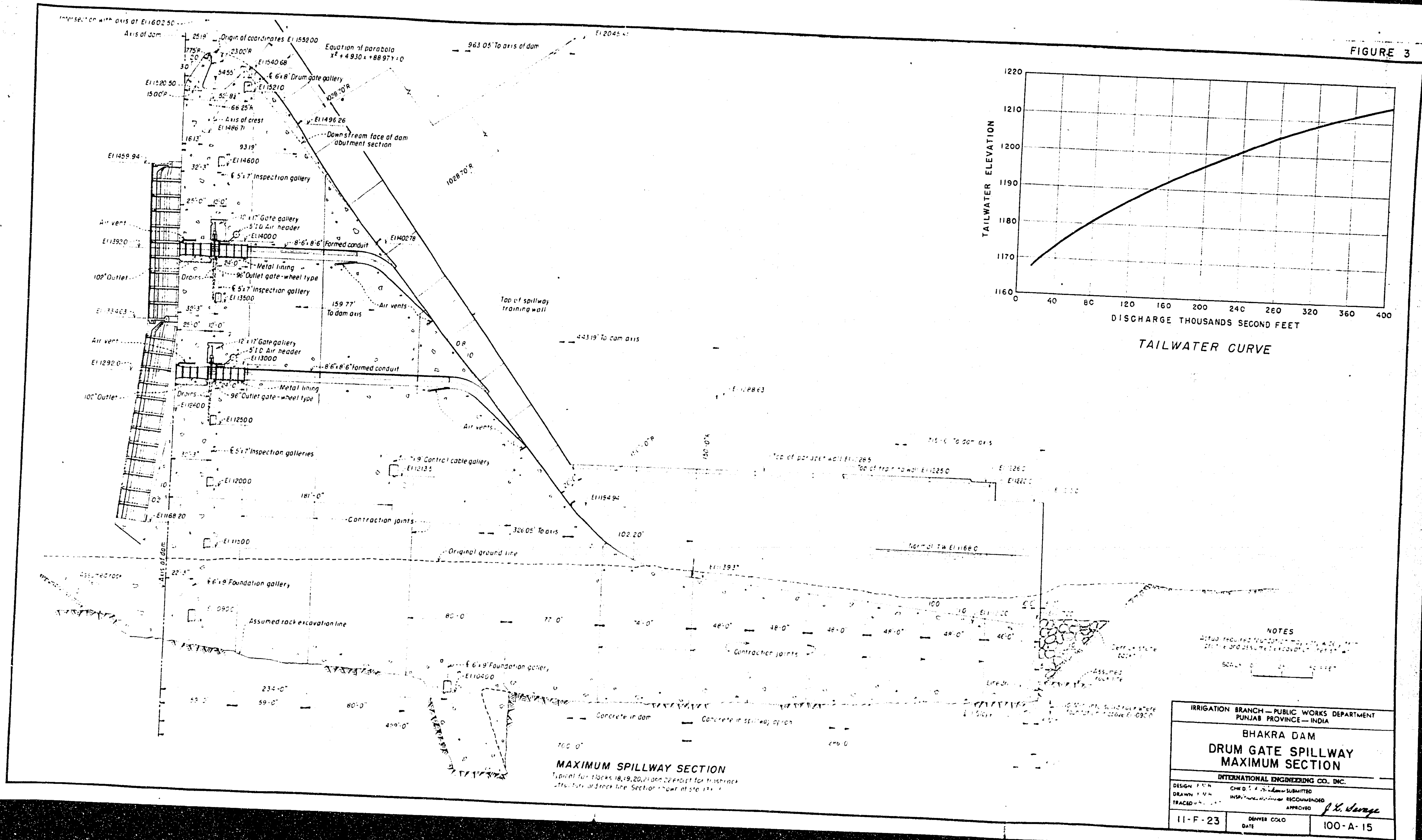


FIGURE 3
TAILWATER ELEVATION
DISCHARGE THOUSANDS SECOND FEET
TAILWATER CURVE
1160
1170
1180
1190
1200
1210
1220
0
40
80
120
160
200
240
280
320
360
400
Axis of dam
Origin of coordinates El 1552.00
Equation of parabola
$x^2 + 4.930x + 88.97y = 0$
6'x8' Drum gate gallery
Axis of crest
Downstream face of dam abutment section
5'x7' Inspection gallery
Air vent
10'x11' Gate gallery
5' I.D. Air header
8'-6"x8'-6" Formed conduit
Metal lining
96" Outlet gate-wheel type
102" Outlet
5'x7' Inspection gallery
Air vents
Top of spillway training wall
12'x17' Gate gallery
8'-6"x8'-6" Formed conduit
100" Outlet
5'x7' Inspection galleries
Control cable gallery
Contraction joints
Original ground line
Assumed rock
6'x9' Foundation gallery
Assumed rock excavation line
Contraction joints
6'x9' Foundation gallery
Concrete in dam
Concrete in spillway apron
MAXIMUM SPILLWAY SECTION
NOTES
IRRIGATION BRANCH — PUBLIC WORKS DEPARTMENT
PUNJAB PROVINCE — INDIA
BHAKRA DAM
DRUM GATE SPILLWAY
MAXIMUM SECTION
INTERNATIONAL ENGINEERING CO. INC.
DESIGN
DRAWN
TRACED
SUBMITTED
RECOMMENDED
APPROVED
J. L. Savage
11-F-23
DENVER COLO
DATE
100-A-15

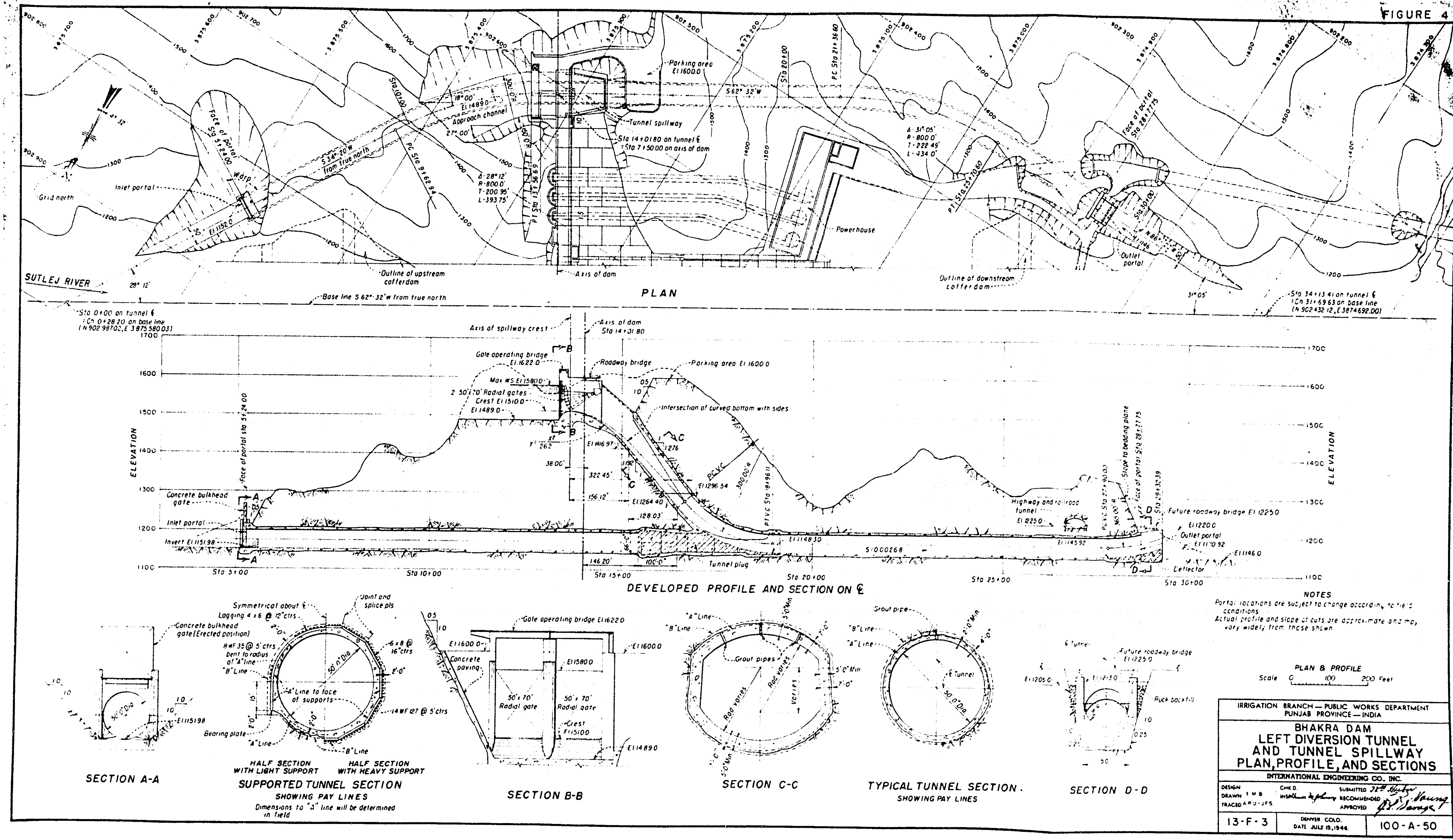


FIGURE 4
PLAN
SUTLEJ RIVER
Grid north
Inlet portal
Face of portal Sta 5+24.00
Approach channel
Tunnel spillway
Parking area El 1600.0
Powerhouse
Outlet portal
Face of portal Sta 28+77.75
Axis of dam
Outline of upstream cofferdam
Outline of downstream cofferdam
Base line S 62°-32' W from true north
S 34°-20' W from true north
DEVELOPED PROFILE AND SECTION ON ℄
ELEVATION
Axis of spillway crest
Axis of dam Sta 14+31.80
Gate operating bridge El 1622.0
Roadway bridge
Parking area El 1600.0
2-50'x70' Radial gates
Crest El 1510.0
Intersection of curved bottom with sides
Concrete bulkhead gate
Inlet portal
Invert El 1151.98
Tunnel plug
Highway and railroad tunnel
Future roadway bridge El 1225.0
Outlet portal
Deflector
Sta 5+00
Sta 10+00
Sta 15+00
Sta 20+00
Sta 25+00
Sta 30+00
SECTION A-A
Concrete bulkhead gate (Erected position)
Symmetrical about ℄
Joint and splice pls
HALF SECTION WITH LIGHT SUPPORT
HALF SECTION WITH HEAVY SUPPORT
SUPPORTED TUNNEL SECTION
SHOWING PAY LINES
Dimensions to "A" line will be determined in field
Gate operating bridge El 1622.0
50'x70' Radial gate
SECTION B-B
Grout pipes
SECTION C-C
Grout pipe
TYPICAL TUNNEL SECTION.
SHOWING PAY LINES
Future roadway bridge
Rock backfill
SECTION D-D
NOTES
Portal locations are subject to change according to field conditions
Actual profile and slope of cuts are approximate and may vary widely from those shown
PLAN & PROFILE
Scale 0 100 200 Feet
IRRIGATION BRANCH — PUBLIC WORKS DEPARTMENT
PUNJAB PROVINCE — INDIA
BHAKRA DAM
LEFT DIVERSION TUNNEL
AND TUNNEL SPILLWAY
PLAN, PROFILE, AND SECTIONS
INTERNATIONAL ENGINEERING CO. INC.
DENVER, COLO.
DATE JULY 15, 1946
13-F-3
100-A-50

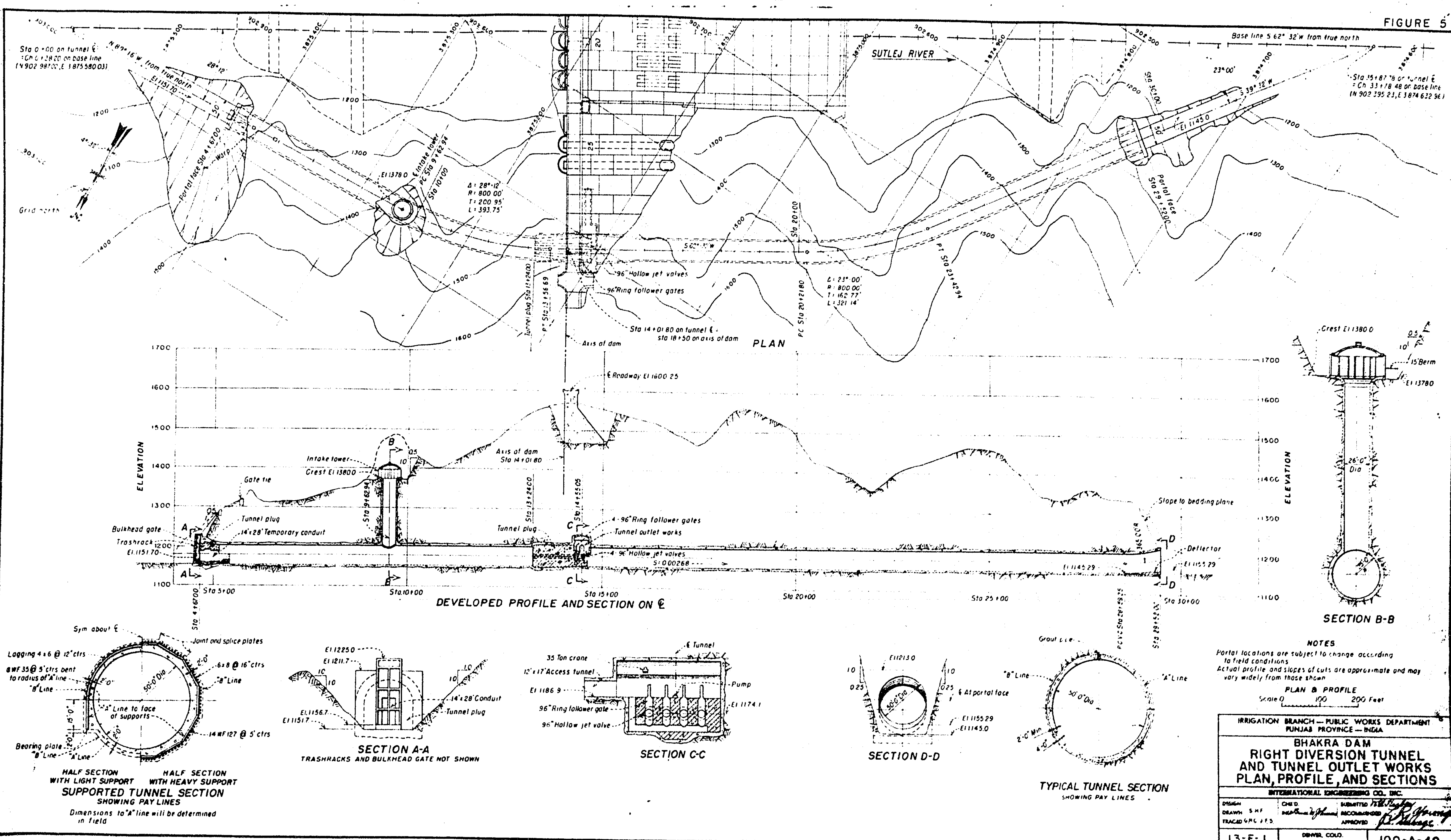


FIGURE 5
SUTLEJ RIVER
Base line S 62° 32' W from true north
Grid north
PLAN
DEVELOPED PROFILE AND SECTION ON ℄
ELEVATION
Intake tower
Crest El 1380.0
Axis of dam
Sta 14+01.80
Gate tie
Bulkhead gate
Trashrack
Tunnel plug
14'x28' Temporary conduit
4-96" Ring follower gates
Tunnel outlet works
4-96" Hollow jet valves
S: 0.00268
Slope to bedding plane
Deflector
96" Hollow jet valves
96" Ring follower gates
Sta 14+01.80 on tunnel ℄ - sta 18+50 on axis of dam
℄ Roadway El 1600.25
SECTION B-B
SECTION A-A
TRASHRACKS AND BULKHEAD GATE NOT SHOWN
SECTION C-C
SECTION D-D
HALF SECTION WITH LIGHT SUPPORT
HALF SECTION WITH HEAVY SUPPORT
SUPPORTED TUNNEL SECTION
SHOWING PAY LINES
Dimensions to "A" line will be determined in field
TYPICAL TUNNEL SECTION
SHOWING PAY LINES
NOTES
Portal locations are subject to change according to field conditions.
Actual profile and slopes of cuts are approximate and may vary widely from those shown.
PLAN & PROFILE
Scale 0 100 200 Feet
IRRIGATION BRANCH — PUBLIC WORKS DEPARTMENT
PUNJAB PROVINCE — INDIA
BHAKRA DAM
RIGHT DIVERSION TUNNEL
AND TUNNEL OUTLET WORKS
PLAN, PROFILE, AND SECTIONS
INTERNATIONAL ENGINEERING CO. INC.
DENVER, COLO.
13-F-1
100-A-40

Summary

The model studies of Bhakra Dam were requested to insure dependable designs of those hydraulic features which could not be safely based on precedent alone. Of major importance in these studies was the composite 1:80 model which, containing all the pertinent features in respective locations, made possible the study of the performance of each singly and collectively under various operating conditions. Additional models were used in the studies of specific features which, because of scale or location in the composite model, could not be reliably investigated. The overall condition of flow in the river channel downstream from the dam was the most important factor studied in the complete model. The features causing this flow were the drum-gate spillway and river outlets, the tunnel spillway, the tunnel outlet works, and the discharge from the powerplants.

The recommended slope for the drum-gate spillway stilling-basin apron was 10:1. The apron length was shorter than desired for the maximum flow of 189,600 second-feet, but it was decided not to increase the length because of unsatisfactory foundation material.

To provide the best flow in the river channel for discharges from the tunnel spillway and the tunnel outlet works, deflector designs were evolved for each tunnel portal. Severe scour in the model resulted from operating either the drum-gate spillway and river outlets or the tunnel spillway at maximum capacity.

In the original design of the approach channel to tunnel spillway, considerable drawdown occurred at the right pier due to flow parallel with the face of the dam. This condition was improved by a training wall extending upstream from the right pier. It was also found necessary to make some changes in the transition below the tunnel spillway crest.

The design of the tunnel outlet works was satisfactory without a vane at the junction of the intake shaft and the diversion tunnel.

From the model studies a new design was developed for the elbow and trough of the river outlets. A rectangular cross-section was used

instead of the usual circular shape. This design was more suitable for operation of the outlets at partial gate openings. In addition, air was supplied to the lower side of the elbow to increase pressures. An eyebrow with a 2-foot rise was placed on the spillway face over these outlets to deflect the water over the spillway to prevent its striking in the outlet troughs.

Black and white movies were taken of the 1:80, 1:32, and 1:17 models, and Kodachrome movies were made of the 1:480 polariscope model.

Models

A total of 6 models was used for the studies of Bhakra Dam. The principal one, on a scale of 1:80, was a composite model of the complete structure. A second model, on a scale of 1:17, included one river outlet. Two models were made of the tunnel outlet works. One of these, on a scale of 1:32, was of the downstream section starting with the valves and ending with the tunnel portal. The other model, on a scale of 1:100, was of the section upstream from the valves. The remaining two models were an electric analogy study of the tunnel spillway crest on a scale of 1:80 and a fluid polariscope model of the drum-gate spillway section on a scale of 1:480.

1:80 COMPLETE MODEL

Model Construction

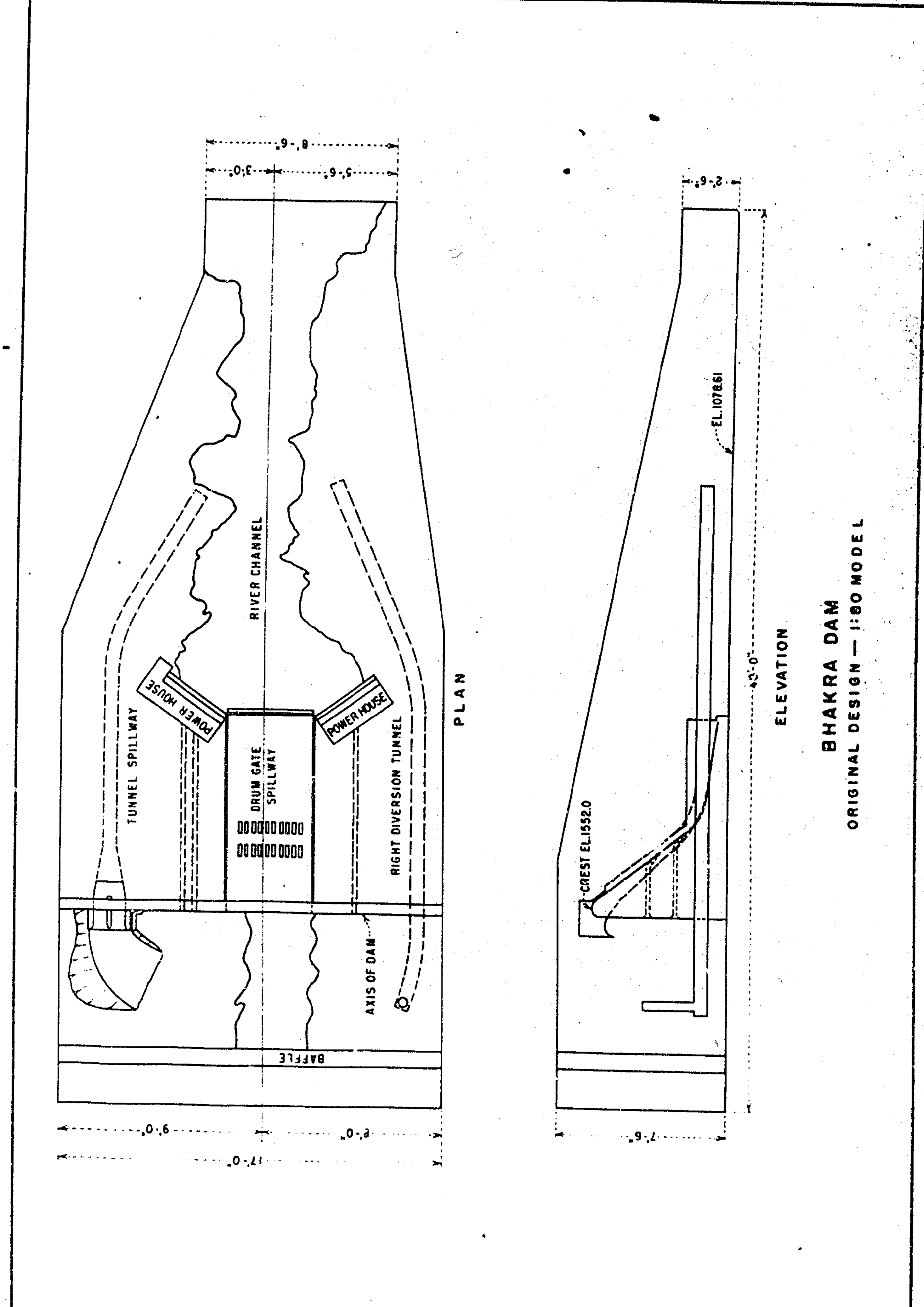
Description of model. The model on a scale of 1:80 was of the entire structure, including powerplants, spillways, and outlets. A drawing indicating the extent of the model is shown in Figure 6. The photograph in Figure 7A shows the original model with surrounding topography. The head box was constructed of wood lined with sheet iron with the downstream side forming the upstream face of the dam as is the usual practice with this type of model. The downstream face of the dam and all topography was built of metal lath supported by wooden strips. The metal lath was then plastered with a 1-inch coating of sand and cement mortar. The box downstream from the dam was built of wood and lined with roofing paper to an elevation slightly above maximum tailwater. The drum-gate spillway section, apron, drum gates, piers, and river outlets were of sheet metal construction. The tunnel spillway crest was of concrete backed with metal lath and metal templates, while sheet metal was used for the training walls and radial gates. The center pier of this spillway was of oil-treated wood. Both diversion tunnels were constructed of sheet iron. The photograph in Figure 7B, taken during assembly, illustrates the method of construction.

Water supply to the model was measured through accurately calibrated laboratory venturi meters which are systematically checked at regular intervals. Elevations of the water above the dam and below the diversion tunnels were measured with hook gages installed in stilling wells connected by tubes to these respective positions in the model.

Drum-gate Spillway

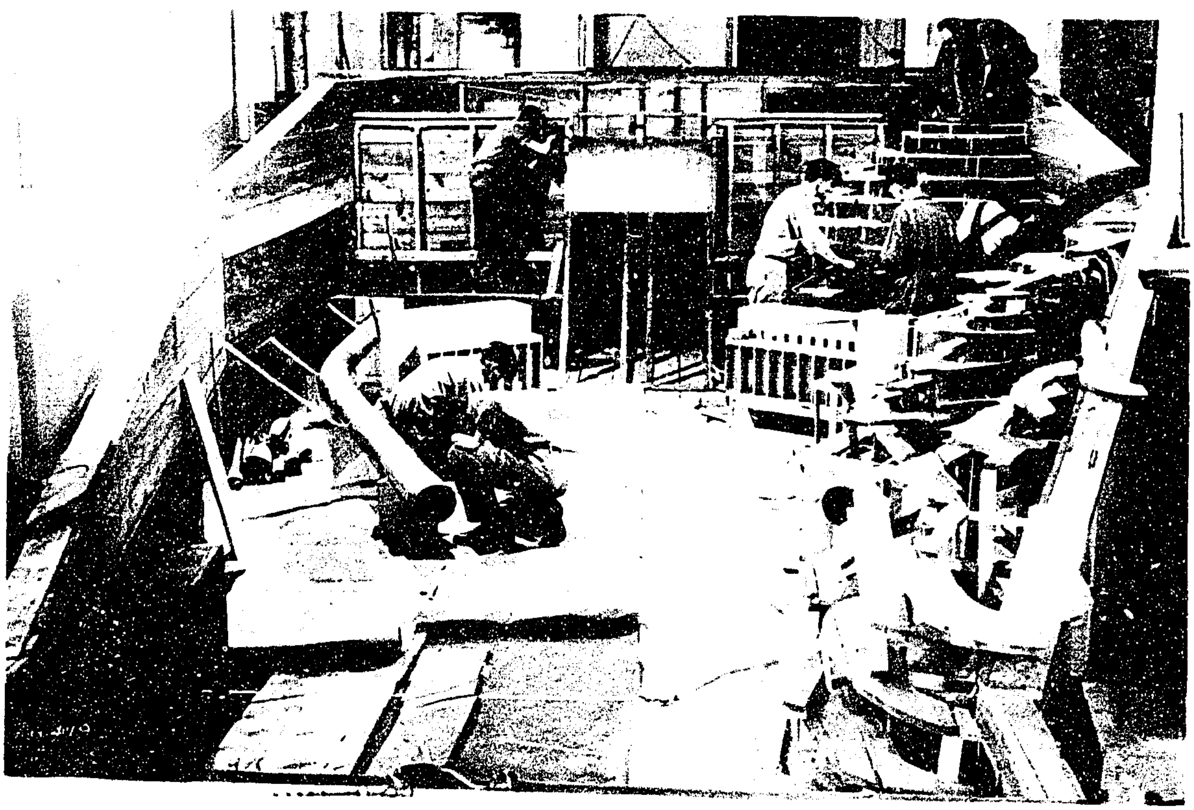
Stilling-basin design. The original design of the drum-gate spillway apron is shown in Figure 8A and illustrated by the photograph in Figure 9. This consisted of an apron with a 7.5:1 slope based on calculations from the momentum formula for the hydraulic jump and

FIGURE 6



BHAKRA DAM
ORIGINAL DESIGN — 1:80 MODEL

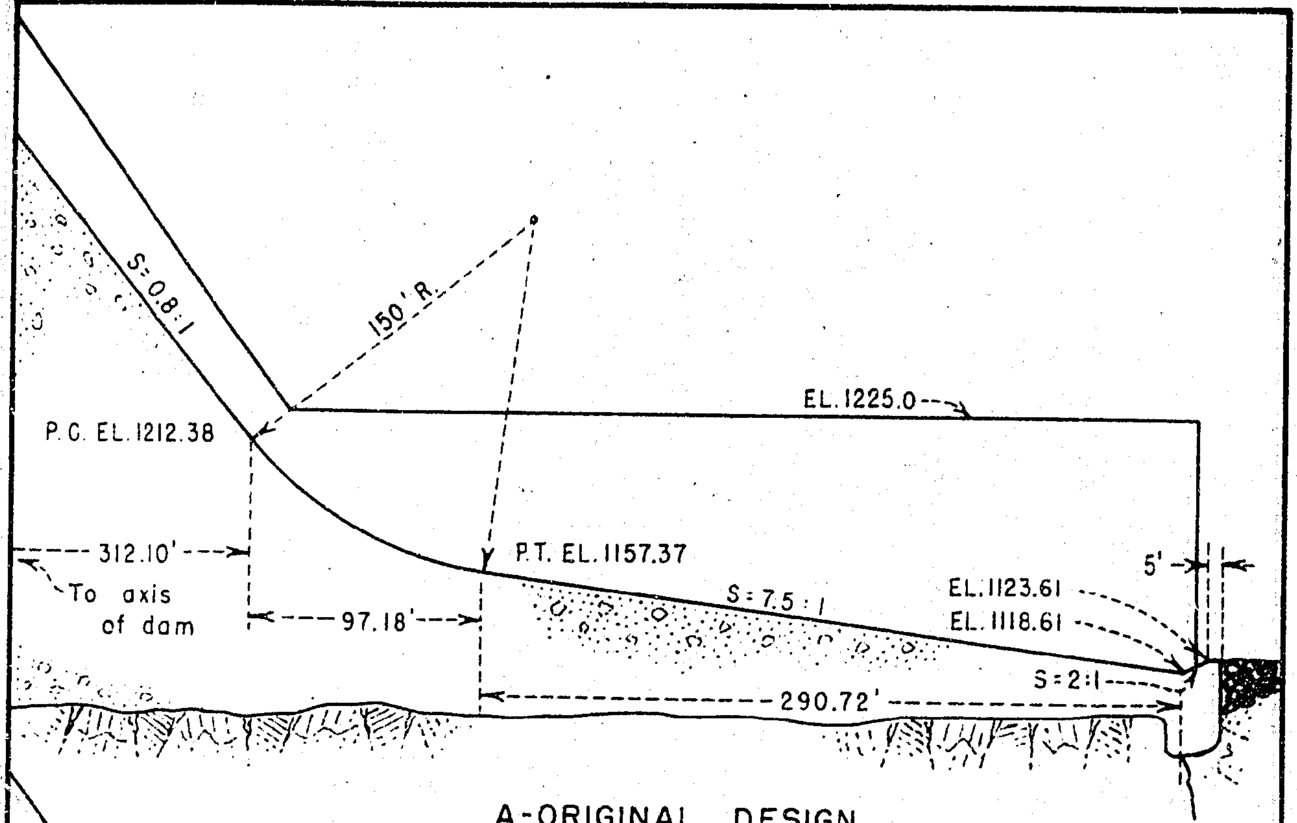
A. Completed model, original design.



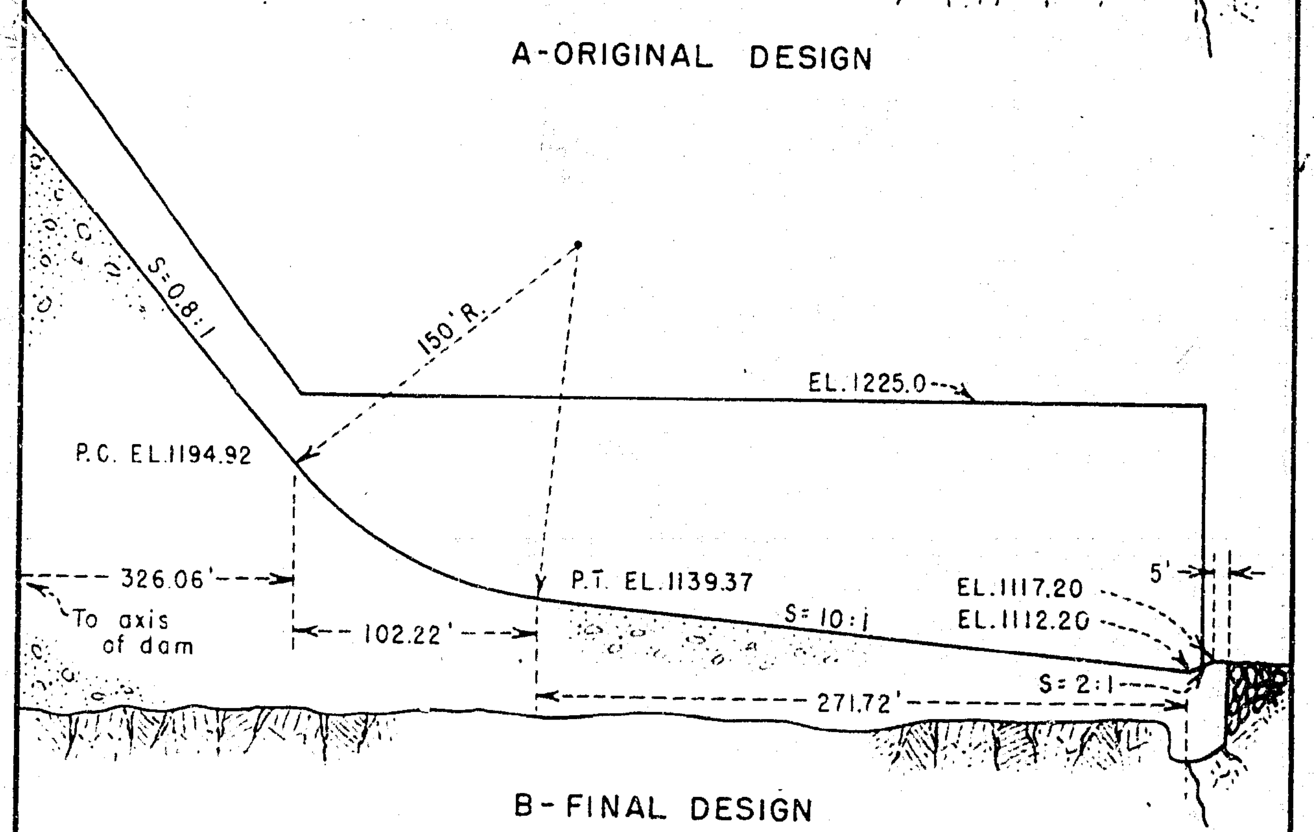
B. Model during construction.

BHAKRA DAM 1:80 MODEL

FIGURE 8



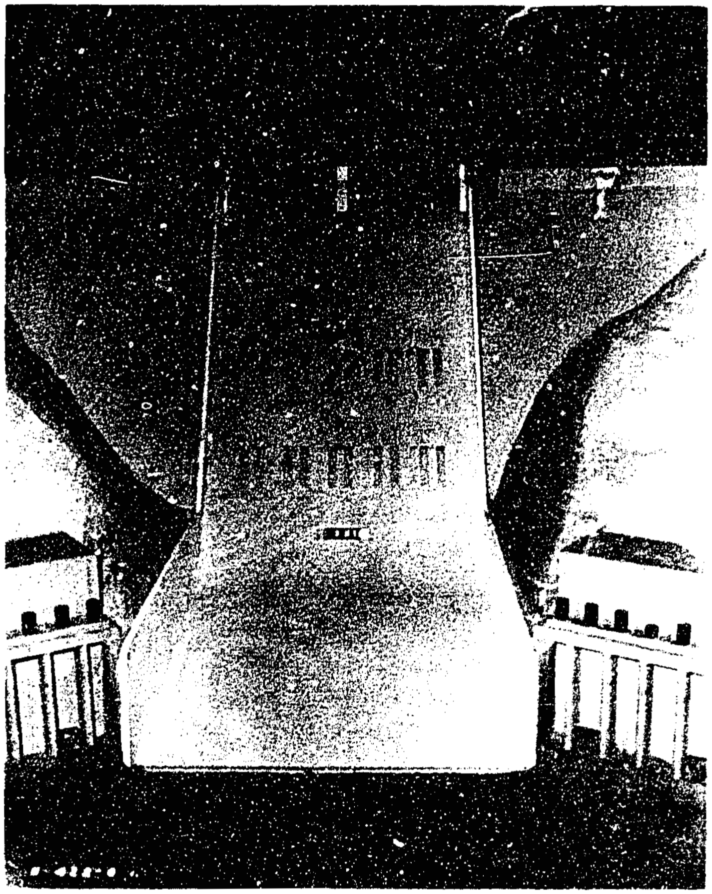
A-ORIGINAL DESIGN



B-FINAL DESIGN

BHAKRA DAM

DRUM GATE SPILLWAY APRON



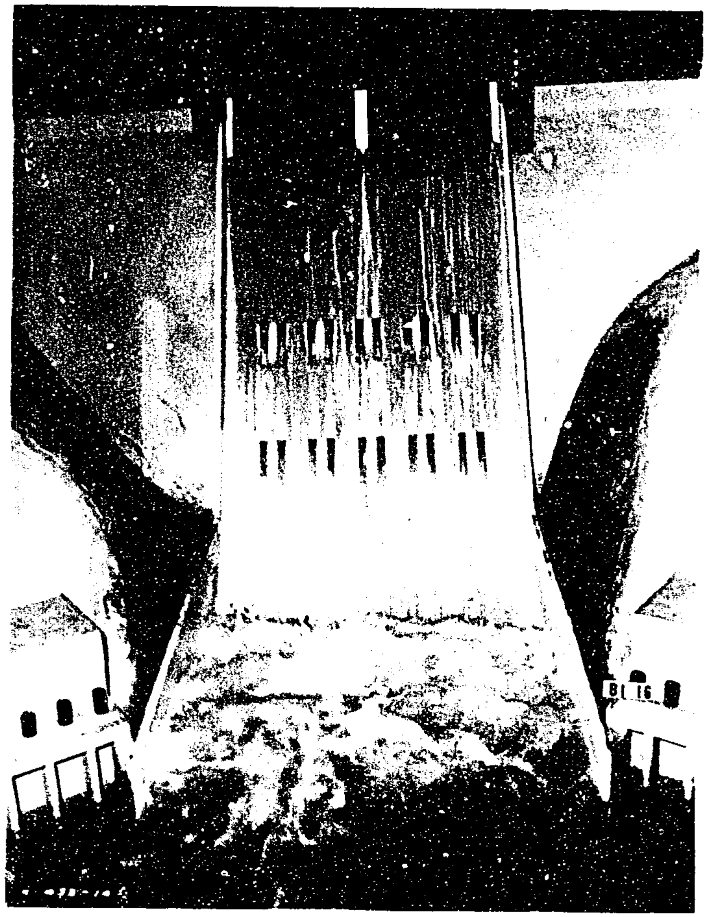
DRUM GATE SPILLWAY WITH ORIGINAL APRON
DESIGN HAVING A SLOPE OF 7.5:1
BHAKRA DAM 1:80 MODEL

coordinated with tailwater elevations such that the location of the front of the jump would remain the same for all discharges. From these calculations the length of the apron for maximum flow was 317 feet, but due to foundation conditions the apron was shortened 26 feet.

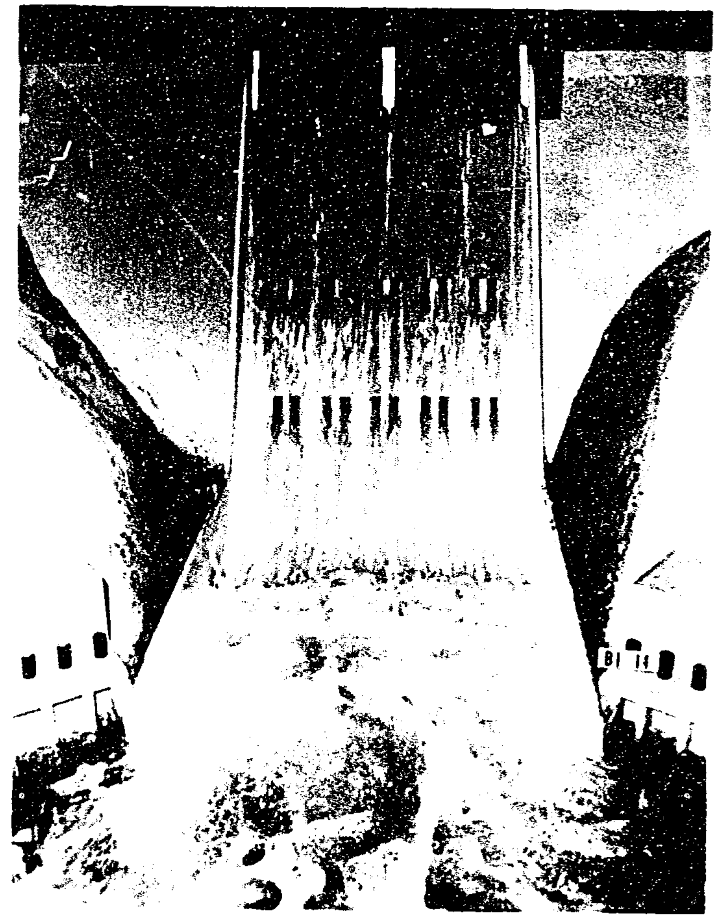
In the initial tests of the stilling-pool, discharges over the apron were varied from 0.39 to 3.31 second-feet, model, corresponding to discharges in the prototype from 22,000 to 189,600 second-feet. These flows were obtained by operating the spillway and river outlets singly and in combination. Tailwater elevations were set to correspond to that which would exist in the prototype for the given discharge according to the tailwater curve in Figure 3. It was observed that for all discharges the location of the jump was too far downstream, thus only a portion of the apron was being utilized as can be seen in the photographs in Figures 10 and 11. Moreover, as the discharge increased, the location of the jump continued to move downstream. This movement of the jump with change in discharge indicated an incorrect apron slope, while the position of the jump, too far downstream at all discharges, showed the apron was too high. This indicated that too little energy was being dissipated over the apron section. The high velocity of the discharge downstream from the apron caused scouring of the river channel.

With the drum-gate spillway only operating, the flow was uniform and of low velocity as illustrated in Figure 10A, while the transverse velocity distribution was uniform across the apron. With maximum flow through the outlets, the velocity on the apron near the training walls was low as expected, as the nearest outlets are some distance from the walls. When both outlets and spillway were operating as shown in Figure 10B, the velocities were highest at the training walls. This concentration of flow at the sides of the apron was a direct result of the transverse distribution of flow on the spillway at the lower set of outlets. At this point the water surface was unstable because of less depth at the training walls. Velocities were higher here since the velocity of the river outlets in the central section were lower than that

FIGURE 10



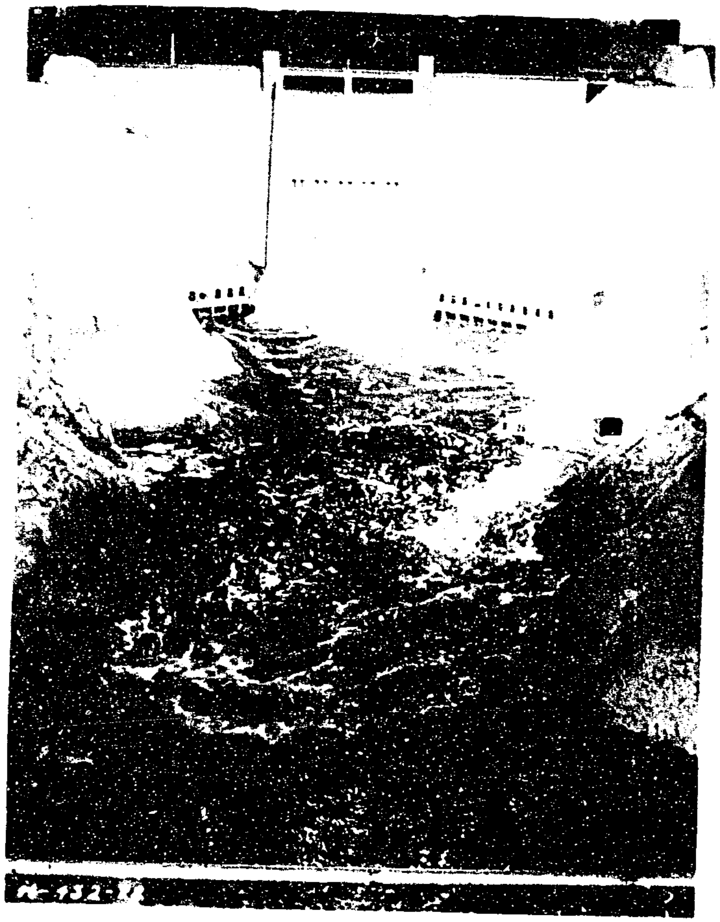
A. Discharge of 93,600 second-feet; drum gate spillway operating.



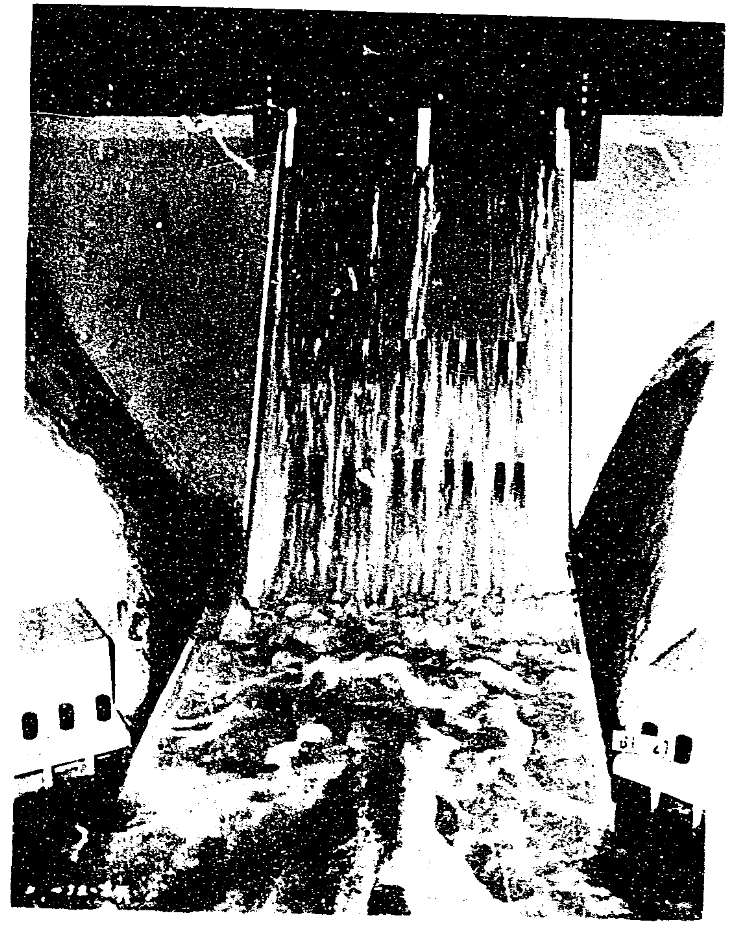
B. Discharge of 189,600 second-feet; drum gate spillway and river outlets operating.

FLOW IN STILLING BASIN ORIGINAL APRON DESIGN
BHAKRA DAM 1:80 MODEL

FIGURE 11



A. Flow in river channel.



B. Flow in stilling basin—189,600 second-feet over apron.

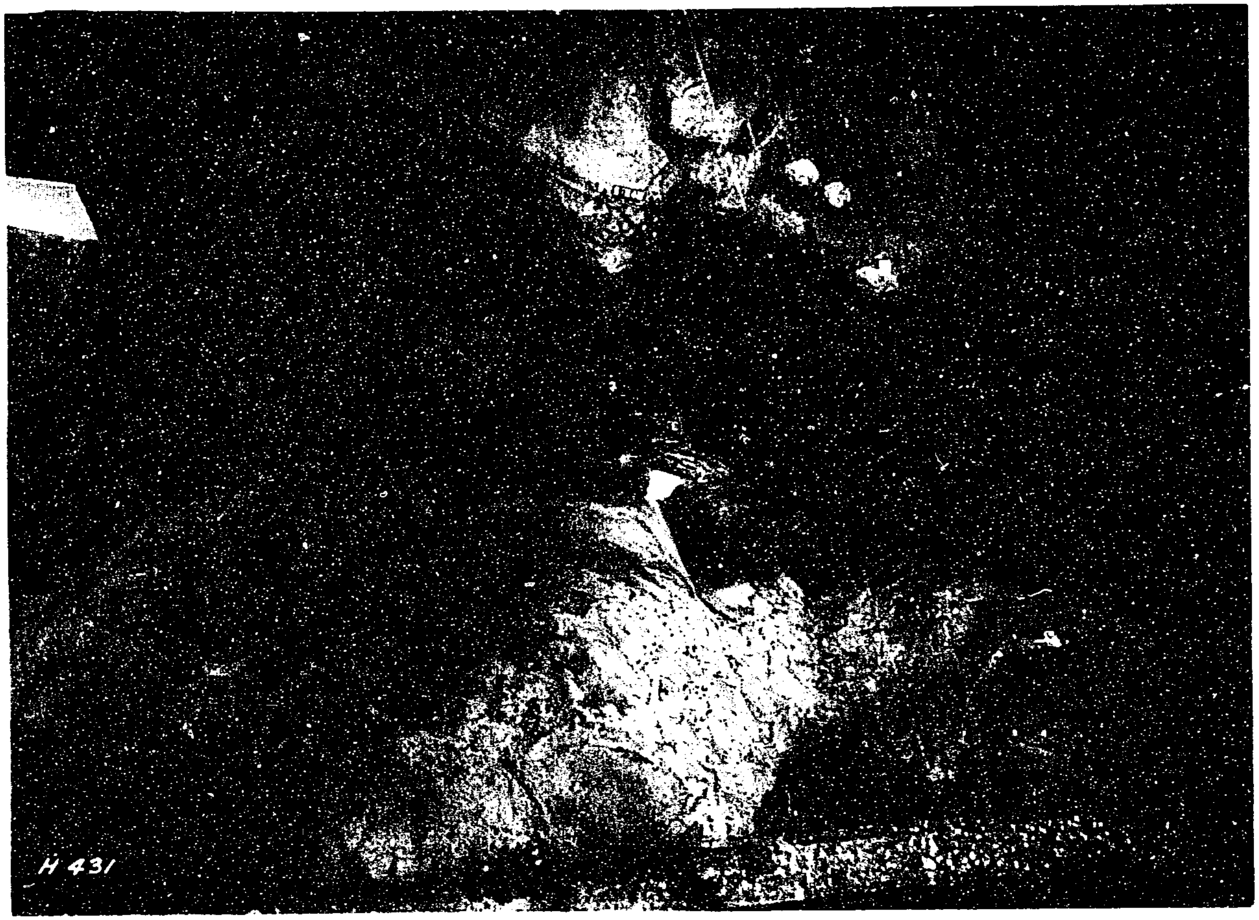
DISCHARGE 356,200 SECOND-FEET, DRUM GATE SPILLWAY, RIVER OUTLETS, AND TUNNEL SPILLWAY OPERATING, ORIGINAL APRON DESIGN, BHAKRA DAM 1:80 MODEL of the flow from the spillway. The depth became more uniform as the water flowed down the spillway due to a transverse flow toward the training walls; meanwhile no appreciable decrease occurred in the velocity at the sides of the spillway. Hence, upon reaching the apron, the depth of water was uniform with higher velocities at the training walls.

Figures 11A and B show the drum-gate spillway and river outlets operating in combination with the tunnel spillway. The effect of the additional flow through the tunnel spillway was to increase the tailwater slightly, but little change was noted in the stilling action.

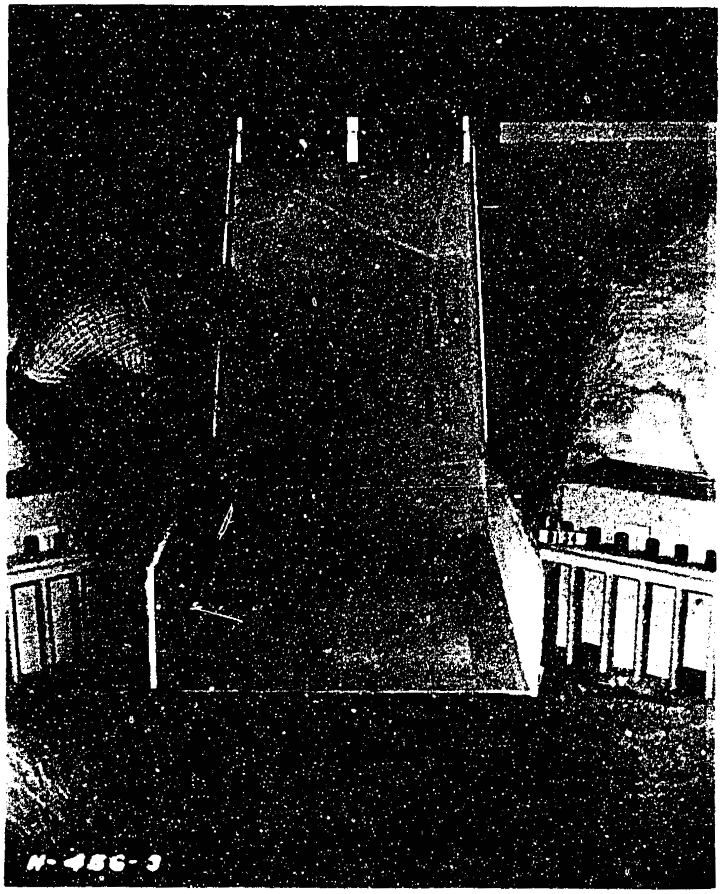
After operating all outlets and spillways at maximum discharge for 2 hours, the photograph in Figure 12 was taken showing resulting erosion of the riverbed. Scour can be seen directly below the apron with a bar formed downstream from this point. The greater scour at the edges of the spillway is evidence of the higher velocity at the training walls.

By increasing the tailwater 0.150 feet in the model corresponding to lowering the apron 12 feet in the prototype the front of the jump remained in the bucket upstream from the apron for all discharges. From these studies a revision of the apron was made to improve the stilling action. In this design, Figure 8B, an apron slope of 10:1 was used with the lower end at elevation 1112.20 in the prototype. This meant that the apron was lowered at this point by 0.105 feet in the model, or 8.40 feet in the prototype instead of 12 feet as required with the 7.5:1 apron. This design is illustrated by the photograph in Figure 13.

Studies were next made of the stilling action on this apron at the various flows as in the original design. With normal tailwater elevation for the several discharges, the jump formed in the proper location on the apron. Under the different flow combinations, the transverse velocity distribution was the same as in the original design, being higher at the training walls for both outlets and spillway operating, and lower at the walls with only the outlets operating. The photographs in Figures 14 and 15 show the operation of the stilling-basin for the various flows on the revised apron.

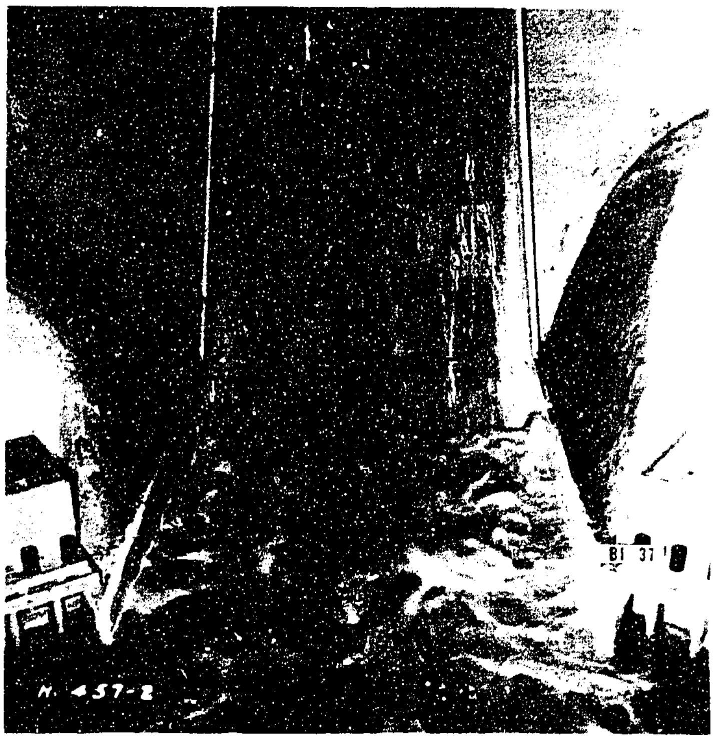


SCOUR IN RIVER CHANNEL AFTER TWO HOURS OPERATION AT 356,200 SECOND-FEET—ORIGINAL DESIGN WITH NO DEFLECTORS ON EITHER TUNNEL OUTLET—BHAKRA DAM 1:80 MODEL.



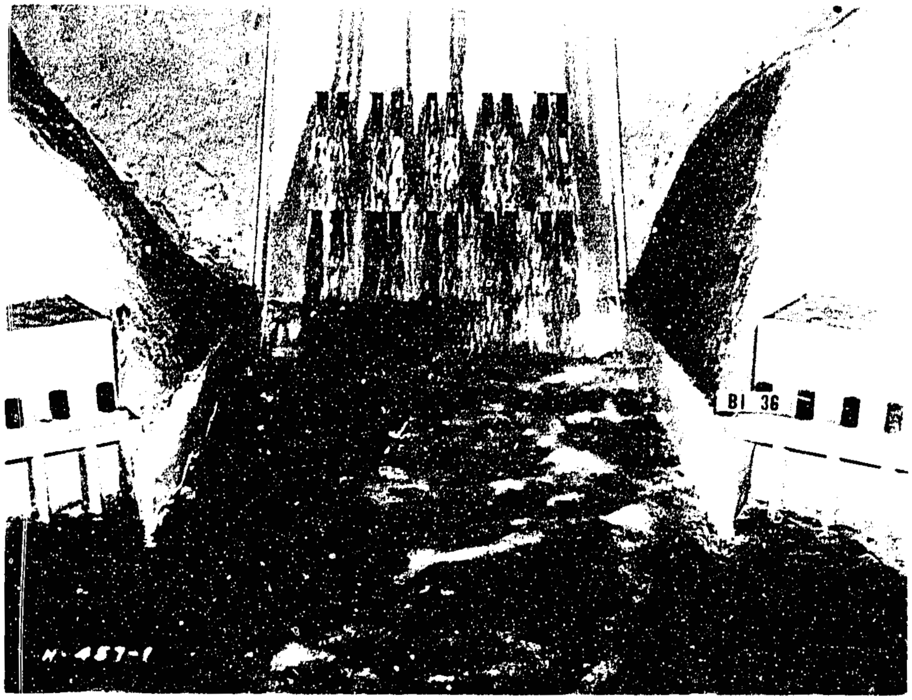
DRUM GATE SPILLWAY WITH FINAL APRON DESIGN
HAVING A SLOPE OF 10:1—BHAKRA DAM 1:80 MODEL

A. Flow over apron 93,600 second-feet; drum gate spillway and penstocks operating.

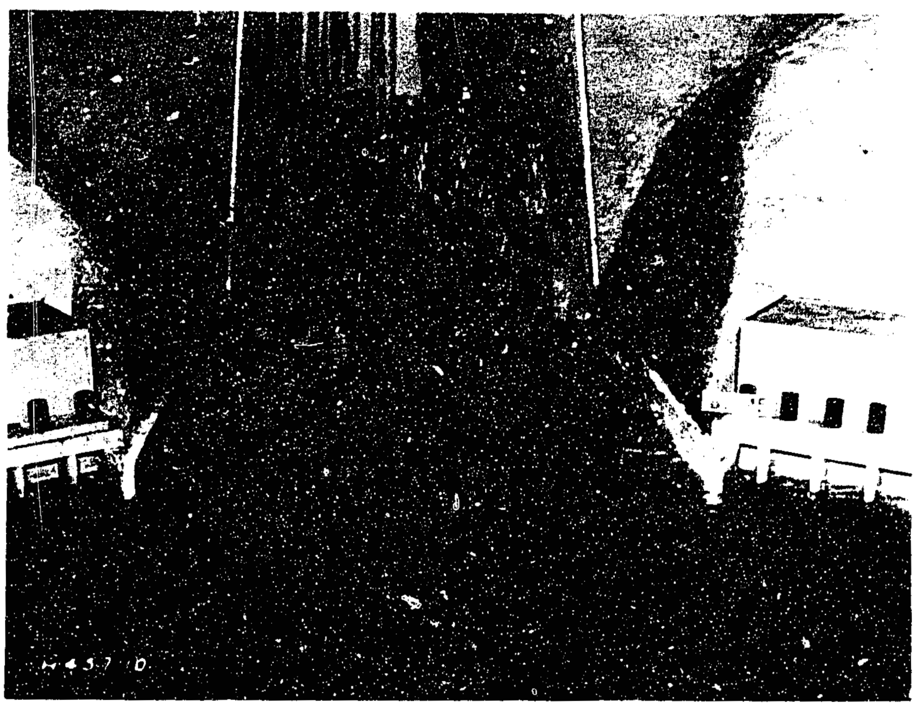


B. Flow over apron 189,600 second-feet; drum gate spillway, river outlets, penstocks, and tunnel spillway operating.

FLOW IN STILLING—BASIN FINAL APRON DESIGN
BHAKRA DAM 1:80 MODEL



A. Flow over apron 96,000 second-feet; river outlets and penstocks operating.

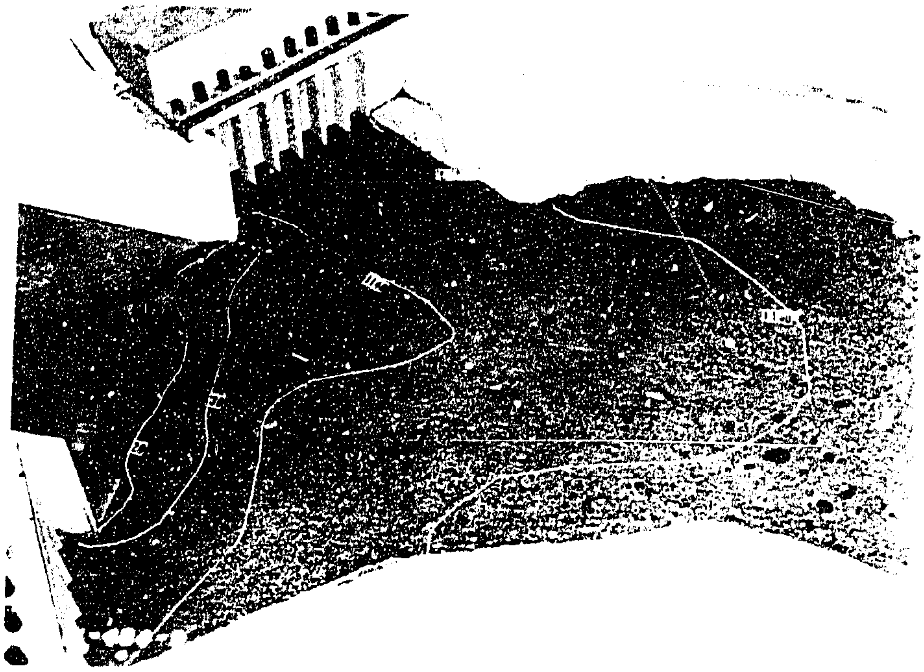


B. Flow over apron 96,000 second-feet; river outlets, penstocks, and tunnel spillway operating.

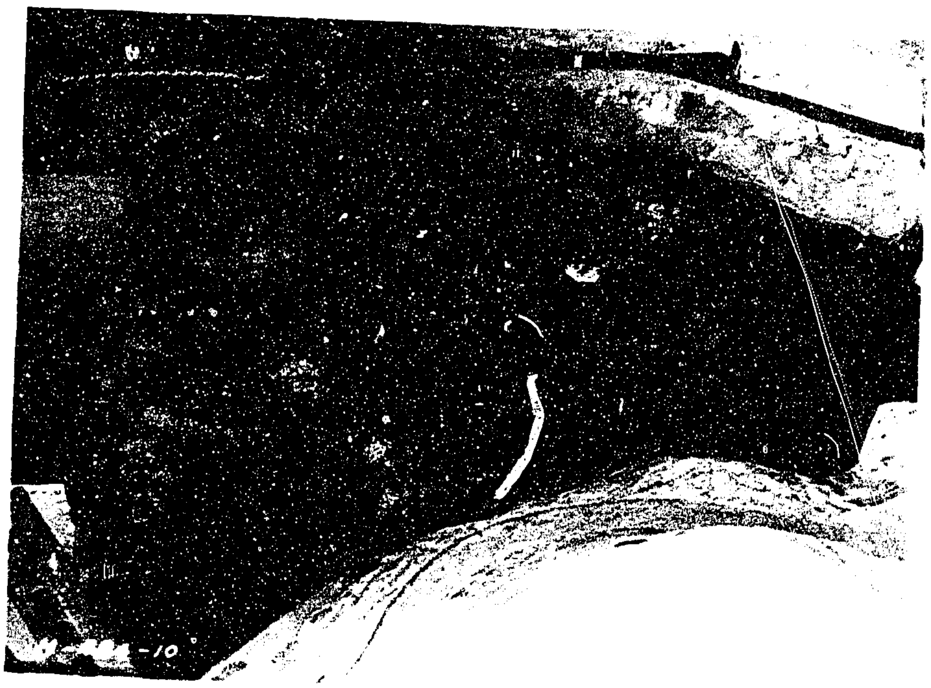
FLOW IN STILLING BASIN FINAL APRON DESIGN
BHAKRA DAM 1:80 MODEL

The drum-gate spillway was operated at maximum discharge for a period of 2 hours and the photograph in Figure 16A shows the resulting scour in the riverbed. Some scour occurred at the end of the apron resulting in a bar farther downstream. This scour pattern was considered quite satisfactory. A second scour test was made with both the drum-gate spillway and outlets operating at maximum discharge for 2 hours. More extensive scour occurred downstream from the apron as shown in Figure 16B than in the previous test. In the latter the eroded material was deposited downstream forming a bar with a maximum elevation 50 feet higher than the top of the sill. The deepest scour existed downstream from the training walls indicating high velocities at the sides of the apron. Inasmuch as a longer run might reduce the bar by carrying away some of the material, the test was repeated with operation continuing for 8 hours. The resulting scour, Figure 17A, was practically unchanged from that of the 2-hour run. A fourth scour test was made with the drum-gate spillway and river outlets operating in combination with the tunnel spillway, all at maximum discharge. The scour downstream from the apron, Figure 17B, showed little change from the previous runs with the drum-gate spillway and outlets operating. The additional rise in tailwater did not decrease the scour or the height of the bar immediately downstream from the drum-gate spillway. Figure 18A shows the scour downstream from the tunnel spillway deflector after this test.

These erosion studies represented the original plan for operating the tunnel spillway which was to be operated only after maximum flow had been reached through the river outlets and over the drum-gate spillway. Since satisfactory scour resulted with operation of the drum-gate spillway alone, a fifth test was made with both spillways operating at maximum capacity to determine the scour downstream from the tunnel spillway deflector. The results, Figure 18B, which is of the final tunnel spillway deflector, showed an increase in erosion over the fourth run due to the lower tailwater since the outlets were not operating. Some improvement was indicated in the overall riverbed scour from that



A. Drum gate spillway operated; discharge 93,600 second-feet.



B. Drum gate spillway and river outlets operated; total discharge 189,600 second-feet.

SCOUR DOWNSTREAM FROM APRON AFTER TWO HOURS OPERATION
FINAL DESIGN, BHAKRA DAM 1:80 MODEL

FIGURE 17

A. Eight hours operation- drum gate spillway and river outlets operated; total discharge 189,600 second-feet.

B. Two hours operation- drum gate spillway, river outlets and tunnel spillway operated; total discharge 356,200 second-feet.

SCOUR DOWNSTREAM FROM APRON, FINAL DESIGN
BHAKRA DAM 1:80 MODEL

A. Drum gate spillway, river outlets, and tunnel spillway operated; total discharge 356,200 second-feet.

B. Drum gate spillway and tunnel spillway operated; total discharge 260,200 second-feet.

SCOUR DOWNSTREAM FROM LEFT DIVERSION TUNNEL AFTER TWO HOURS OPERATION, FINAL DEFLECTOR DESIGN
BHAKRA DAM 1:80 MODEL

obtained by following the original plan for operation of the spillways. Because of the uncertainty in model prototype comparison of scour, the final method of operation of the spillways should be determined in the prototype.

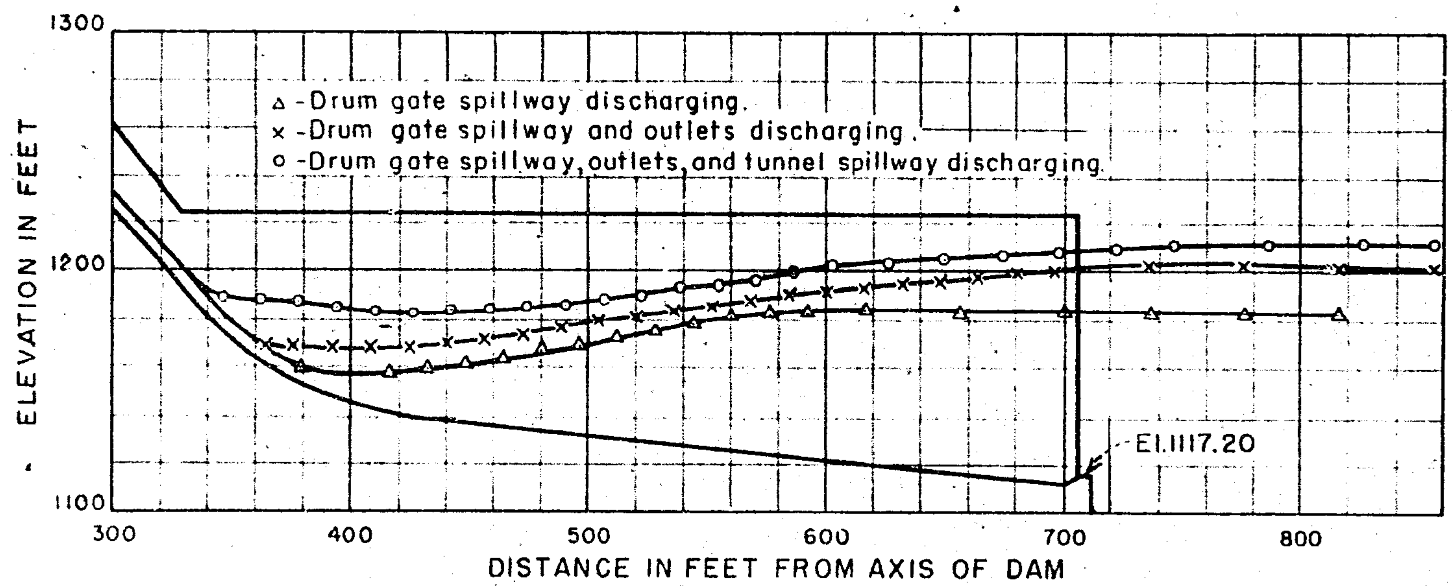
From these studies the apron with a slope of 10:1 was selected as the recommended design. With the limitation of apron length, it appeared that no improvement in the stilling action would result from further changes in the apron. Water surface profiles were taken in the stilling-basin, Figure 19, for 3 different conditions of flow.

Program for operation of river outlets. In the operation of the river outlets, past experience has shown the importance of maintaining as uniform flow distributions as possible in the stilling-basin. For instance, if only a pair of outlets were discharging at the side of the spillway an eddy would form in the stilling-pool. The upstream flow of this eddy would carry riverbed material of various sizes including boulders onto the apron. The resulting abrasive action of this material on the concrete apron would eventually result in serious damage to the apron. If only one or two outlets at the center of the spillway were operating an eddy would form on each side of the spillway resulting in similar abrasive action and consequent damage.

To obtain symmetrical operation of the stilling-pool, it is recommended that the outlets be operated symmetrically for all conditions of discharge.

No attempt is made to give a detailed operational procedure for all conditions of flow, but to indicate the general procedure to secure uniform flow distribution in the stilling-pool.

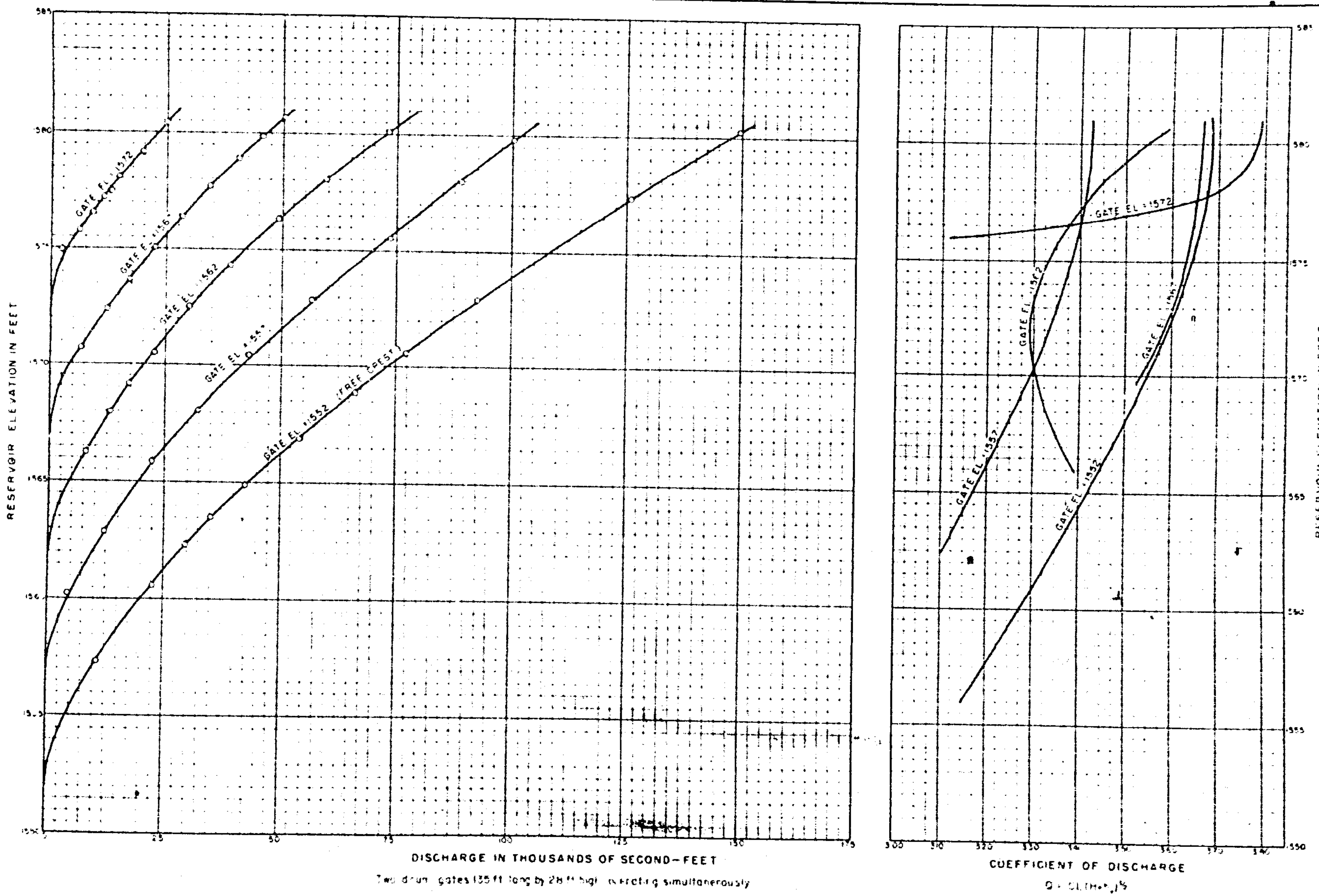
Head discharge relationships. Head discharge and discharge coefficient curves for free crest and gate settings at 5-foot intervals are shown plotted on Figure 20 for the drum-gate spillway. In each case the coefficient of discharge is referred to the highest point on the gate. Entrance flow to the drum-gate spillway crest was uniform under all operating conditions and no problem was encountered with this portion of the spillway or with the drum gates.



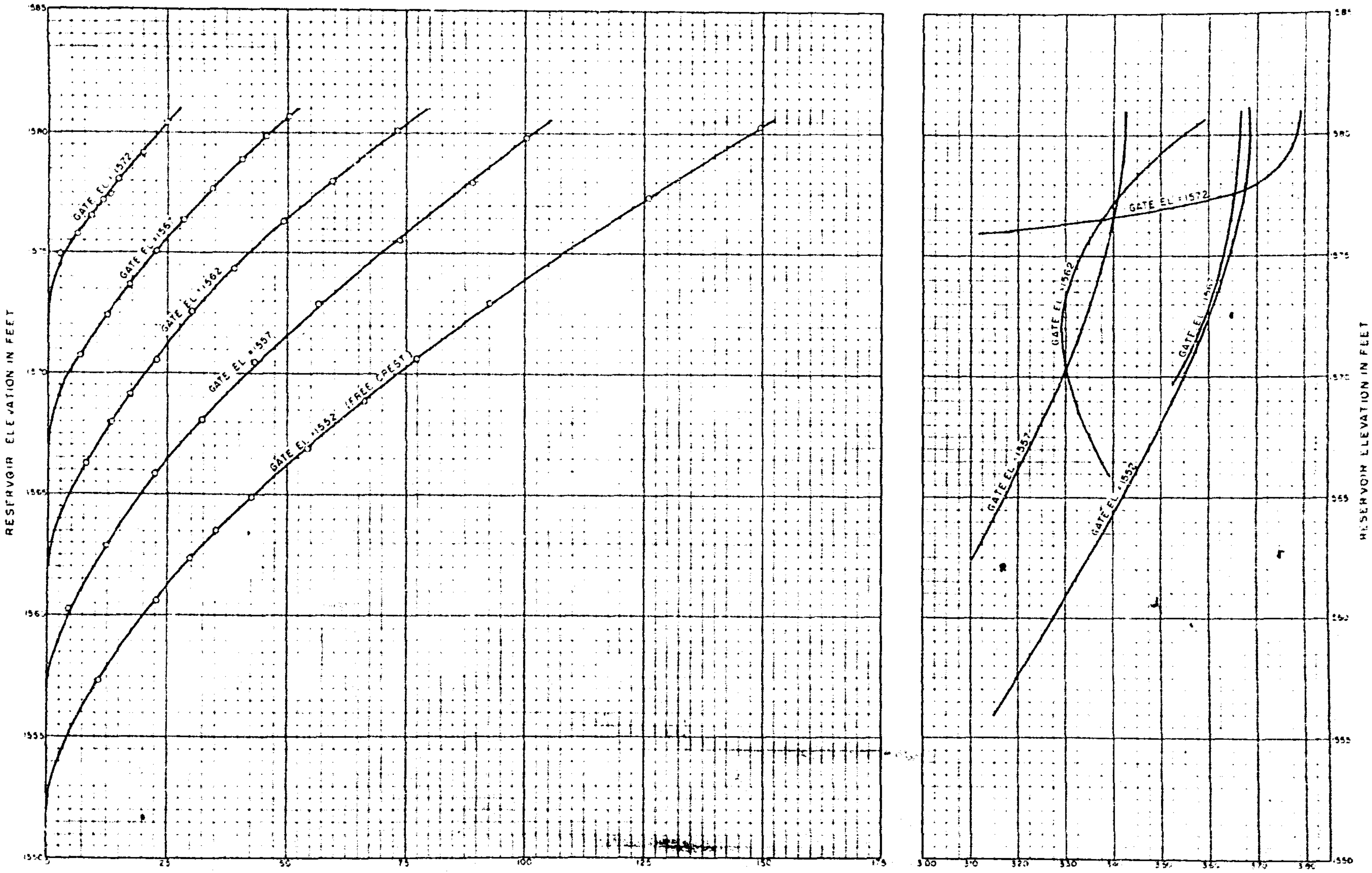
BHAKRA DAM

STILLING BASIN MAXIMUM DISCHARGE PROFILES

FIGURE 19



BHAKRA DAM
DRUM GATE SPILLWAY DISCHARGE CAPACITY



Two drum gates 135 ft long by 28 ft high operating simultaneously

BHAKRA DAM
DRUM GATE SPILLWAY DISCHARGE CAPACITY

FIGURE 20

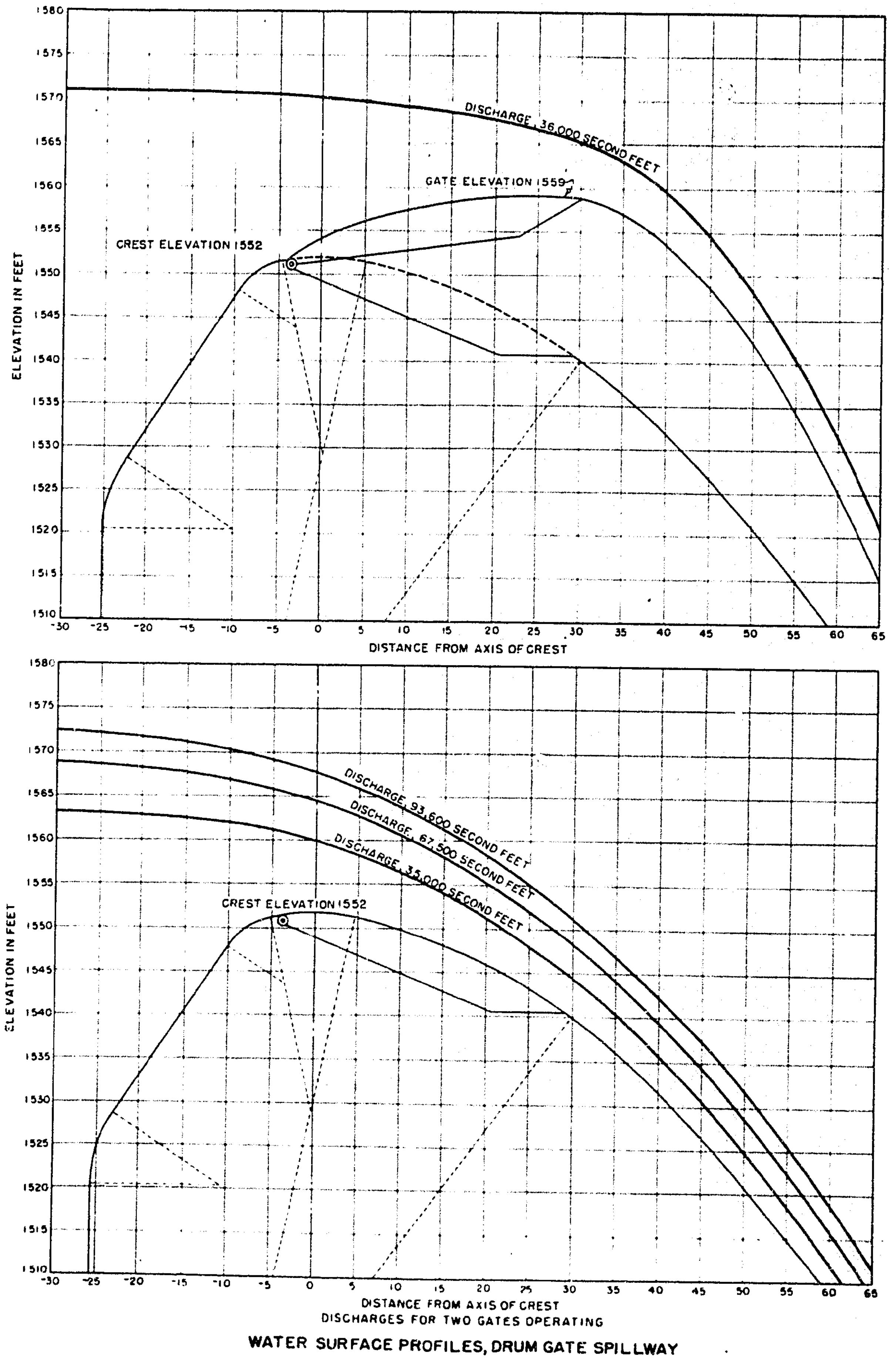
As in the case of the river outlets the drum-gate spillway should be operated to maintain uniform flow distribution in the stilling-basin at all discharges. To attain this condition it is only necessary to have equal flow over each gate. Thus the gate settings should be the same at all times.

Water surface profiles at various gate openings are shown in Figure 21. These curves were obtained from past studies on this crest design.

River Outlets

Eyebrow deflectors. The 20 outlets through the dam in the drum-gate spillway section are arranged in 2 tiers of 5 pairs each, Figures 2 and 3. Each pair in the lower tier is directly below a pair of outlets in the upper tier. The design of these outlets was determined by studies on a 1:17 model of one of the outlets as discussed in a later section. The final trough length was made 46.87 feet instead of 59.28 feet as in the original design. Eyebrow deflectors consisting of raised sections on the face of the spillway were placed immediately above the outlet troughs. The purpose of the eyebrows was to lift the sheet of water flowing over the spillway so that it would not impinge on the outlet troughs. Two factors influenced the design of the eyebrows: the length of the outlet trough, and the velocity of the water over the deflector. Since the trough length had been fixed from the studies on the 1:17 model, the velocity of the water was the only remaining factor to be considered in this design. This velocity, however, was subject to some variation, being highest at maximum flow over the spillway crest and lowest with a small flow. The velocity would have an intermediate value with both the spillway and river outlets operating. In the case of the lower tier deflectors, it was necessary to lift the flow from the upper outlets over the lower troughs. Because of the variation in velocity, it was apparent that the resulting trajectory would not remain constant. Fortunately, the point at which the sheet would return to the spillway face could vary over a range of about 50 feet along the spillway slope,

FIGURE 21



WATER SURFACE PROFILES, DRUM GATE SPILLWAY that is, from the lower end of the upper trough to the upper end of the lower tier deflectors.

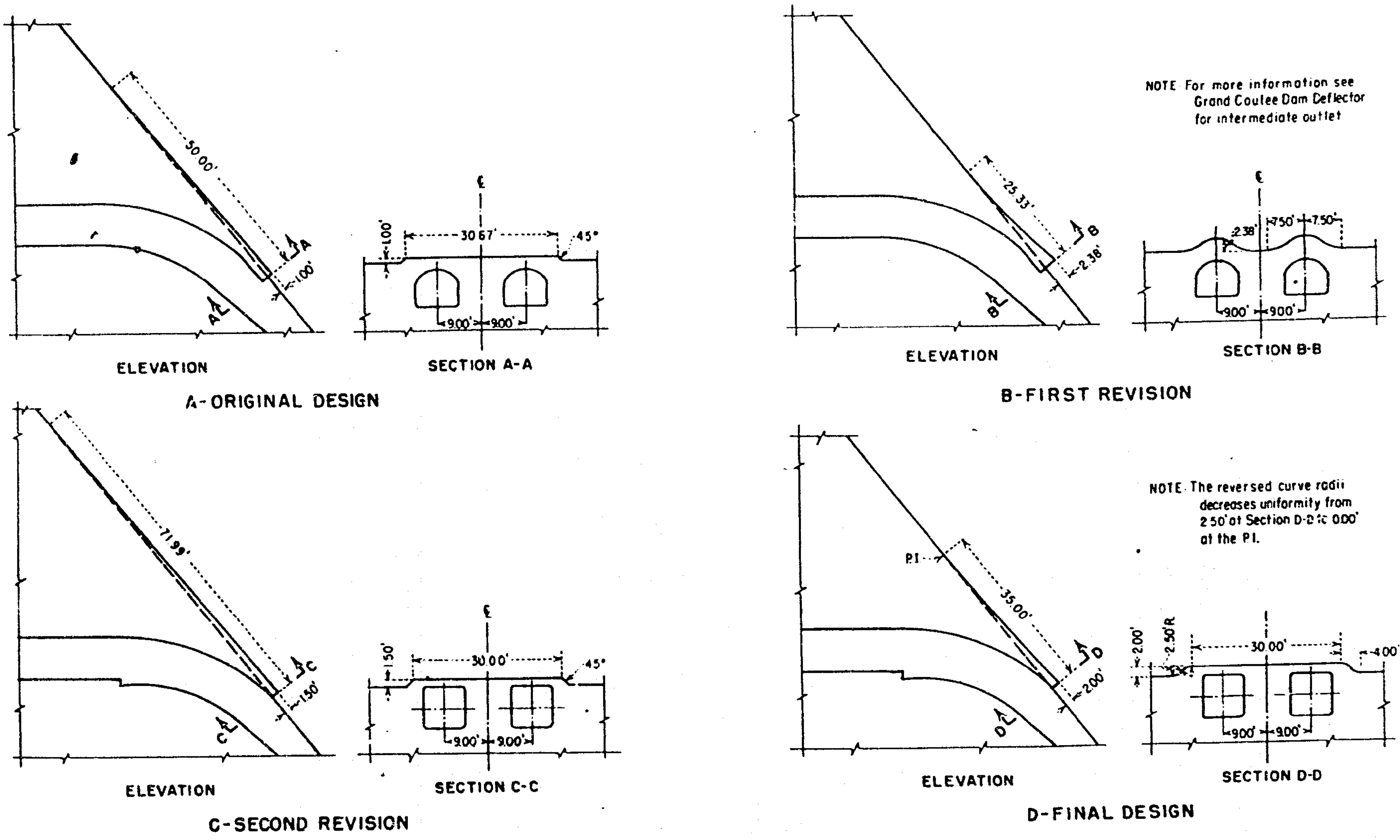
The original eyebrow design is shown in Figure 22A with a photograph of the installation in the model in Figure 23A (marked A). In the operation of this design the deflectors did not lift the sheet free of the troughs at the lower flows. The rise of 1 foot at the lower end of the deflector was insufficient. The operation of this eyebrow is illustrated at various flow conditions by the photographs in Figures 23B and 24 (marked A).

The first revision is shown in Figure 22B and marked B in Figure 23A. This design was used on the intermediate outlets of Grand Coulee Dam and consists of an individual eyebrow for each outlet instead of one deflector for each pair of outlets as in the previous design. Figures 23B and 24, show this deflector, marked B, in operation. At the higher flows the sheet from the upper tier was lifted to such an extent that it returned to the spillway striking the lower outlet troughs. In addition, the width of the deflector was insufficient, the troughs in this installation being wider than those on Grand Coulee Dam.

The eyebrow in Figure 22C having a rise of 1.50 feet was the second revision. The lift of the sheet with this design was insufficient at the lower flows. No photographs were taken of this design.

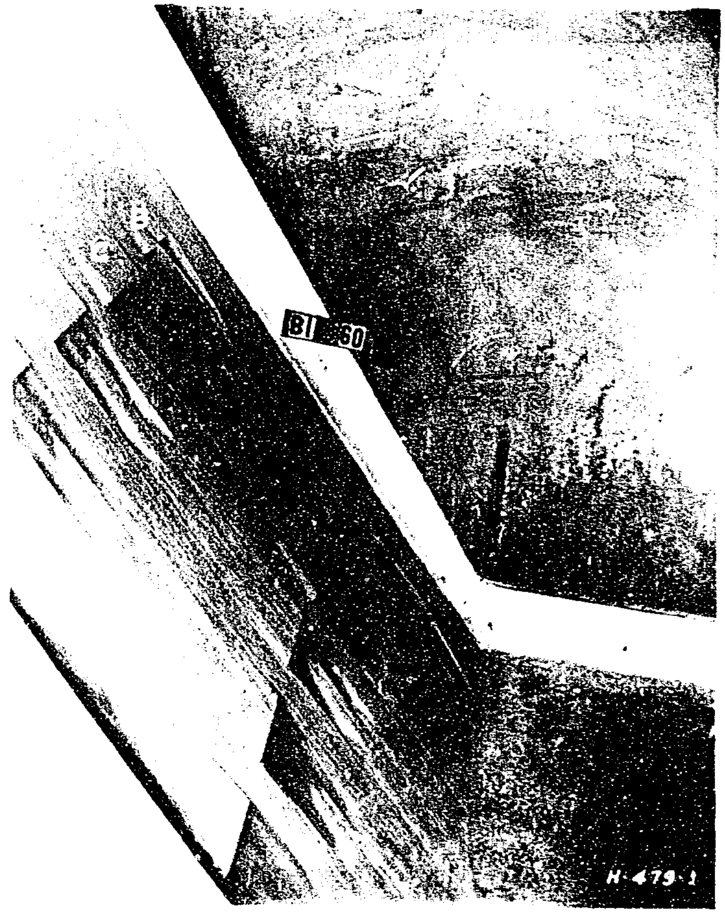
The design of the fourth deflector investigated, Figure 22D, had a rise of 2 feet at the lower end and a length of 35 feet. The width of the flat section was 30 feet and was connected to the spillway face by two 2.5-foot radii at the lower end. These radii decreased uniformly to zero at the upstream end of the eyebrow. This design is marked C in Figure 23A. The 2-foot rise was desirable structurally since it provided more strength to the top of the elbow than the previous design. This eyebrow served a pair of outlets. The operation is shown on Figures 23B and 24, marked C. At low flows the sheet of water was lifted sufficiently to clear the outlet troughs and at maximum flows it was not raised to a point that it interfered with the lower outlets. Accordingly, this design was considered satisfactory and is recommended.

FIGURE 22



BHAKRA DAM
EYEBROWS OVER RIVER OUTLETS

A. No flow—looking upstream.

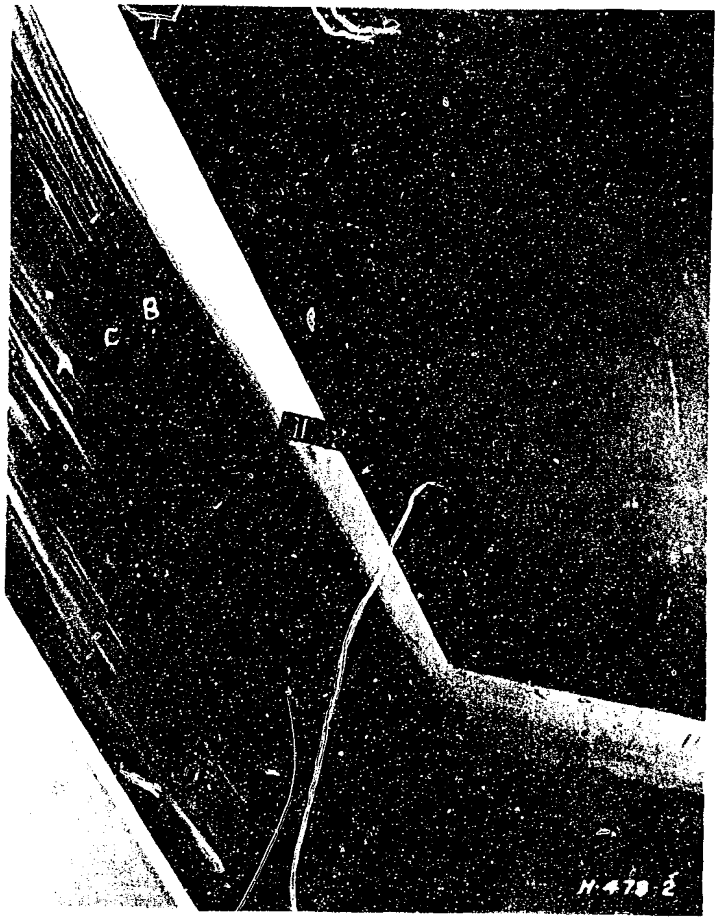


B. Discharge of 20,000 second-feet over drum gate spillway.

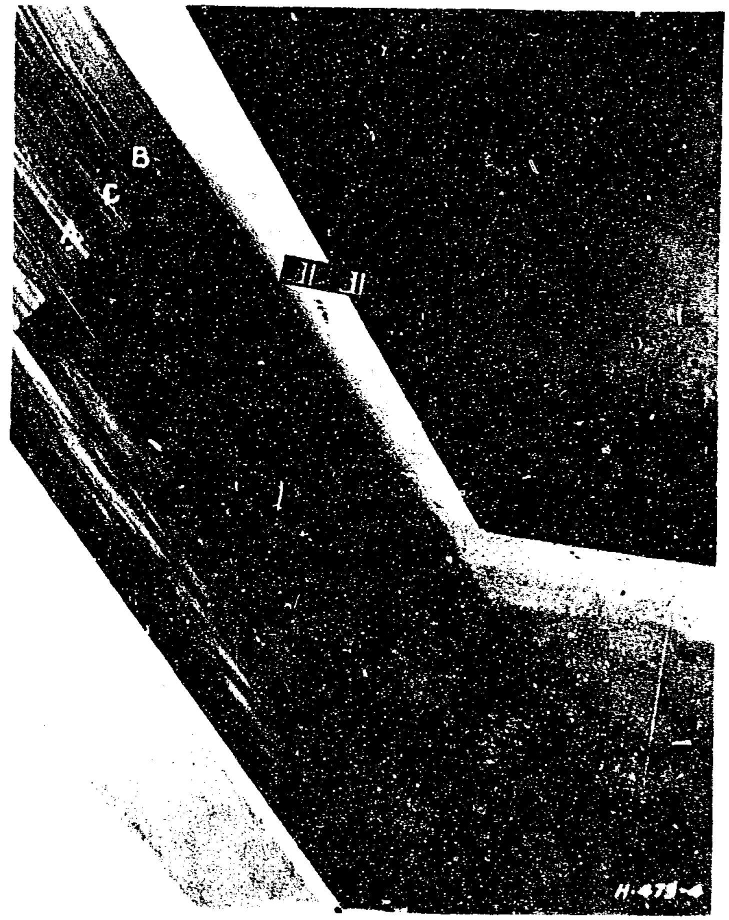
EYEBROW DEFLECTORS FOR RIVER OUTLETS
BHAKRA DAM 1:80 MODEL

FIGURE 23

FIGURE 24



A. 93,600 second-feet over drum gate spillway.



B. 93,600 second-feet over drum gate spillway and 96,000 second-feet through river outlets.

EYEBROW DEFLECTORS FOR RIVER OUTLETS
BHAKRA DAM 1:80 MODEL

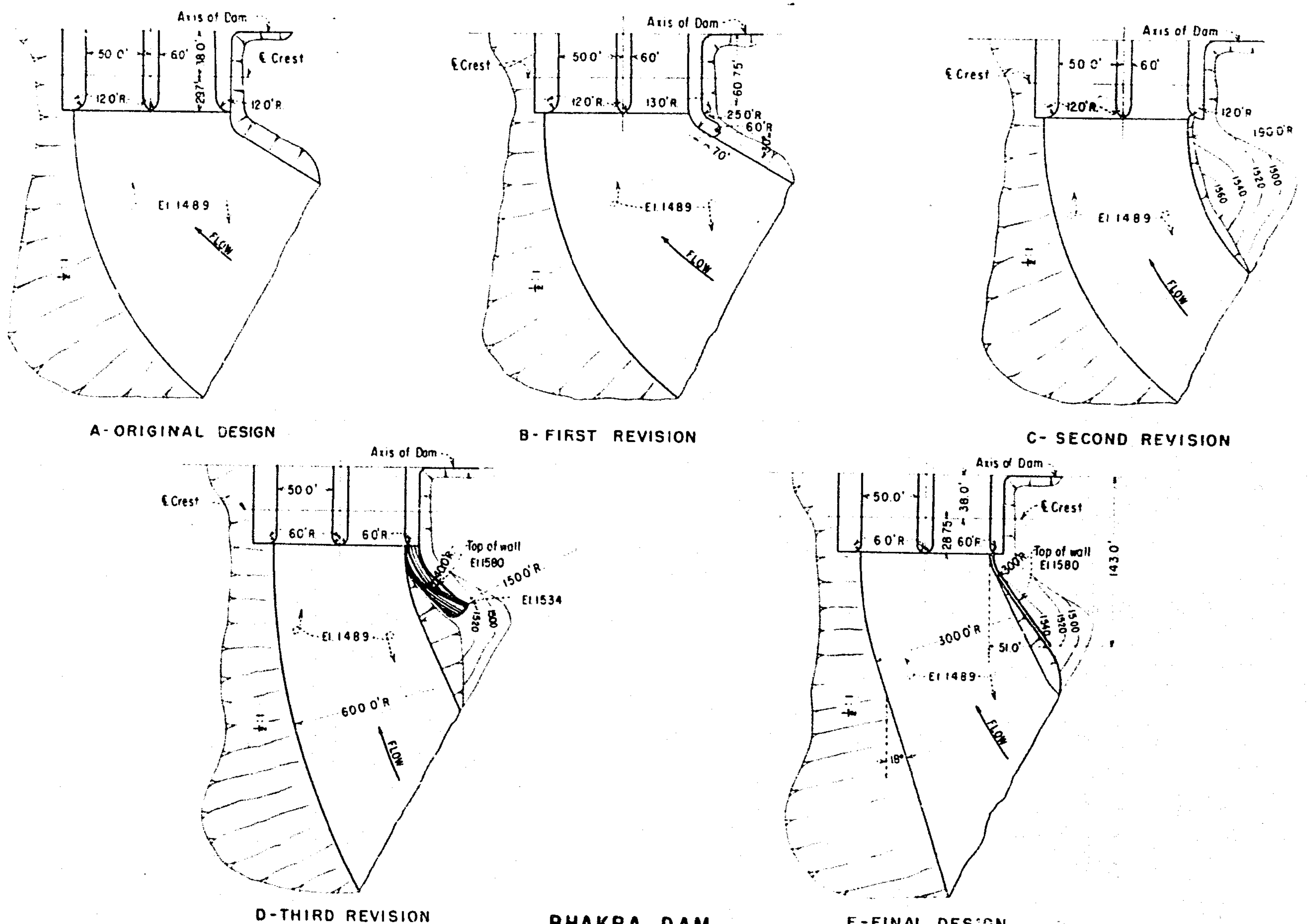
Tunnel Spillway

Entrance design. The original design of the entrance to the tunnel spillway, located in the left abutment of the dam, is shown in Figure 25A and illustrated by the photograph in Figure 26A. To provide an entrance to the spillway, a curved approach channel was excavated in the canyon wall upstream from the overflow crest, and to a depth of 21 feet below the crest. No material was left in place on the reservoir side above this floor elevation. In the initial test of the entrance design, observations of various flows were made up to a maximum of 2.91 second-feet in the model corresponding to 166,000 second-feet in the prototype. At the spillway entrance near the right pier, considerable depression of the water surface existed for all but the very low flows. This was caused by the high-velocity flow approaching from various directions and converging at the nose of the right pier. The sudden change in direction of the flow at this point resulted in an angular acceleration which created a contraction at the entrance followed by a rise in the surface downstream in the transition section due to recovery of velocity head. This condition is shown in the photograph in Figure 26B taken at maximum flow.

An extension of the right pier in the form of a curved wall as shown in Figure 25B was investigated. When the spillway was operated with this design, little change was noted in the conditions of flow. The extension did not change the magnitude of the water surface depression caused by the cross flow as can be seen in Figure 27A; however, its location was moved upstream by the length of the new wall.

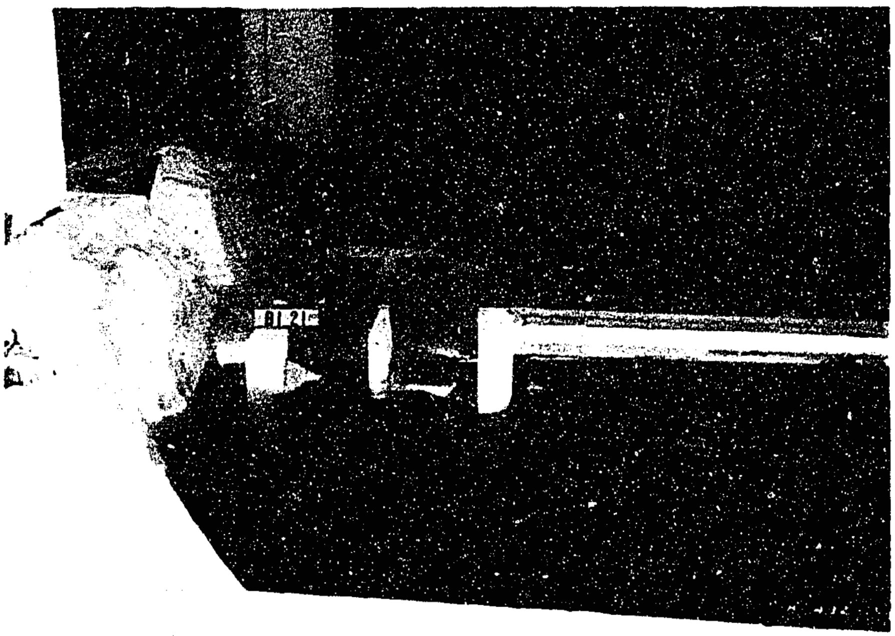
In the second revision the approach channel width was reduced thus leaving in place the rock directly upstream from the right pier to form a barrier for reducing the cross flow. This design is shown in Figure 25C and illustrated in the photograph, Figure 27B. It was foreseen that the notch formed between the rock and the pier should be filled to reduce the cross flow. The required wall would be much smaller than needed in the original design. Operation of the spillway revealed a depression of the water surface at the right pier entrance of greater magnitude than

FIGURE 25



BHAKRA DAM
TUNNEL SPILLWAY ENTRANCE

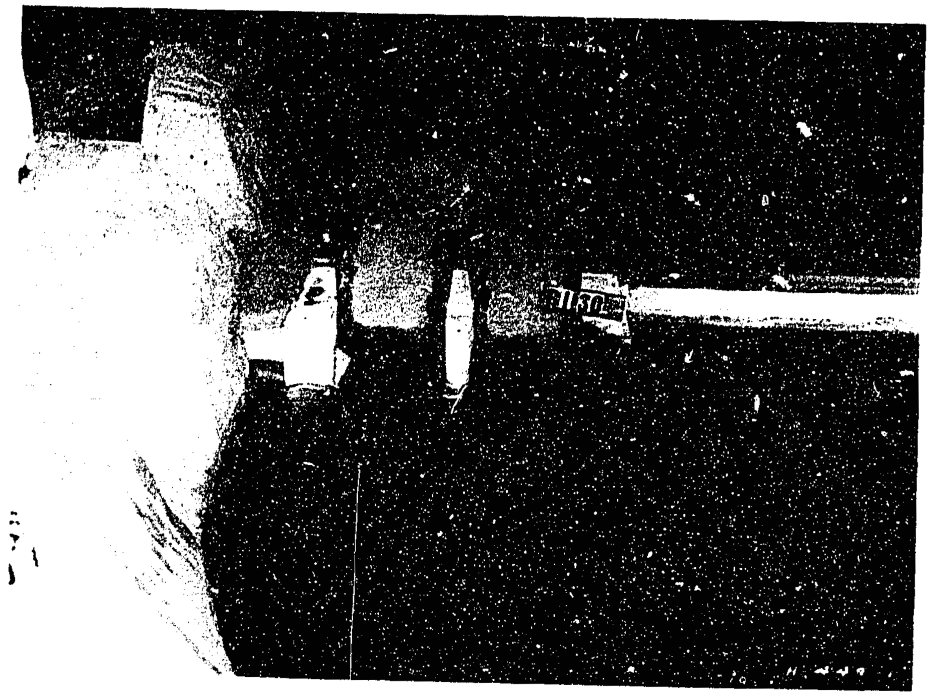
A. No flow—looking downstream.



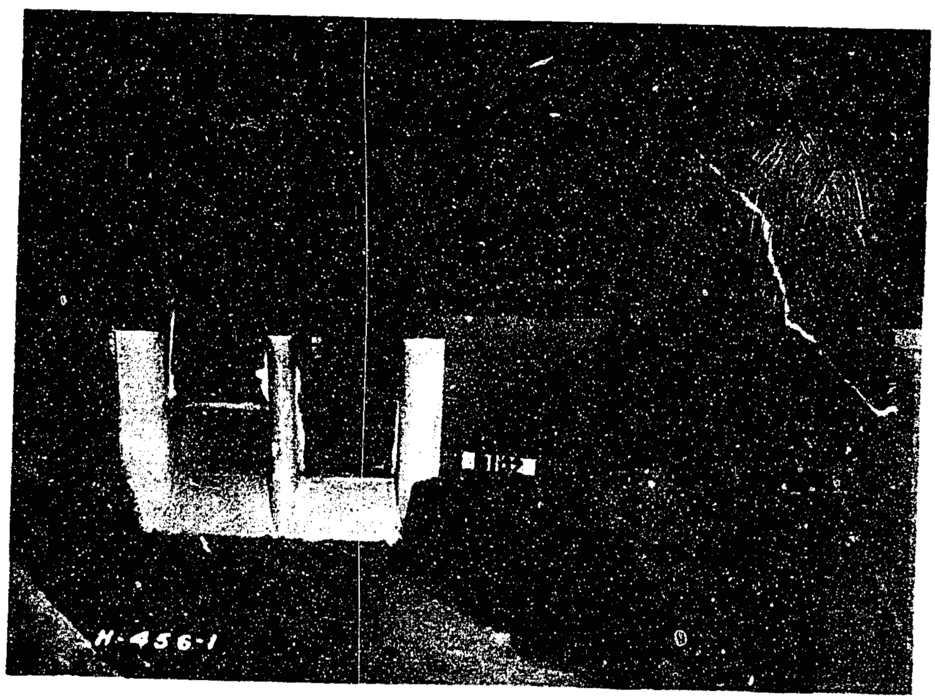
B. Discharge 166,600 second-feet.

ENTRANCE TO TUNNEL SPILLWAY, ORIGINAL DESIGN
BHAKRA DAM 1:80 MODEL

FIGURE 27



A. First revision—discharge 166,600 second feet.



B. Second revision—looking downstream.

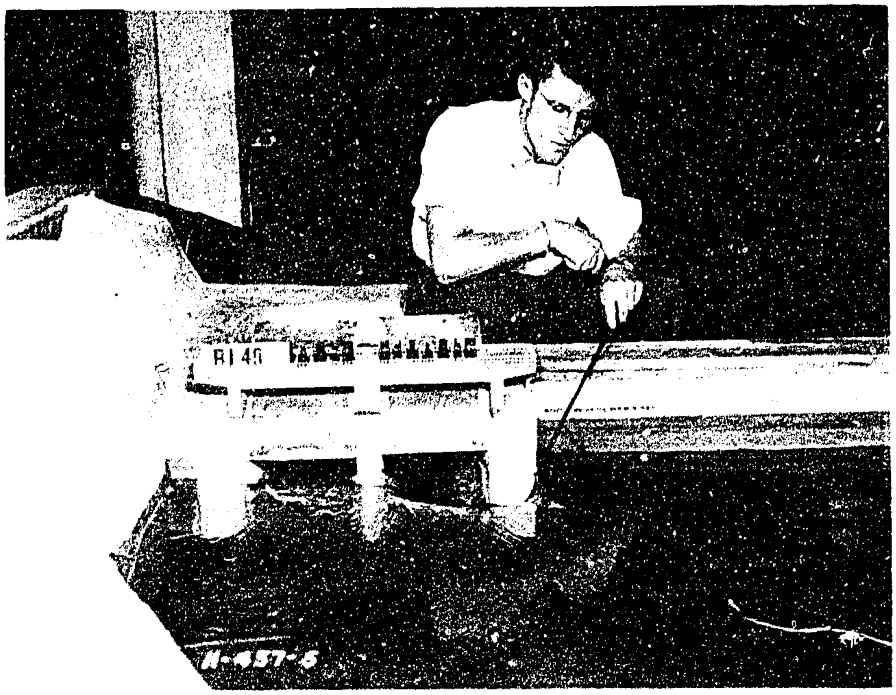
ENTRANCES TO TUNNEL SPILLWAY
BHAKRA DAM 1:80 MODEL

in all earlier designs, Figure 28A. At the left side of the entrance, the water did not follow along the curved left bank, but followed a straight course from the left upstream end of the channel to the left pier. Figure 28B shows the effect of the point at the upstream end of the channel bank. The slight surface disturbance from this point downstream indicated interference with the flow approaching the spillway entrance.

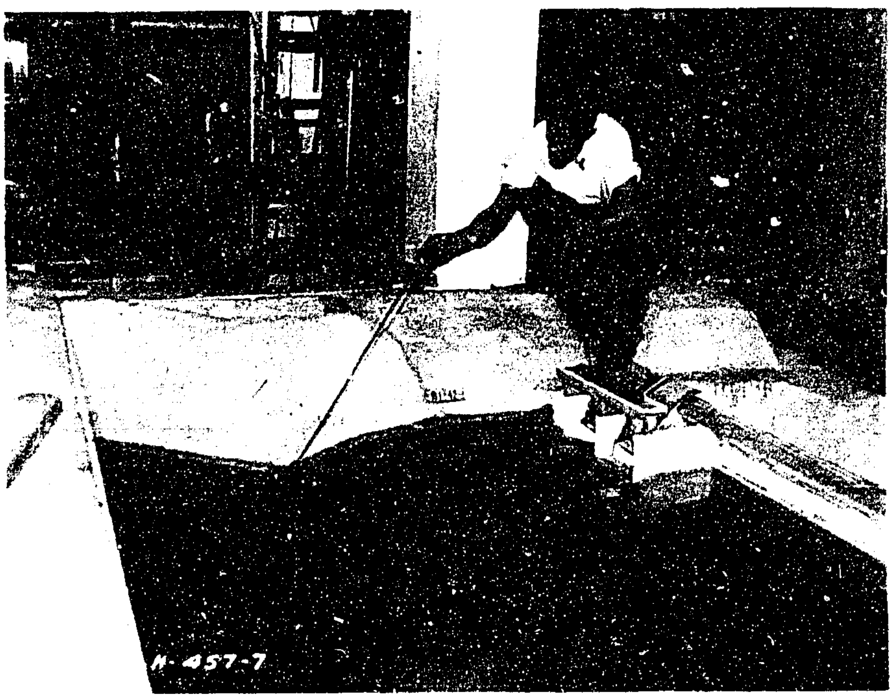
The third revision to the spillway entrance is shown in Figure 25D. The wall alinement along the left bank was changed by increasing the excavation at the upstream end, thus reducing the projection of the point. Excavation downstream in the curved portion was at the same time reduced so that the total amount of material to be moved was not changed appreciably. The excavation upstream from the right pier was also further reduced by making a narrower entrance to the channel. A concrete wall with the top at elevation 1580 started at the right pier and continued upstream for 30 feet, then the top of the wall decreased uniformly to elevation 1560 at a distance of 75 feet upstream from the pier. Figure 29A illustrates this new approach channel. With maximum discharge, flow conditions along the left bank were improved as expected, but the flow did not follow the center portion of the curved wall. The contraction still existed at the upstream end of the new wall at the right pier, but to a much smaller degree than in any of the previous designs. This wall was curved near the upstream edge of the pier with the remainder straight, making a large angle to the direction of entrance flow, with the result that the impact of the water against this wall raised the water surface and created a large vortex, Figure 29B.

Because of the undesirable flow conditions in the above design, a fourth revision was made to the entrance. At the left bank the curvature of the wall was further reduced. Upstream from the right pier the alinement of the wall was changed by shortening the curve and directing the straight portion upstream at a smaller angle to the direction of flow. Excavation of the rock near this wall was increased, giving a wider entrance to the channel but resulting in less rock on which to rest the wall as shown in Figure 25E. This new entrance is illustrated by the photograph in Figure 30A. In Figures 30B and 31 views are shown of flow

FIGURE 28



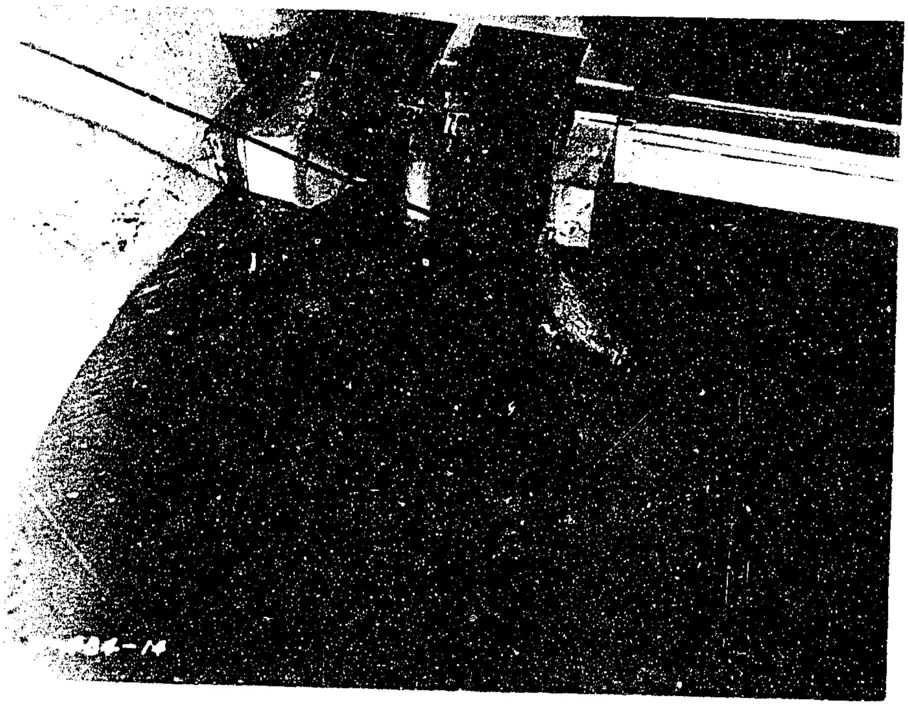
A. Depressed water surface at right pier.



B. Interference to flow of point on left bank.

ENTRANCE TO TUNNEL SPILLWAY—SECOND REVISION
DISCHARGE 166,600 SECOND-FEET
BHAKRA DAM 1:80 MODEL

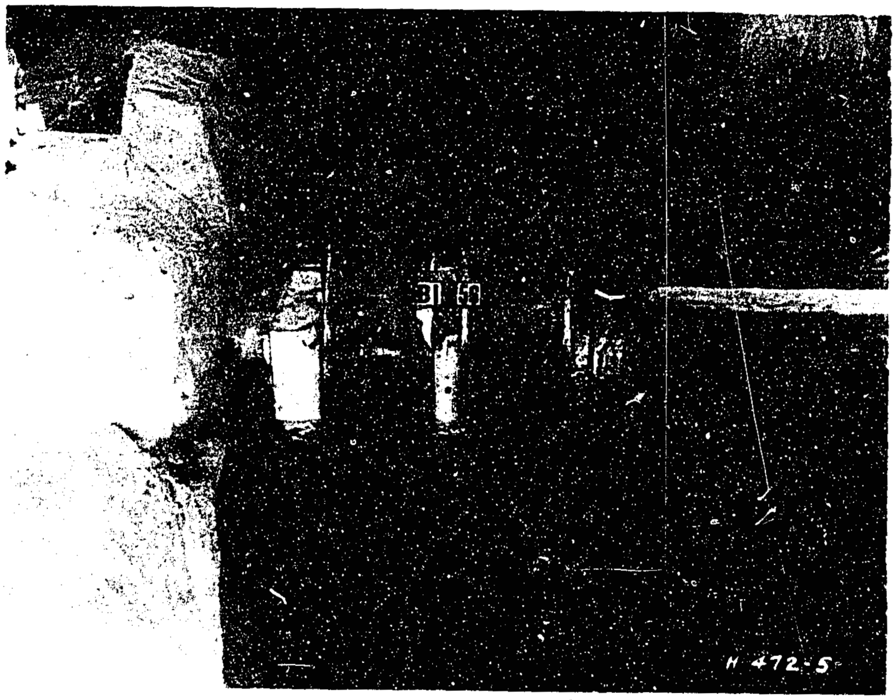
A. No flow—looking downstream.



B. Discharge 166,600 second-feet.

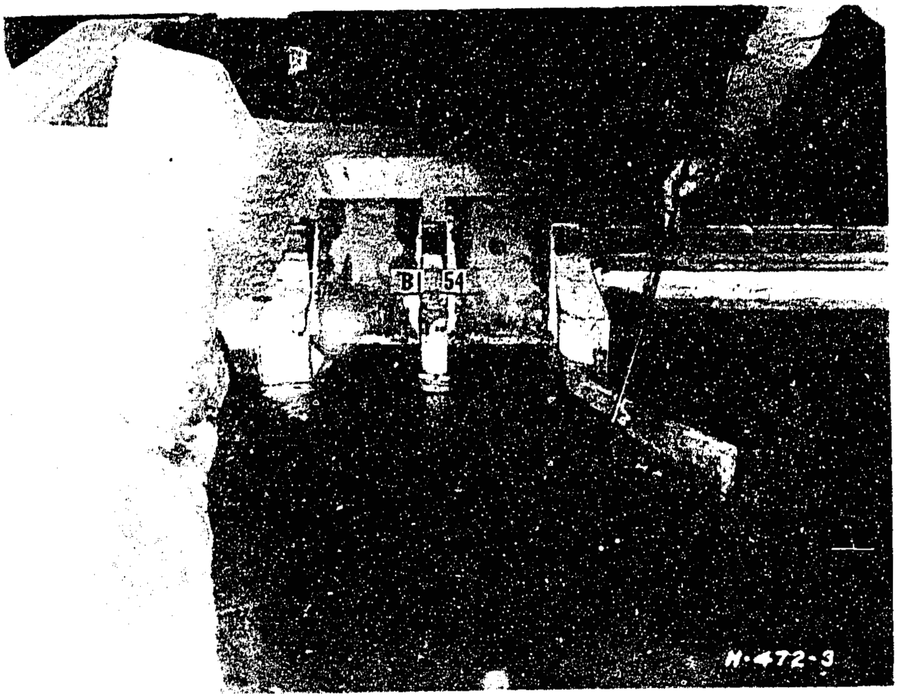
ENTRANCE TO TUNNEL SPILLWAY—THIRD REVISION
BHAKRA DAM 1:80 MODEL

A. No flow—looking downstream.

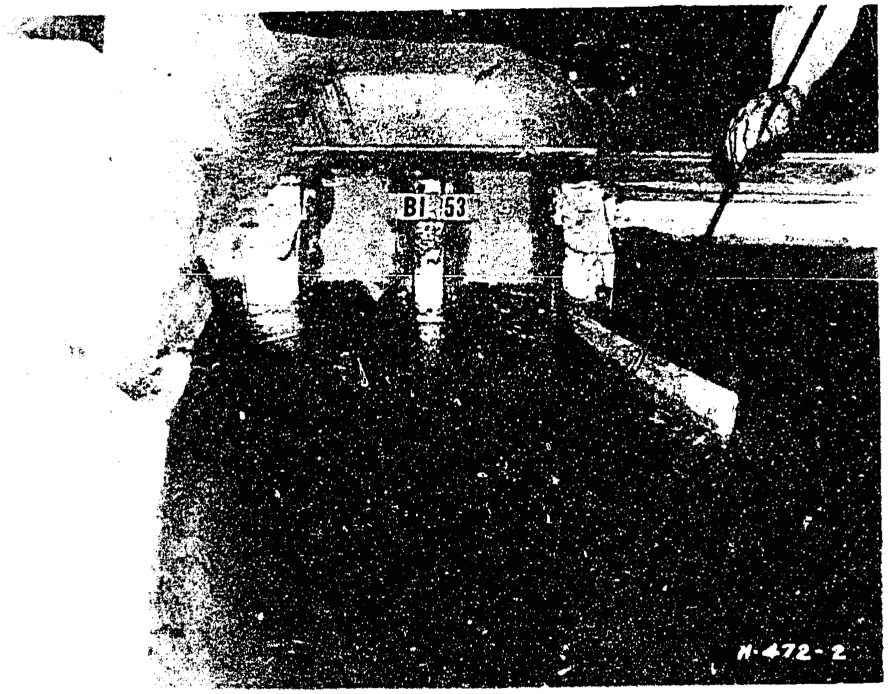


B. Discharge 100,000 second-feet.

ENTRANCE TO AUXILIARY SPILLWAY, FINAL DESIGN
BHAKRA DAM 1:80 MODEL



A. Discharge 166,600 second-feet.



B. Discharge 138,000 second-feet. Gates at elevation 1550.

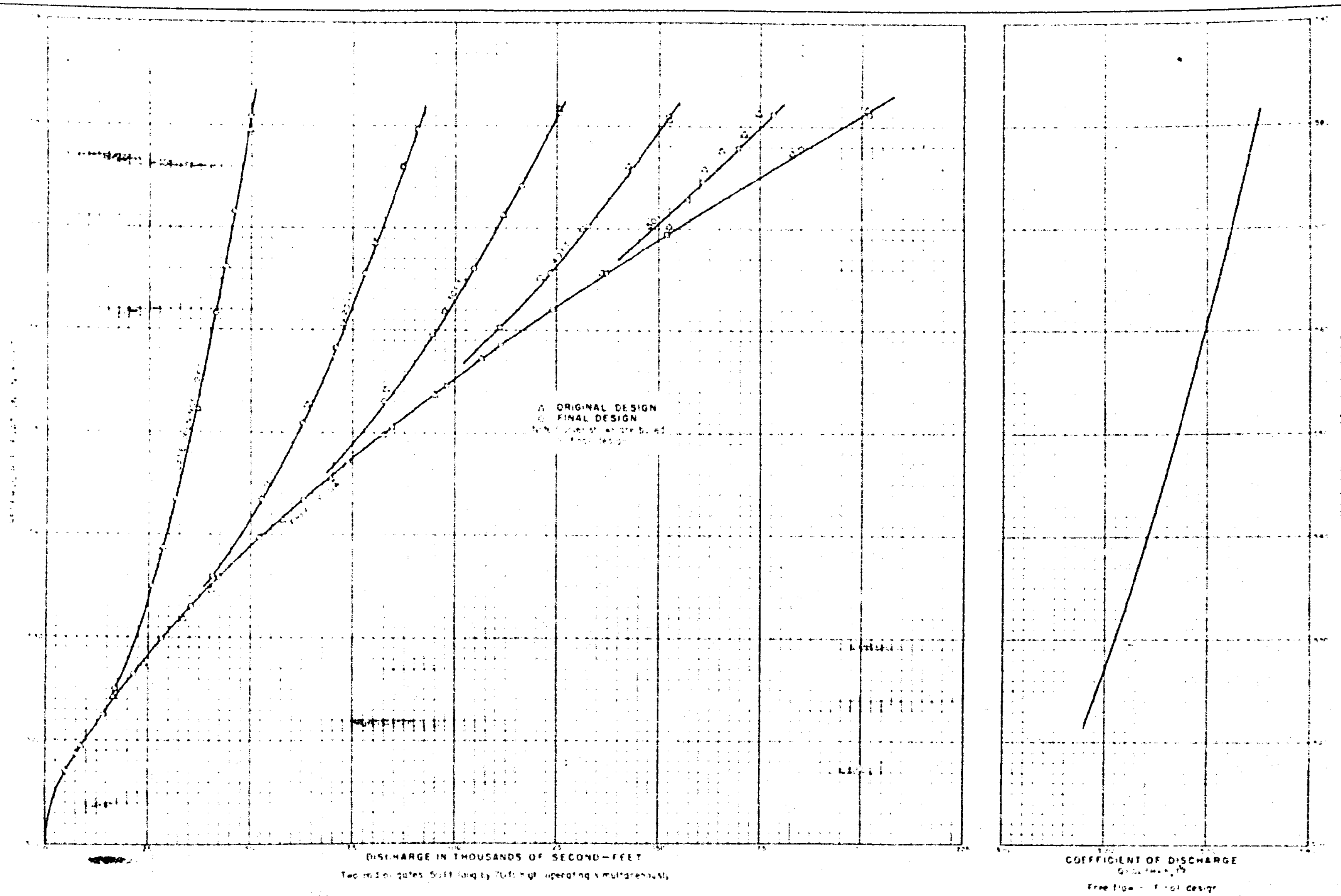
ENTRANCE TO AUXILIARY SPILLWAY, FINAL DESIGN
BHAKRA DAM 1:80 MODEL

under varying conditions as described under the photographs. The contraction at the upstream end of the wall was much less than in all other designs. Along the wall downstream from this point small waves occurred at the higher flows, but from the spillway crest downstream the surface was smooth. This fourth revision met the requirement of smoothing the flow with a minimum of structure, and was selected as the recommended design. It was found that increasing the length of the wall would not improve the flow sufficiently to justify the additional expense.

Spillway calibration. Two calibrations of the tunnel spillway were made--first, with the recommended wall design at the entrance, and secondly, with the original entrance design which was without a wall. The data for the original entrance design was obtained to determine the effect of the wall on the coefficient of discharge. The discharge curves for free crest and gate openings at 10-foot intervals are shown in Figure 32, together with the coefficient of discharge curve for free crest. The results of calibrations both with and without the concrete wall are indicated. The curves are drawn through the points obtained with the final entrance design. The contraction existing without the wall caused little loss in discharge since the velocity at the contraction increased sufficiently to overcome the decreased area produced by contraction. Water surface profiles were taken with the original and final entrance designs, Figures 33 and 34. The original entrance design shows a rough surface near the right training wall.

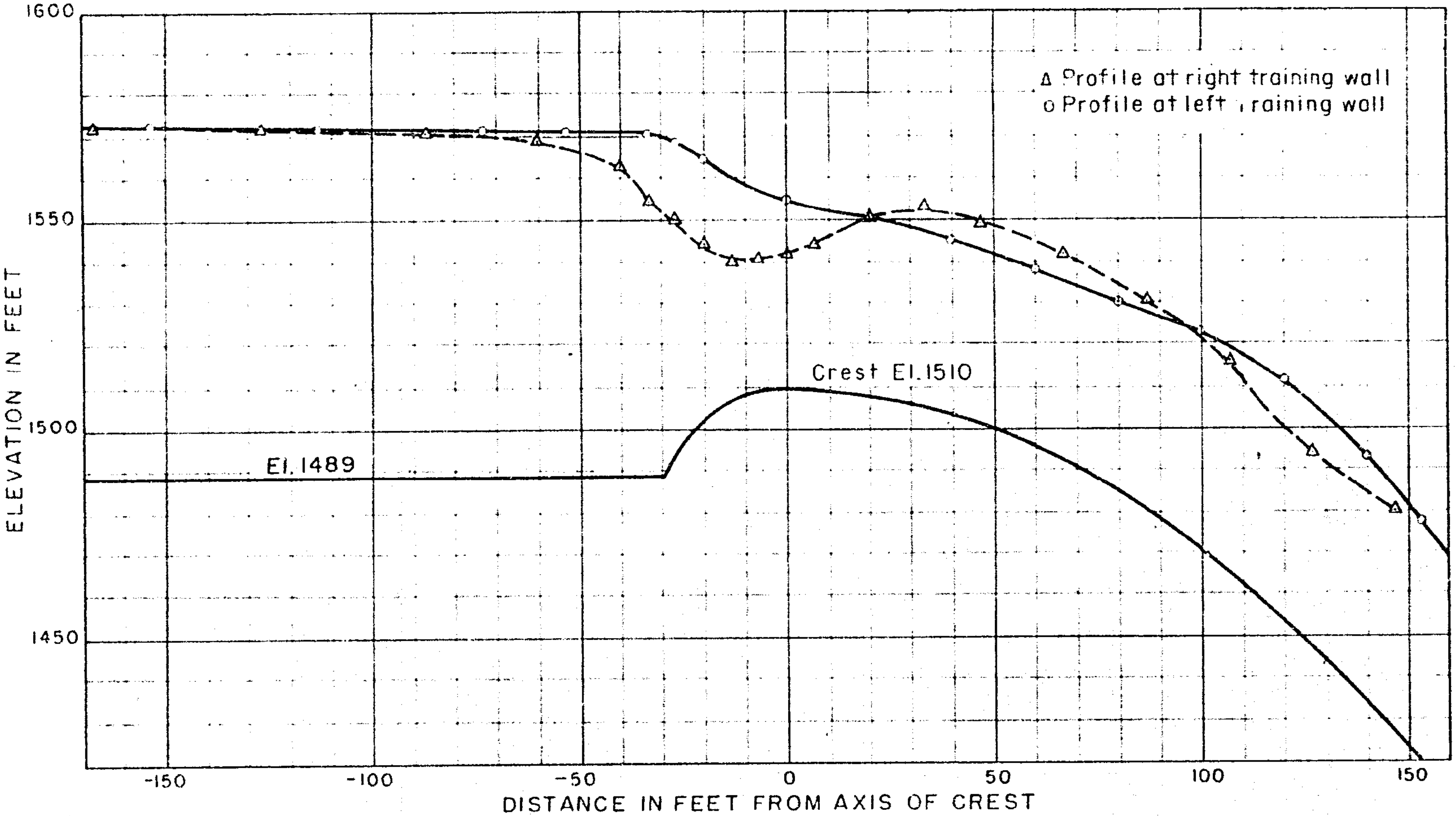
Transition section. The original design of the spillway from the crest to the first tunnel elbow is shown in Figure 35. The open portion of this system, called the transition section, is shown in the photograph in Figure 36A. Steps as indicated in the photograph were placed on either side of the center pier to provide aeration under the sheet of water. Mr. Savage requested the steps since it was known that any additional air that could be supplied to the water would help cushion the impact of the jet against the elbow in the tunnel thus reducing any unfavorable conditions that might develop.

When operating at maximum discharge the depth of the water over the floor of the transition section was greater at the training walls than



BHAKRA DAM
TUNNEL SPILLWAY DISCHARGE CAPACITY

FIGURE 32

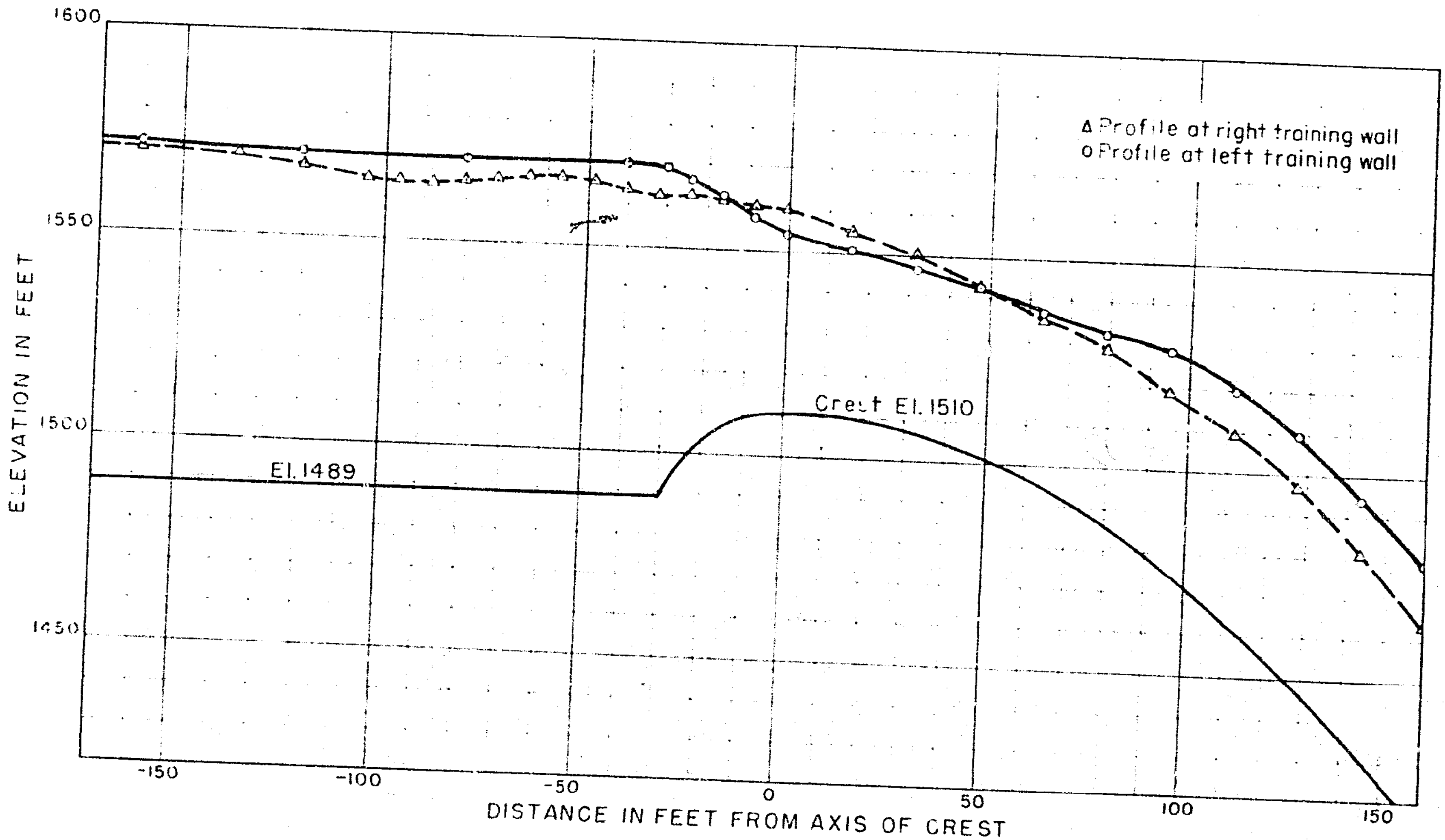


BHAKRA DAM

TUNNEL SPILLWAY - ORIGINAL ENTRANCE DESIGN
UPPER NAPPE PROFILE FOR MAXIMUM DISCHARGE

FIGURE 33

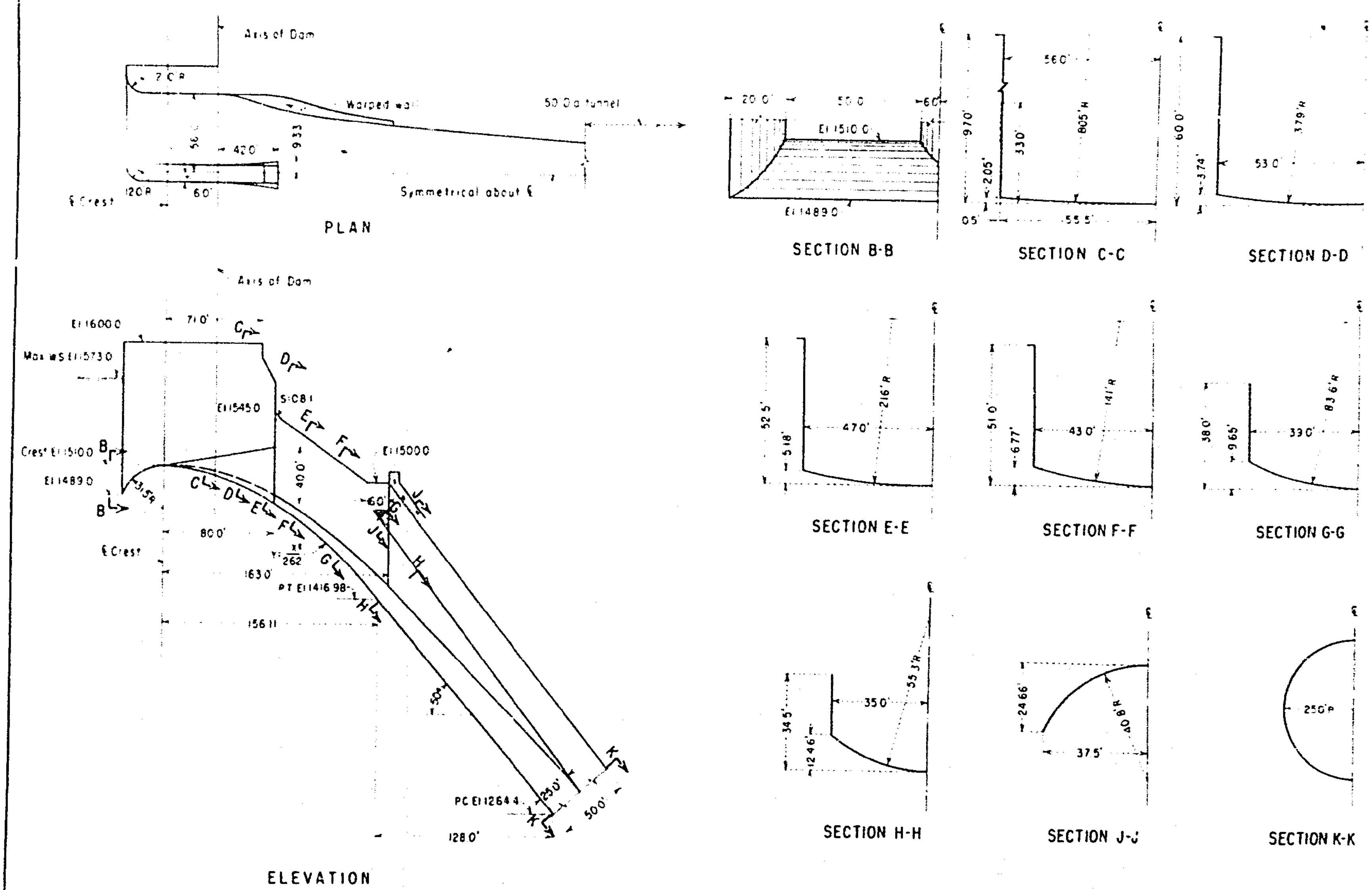
FIGURE 34



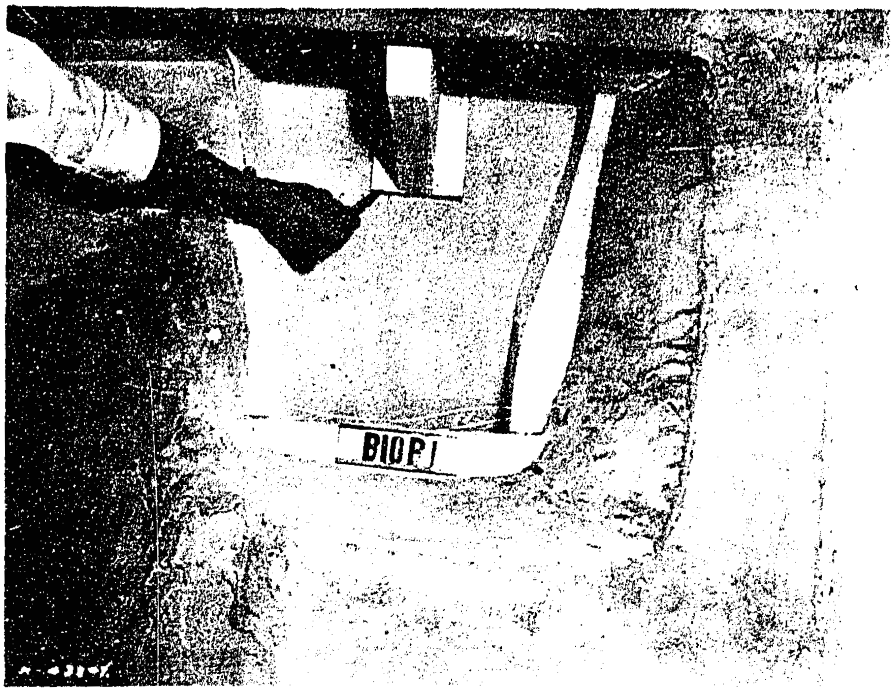
BHAKRA DAM

TUNNEL SPILLWAY - FINAL ENTRANCE DESIGN

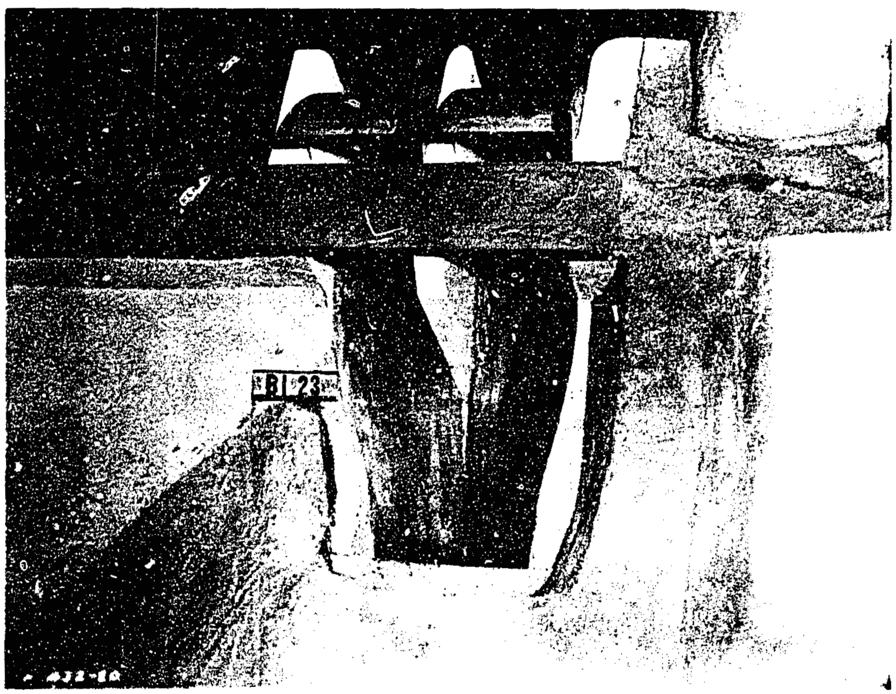
UPPER NAPPE PROFILE FOR MAXIMUM DISCHARGE



BHAKRA DAM
TUNNEL SPILLWAY—ORIGINAL DESIGN



A. No flow—looking upstream.



B. Discharge 166,600 second-feet.

TUNNEL SPILLWAY TRANSITION SECTION, ORIGINAL DESIGN
BHAKRA DAM 1:80 MODEL

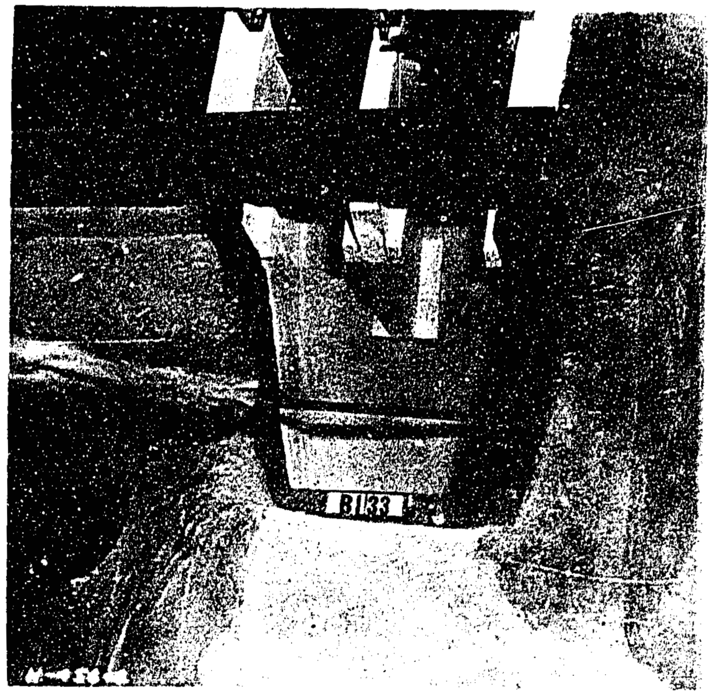
in the center due to the convergence of the walls. Water overtopped the walls (Figure 36B). As anticipated, the convergence of these walls was too abrupt. The steps at the downstream end of the pier, which were provided to aerate the jet of water, appeared to function satisfactorily as far as visual observations were concerned. Upon entering the tunnel the surface of the water at the training walls impinged upon the upper corners of the tunnel section.

The transition section was modified by raising and by straightening the training walls as shown in Figure 38 to give a slower rate of convergence, thus utilizing the full length of the section to effect the change. The photographs in Figure 37 show this new section. By increasing the radius of curvature of the roof of the tunnel, impingement was eliminated.

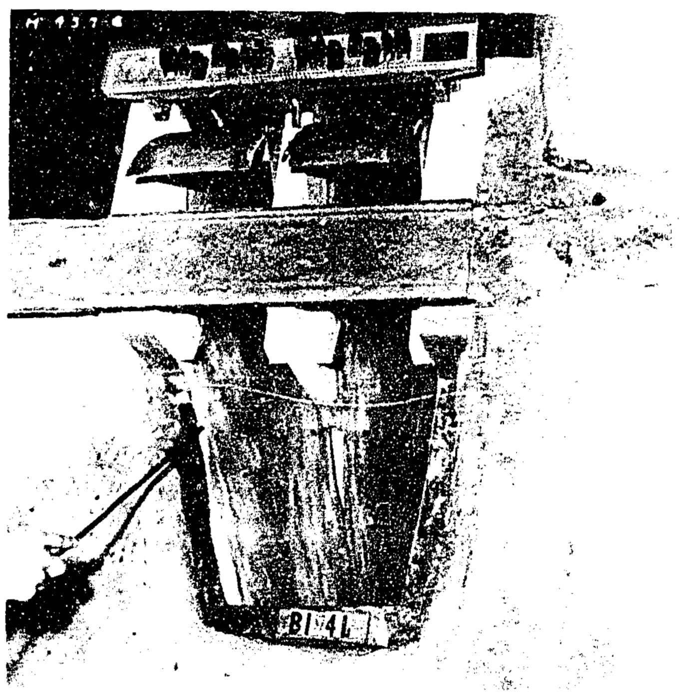
The spillway was again operated at various flows. The water surface in the transition section was very similar to the original design, but the entrance to the tunnel was improved by the more gradual convergence of the training walls. The wall heights and tunnel clearance were adequate at the maximum discharge. The photograph, Figure 37B, shows maximum flow in this section.

<u>Spillway deflector</u>. It was realized that model studies would be required to obtain a proper design for the deflector at the downstream tunnel portal. The first operation of the model was without a deflector because observation of flow conditions and resulting scour in the river channel was desired as a matter of record, since the tunnel will be operated without a deflector during the construction period of the dam. During this time the tunnel will operate at a maximum head of only 150 feet. Photographs in Figure 39 show the tunnel exit at maximum discharge under various combinations of flow. The portal opening was nearly submerged, but the jet issued at high velocity creating a very turbulent flow in the river channel with a large eddy forming upstream. Excessive scour occurred near the left bank downstream as can be seen in Figure 12.

A deflector was installed with a length of 130 feet and a rise of 20 feet, prototype, as shown in the drawing, Figure 40A. Satisfactory

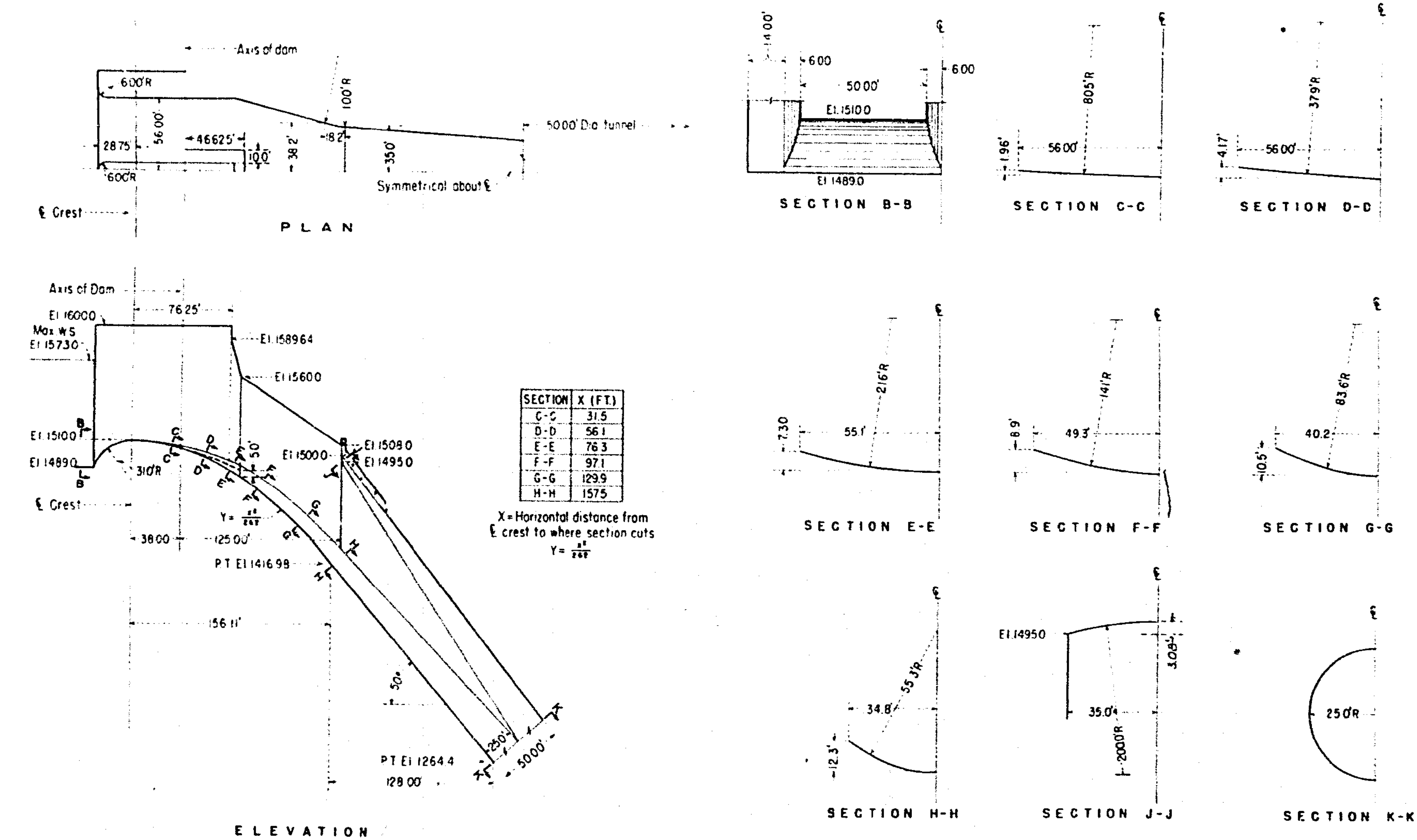


A. No flow—looking upstream.



B. Discharge 166,600 second-feet.

TUNNEL SPILLWAY TRANSITION SECTION, FINAL DESIGN
BHAKRA DAM 1:80 MODEL



SECTION	X (FT.)
C-C	31.5
D-D	56.1
E-E	76.3
F-F	97.1
G-G	129.9
H-H	157.5

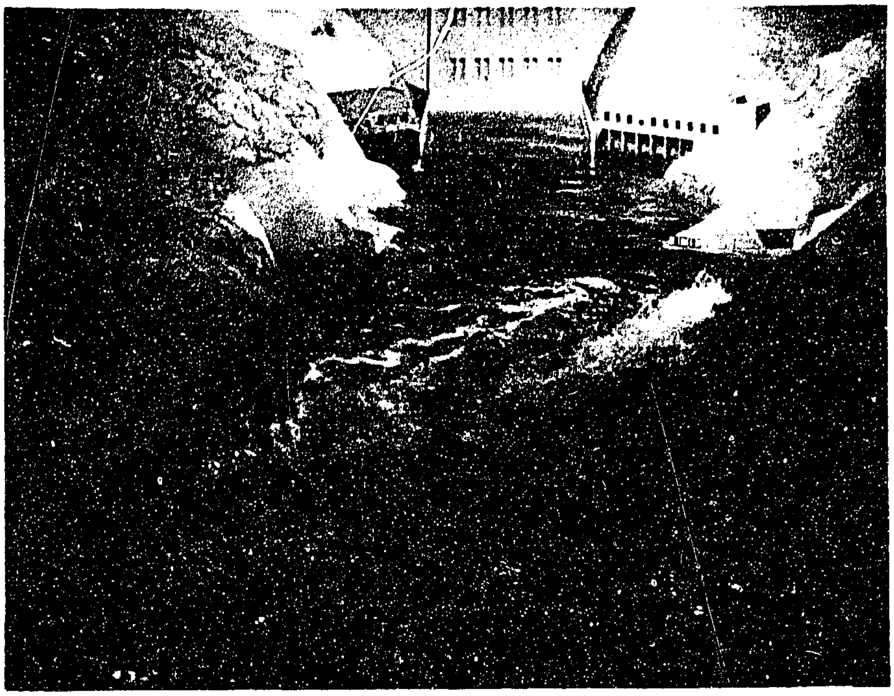
X = Horizontal distance from ℄ crest to where section cuts
$Y = \frac{x^2}{268}$

BHAKRA DAM

TUNNEL SPILLWAY - FINAL DESIGN

FIGURE 38

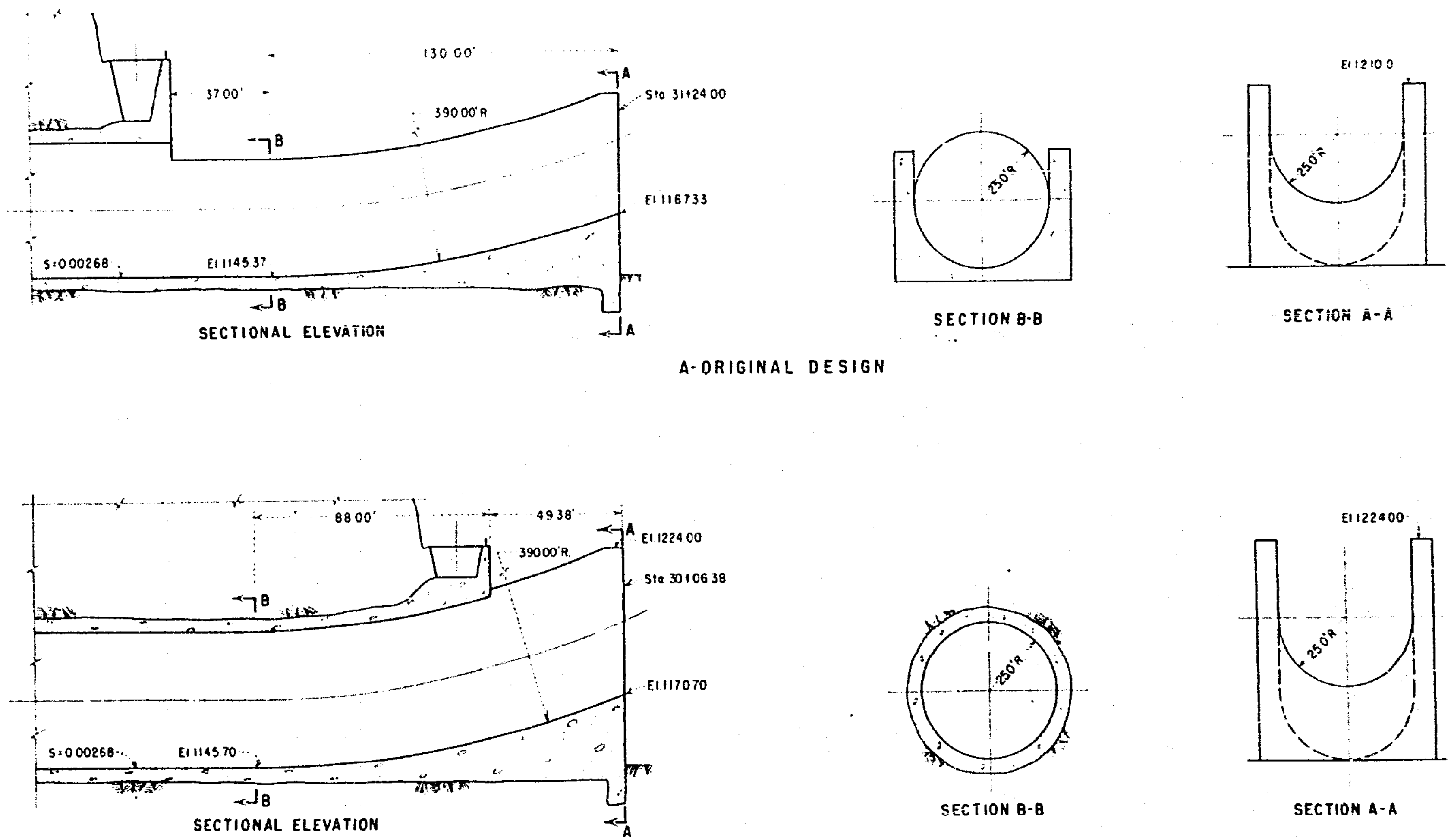
FIGURE 39



A. Looking upstream; tunnel spillway operating at 166,600 second-feet.

B. Looking downstream; drum gate spillway, river outlets, and tunnel spillway operating; total discharge 356,200 second-feet.

LEFT DIVERSION TUNNEL PORTAL, NO DEFLECTOR
BHAKRA DAM 1:80 MODEL

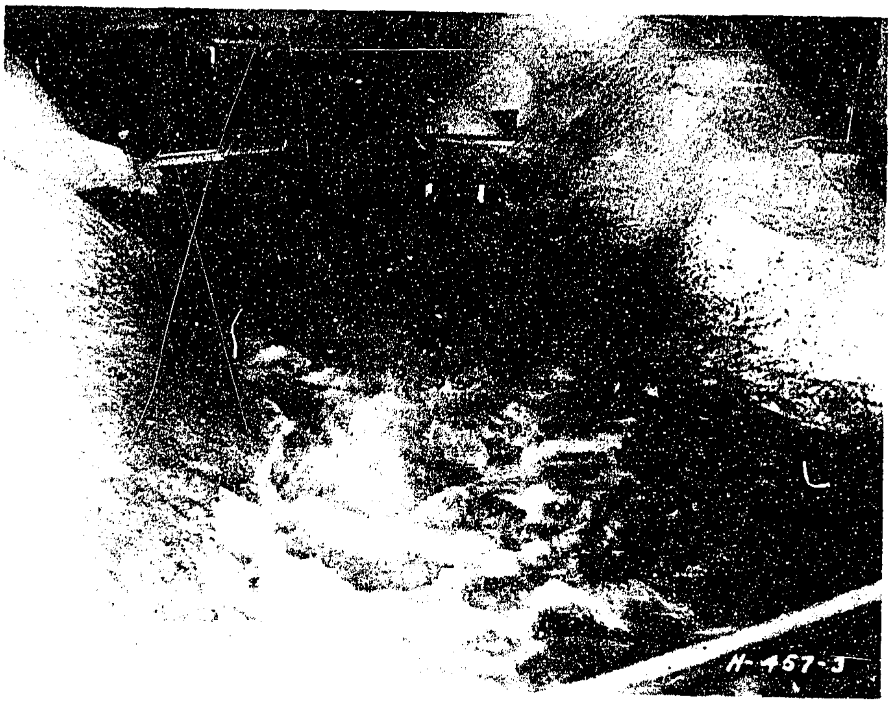


BHAKRA DAM
LEFT DIVERSION TUNNEL DEFLECTOR

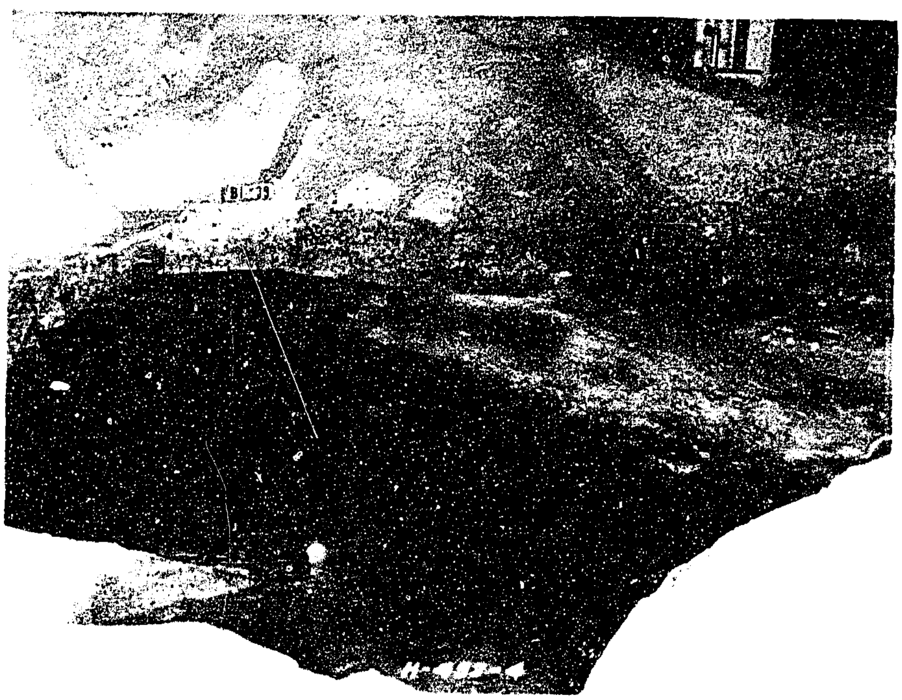
operation was noted at various flows. The lifting of the jet improved the flow in the river channel, eliminating the large eddy formerly present upstream. There was some impingement of the jet on the right bank downstream due to the alinement of the tunnel. Figure 41 shows this action with the tunnel spillway only operating. When the drum-gate spillway and outlets through the dam were operated in combination, the increased tailwater caused a flow of water over the wall of the deflector at the tunnel portal which added unnecessary volume to the jet. The water surface was highest on the left side of the jet due to the action of the horizontal elbow in the tunnel.

Because of the magnitude of the deflector in the prototype, considerable saving was effected by moving the deflector upstream and gaining most of the rise in the tunnel. Accordingly, the deflector was moved upstream 125 feet placing the lower end at station 29+99. The consequent rise in the roof of the tunnel at the portal, using this plan, was only 7 feet with the end of the deflector protruding 42 feet beyond the exit of the tunnel. The rise of 20 feet in the invert and the length of the arc remained as in the previous design. The movement of the deflector upstream caused an unexpected change in the conditions of flow in the river channel. A large eddy formed in the river abreast of the portal indicating that there was not sufficient lift to the deflector. It was observed that the absence of the eddy in the previous test was due to the effect of the right bank which prevented the formation of a whirlpool. In the latter case the distance to the right bank was increased giving space for an eddy to form.

To improve these conditions the deflector was raised an additional 5 feet. This was accomplished by maintaining the same radius of curvature and adding to the downstream end making the deflector extend downstream from the portal a total distance of 49.38 feet with a total rise of 25 feet. The design of this deflector is shown in Figure 40B. With this design eddies were absent for all flow conditions. While the water surface was rough in the river channel, it was satisfactory as this condition was independent of any alteration that could be made to the



A. Looking upstream.



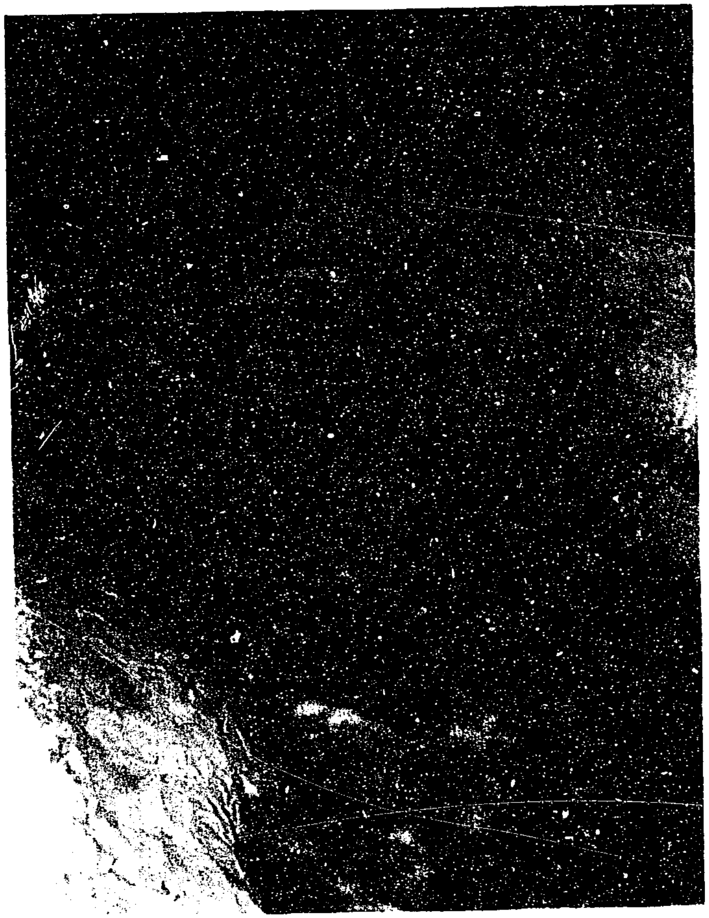
B. Looking toward left bank.

DISCHARGE OF 166,600 SECOND-FEET
LEFT DIVERSION TUNNEL DEFLECTOR, FIRST DESIGN
BHAKRA DAM 1:80 MODEL

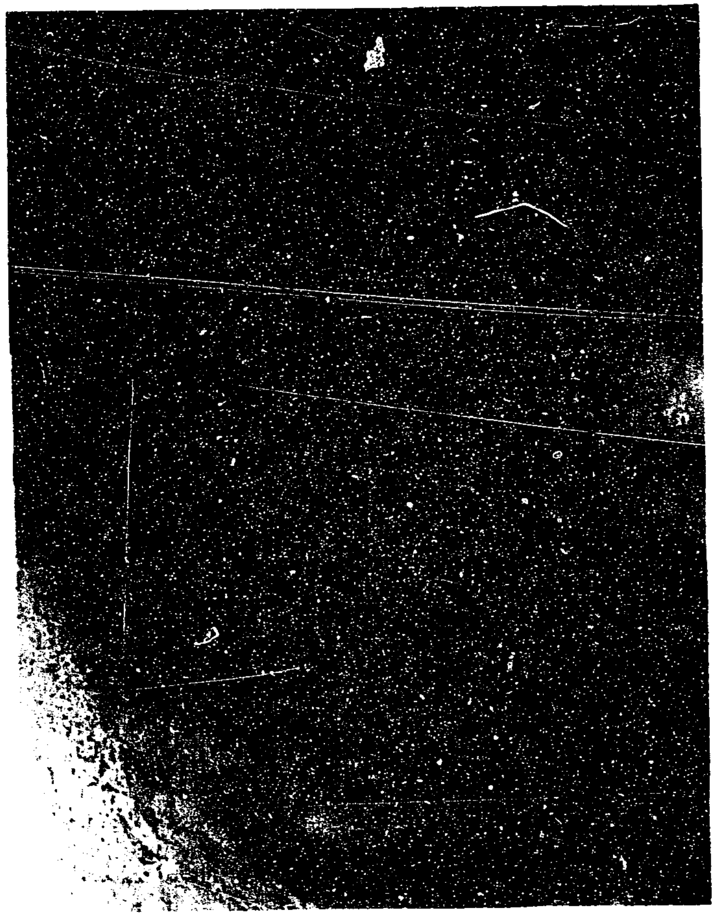
deflector. The photographs in Figure 42 show the flow for the two operating conditions. The upper profile of the jet at the centerline and at the left side is shown in Figure 43 for maximum flow. The water surface at the left side was higher than at the center due to the influence of the elbow in the tunnel upstream. The profile on the right side corresponded closely to that on the centerline.

Lowering of powerhouse tailwater. A gage was installed in the model on the left bank at the lower end of the drum-gate spillway to measure the lowering of the tailwater at the powerhouse caused by the operation of the tunnel spillway. During these tests 15,000 second-feet entered the river continuously from the two powerhouses. At various discharges of the tunnel spillway simultaneous readings were made using the gages at the powerhouse and at the lower end of the tailwater box. From this data the curve, Figure 44, was drawn showing the relationship between drawdown at the powerhouse and tunnel spillway discharge. With substantial flow over the drum-gate spillway or river outlets, the lowering of the tailwater becomes negligible.

FIGURE 42



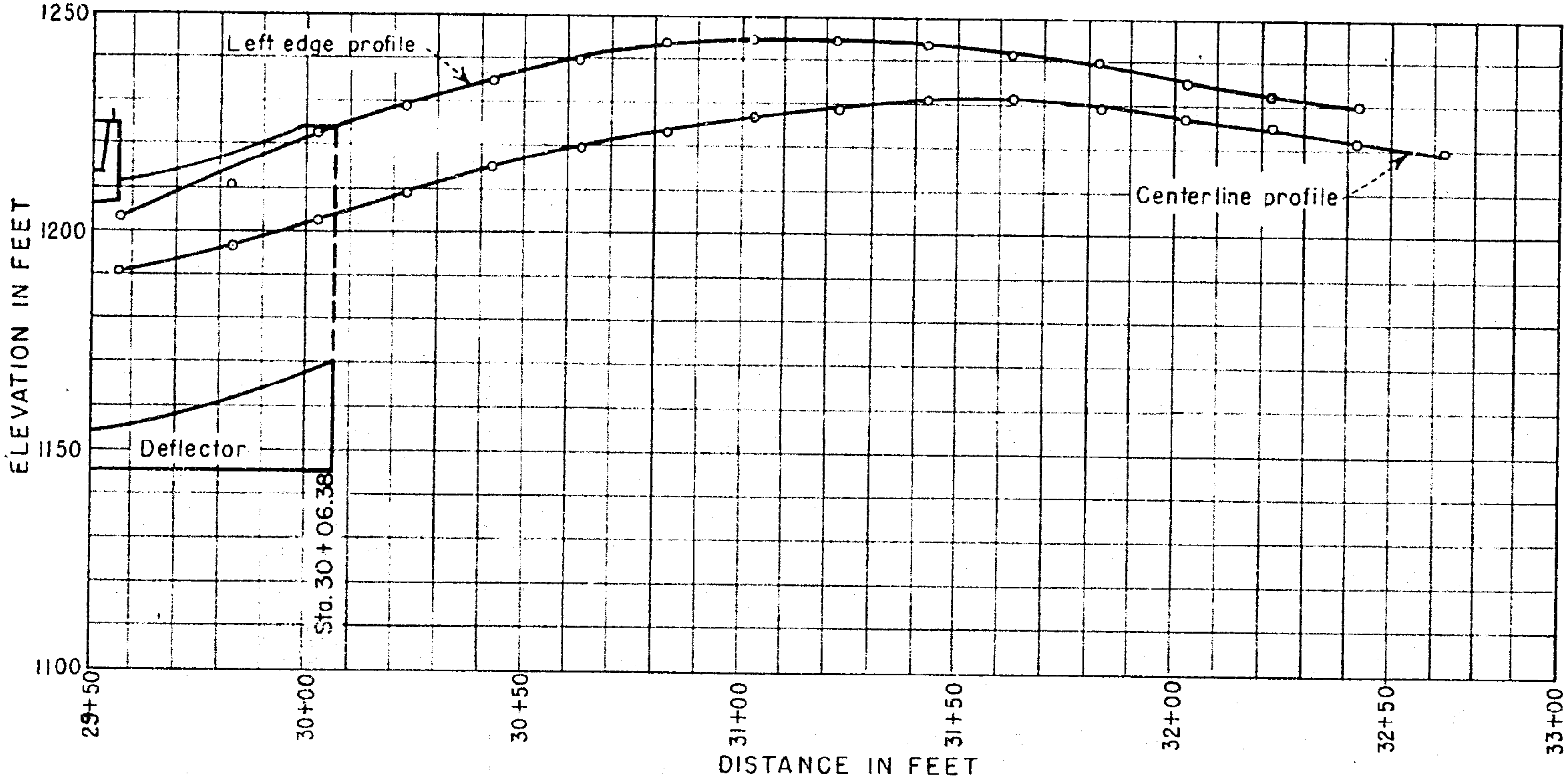
A. Discharge 100,000 second-feet.



B. Discharge 166,600 second-feet.

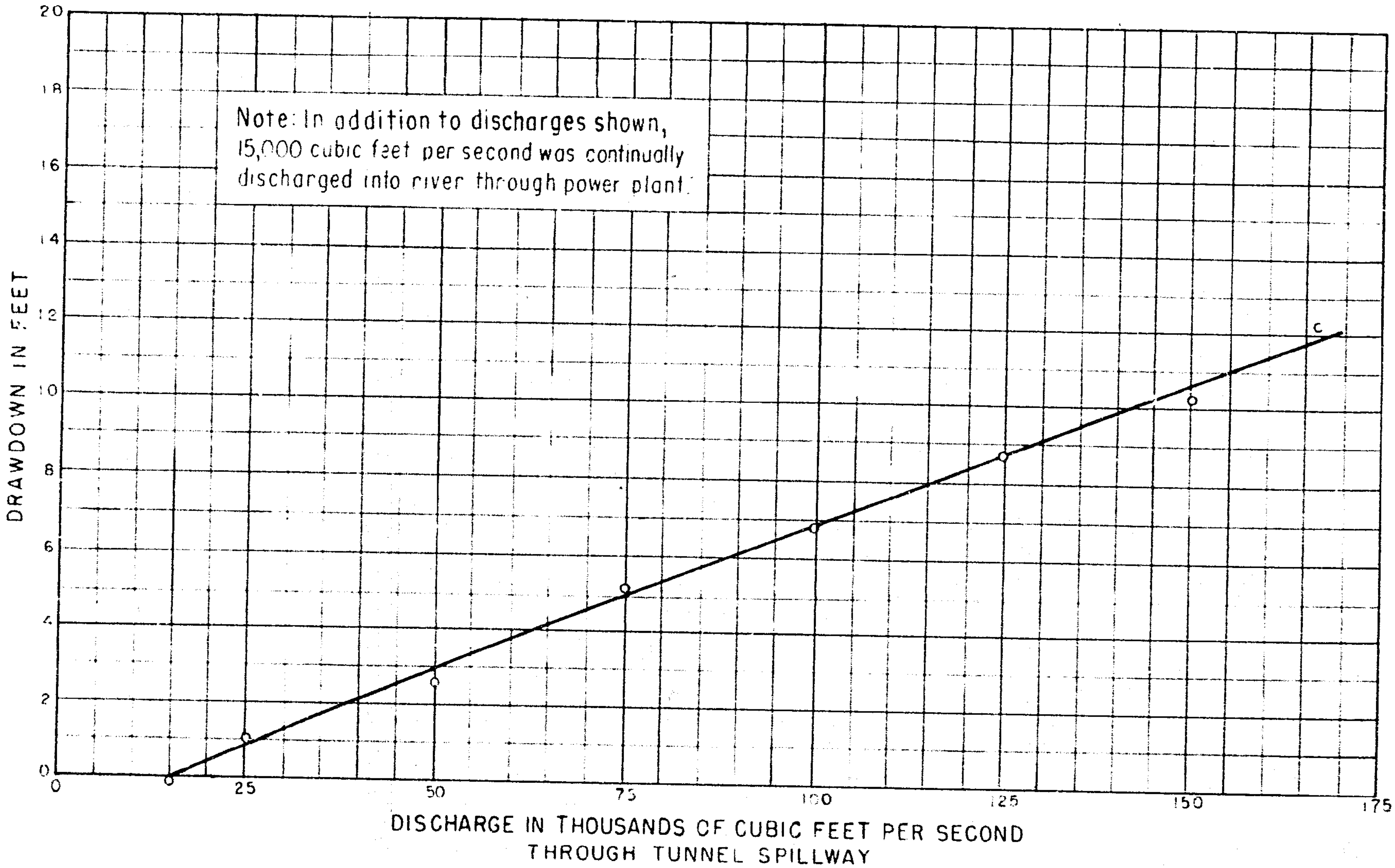
LEFT DIVERSION TUNNEL DEFLECTOR, FINAL DESIGN
BHAKRA DAM 1:80 MODEL

FIGURE 43



BHAKRA DAM
LEFT DIVERSION TUNNEL DEFLECTOR UPPER NAPPE
PROFILE FOR MAXIMUM DISCHARGE
OF 166,600 SECOND-FEET

FIGURE 44



BHAKRA DAM

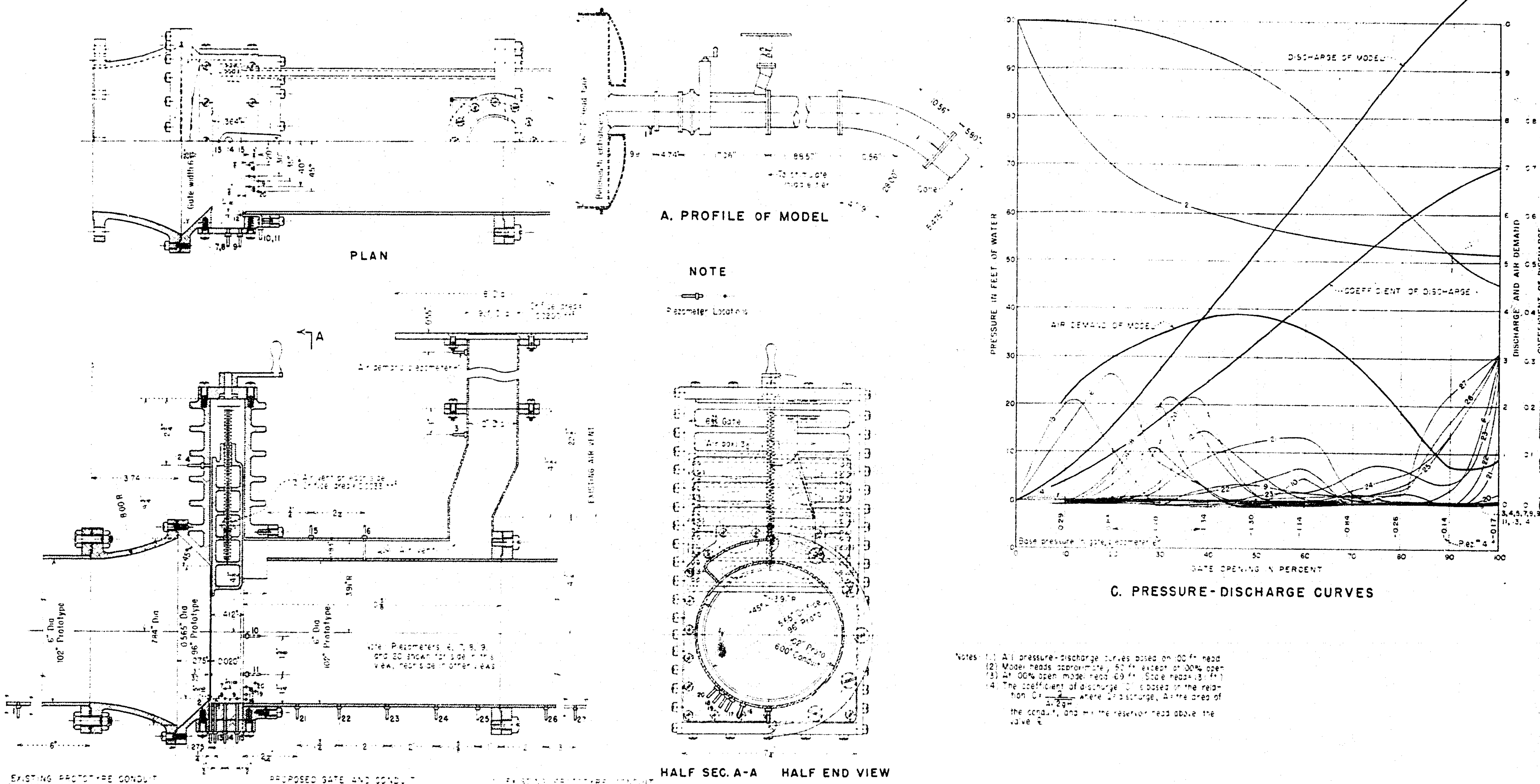
LOWERING OF POWERPLANT TAILWATER PRODUCED BY TUNNEL SPILLWAY DISCHARGE

1:17 MODEL OF RIVER OUTLET

Model Construction

Description of model. A 1:17 model of an outlet in Shasta Dam was available in the hydraulic laboratory which, with some alterations, served as a model for the outlets in Bhakra Dam, Figure 45. The portions of this model that were used consisted of a cylindrical pressure tank containing a floating plate and bellmouth entrance, a control gate, and a section of conduit connecting the head tank and gate. The entrance section of the gate was changed from a bell shape to a conical one with a wax filler. This alteration was made to simplify the structural shape since basic tests in the design of the outlet gate indicated this design was satisfactory. The conduit downstream from the gate was made of transparent plastic to permit observation of flow and had a horseshoe-shaped cross-section with a flat bottom. This conduit section was developed along with tests to design the control gate (Hydraulic Laboratory Report No. 201). The elbow and trough at the exit of the conduit were made of sheet metal. In the earlier tests the spillway face was made of wood, but was later replaced with sheet metal for the final studies. The final design of the Bhakra Dam outlet model is shown in Figure 46. Air to the control gate was supplied by a vertical 2-inch transparent plastic pipe connected to a chamber on top of the conduit downstream from the gate. A sharp-edged orifice was placed at the top of this tube to measure the air supply. The area of this 2-inch diameter pipe was equivalent to two 24-inch air supply pipes in the prototype. Pressures within the model were recorded from piezometers of 3/32-inch or less diameter installed at selected points in the conduit and exit section.

Flow to the model was supplied by a 12-inch centrifugal pump direct-connected to a 100-horsepower motor. Regulation was afforded by a valve in the line between the pump and the head tank. There was no measuring device in the line as in the Shasta tests due to rearrangement of the laboratory piping. It was therefore necessary to use the same discharge curves for Bhakra Dam as were obtained in the Shasta tests, Figure 45C.



ELEVATION

B. DETAILS OF GATE

CENTRAL VALLEY PROJECT - CALIFORNIA

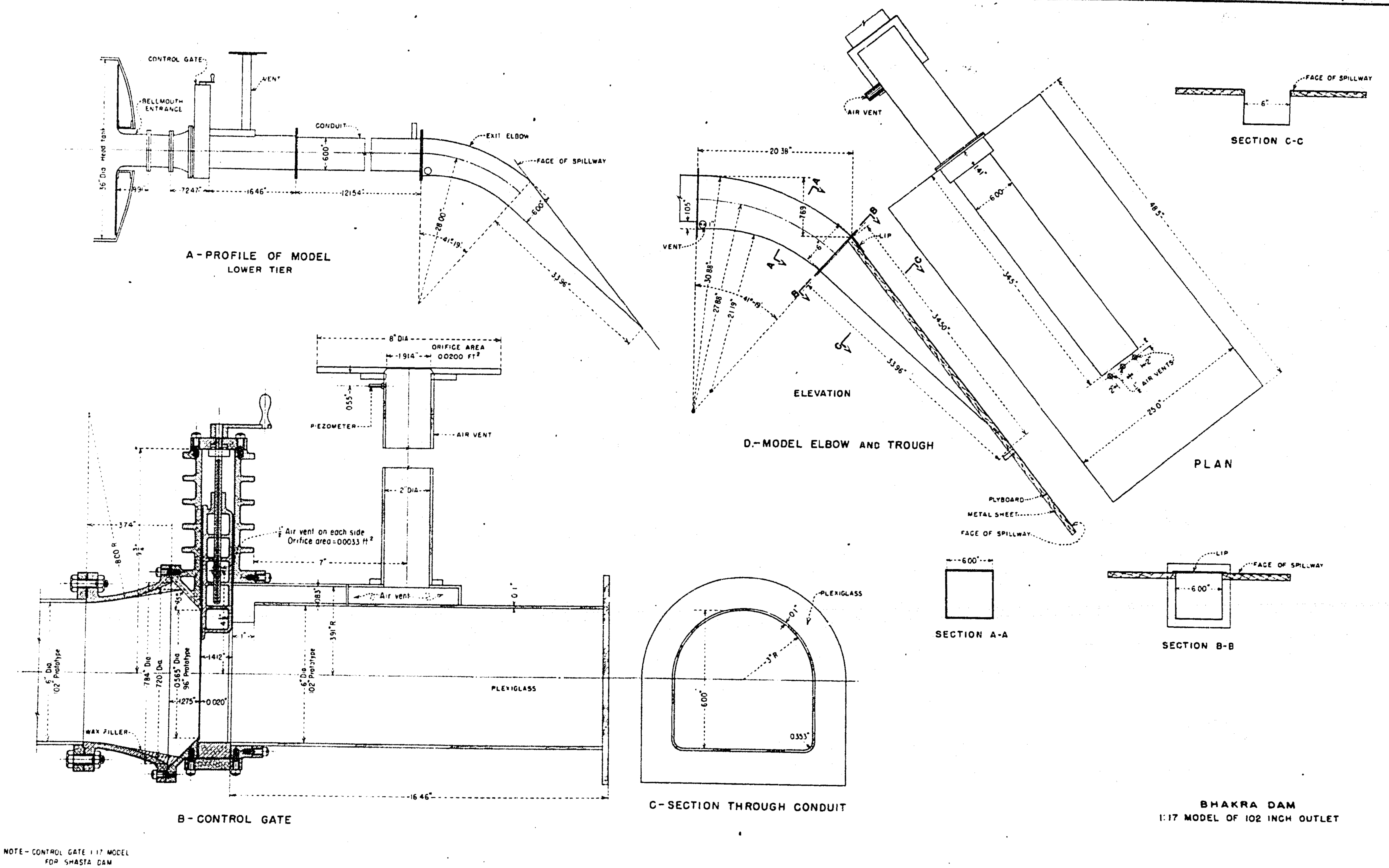
SHASTA DAM

CONTROL GATE FOR 102-INCH OUTLETS

PRESSURE, DISCHARGE AND AIR DEMAND CURVES

1:17 MODEL OF THE FINAL DESIGN

FIGURE 46



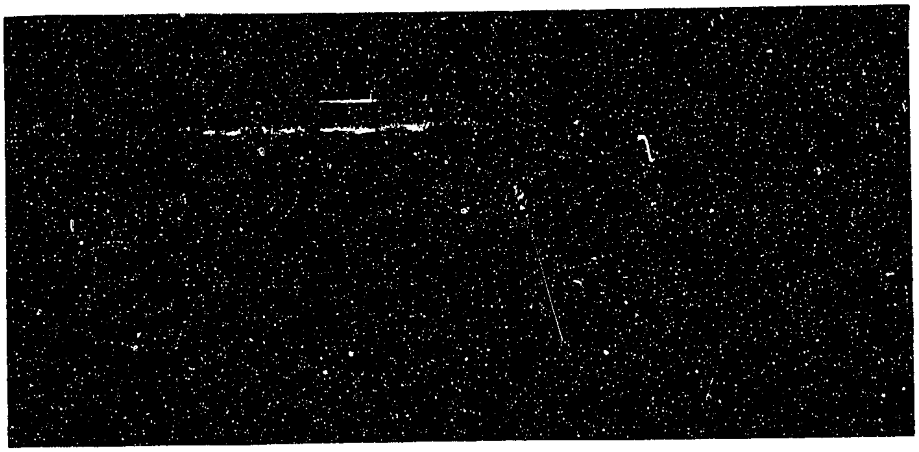
BHAKRA DAM
1:17 MODEL OF 102 INCH OUTLET

Results

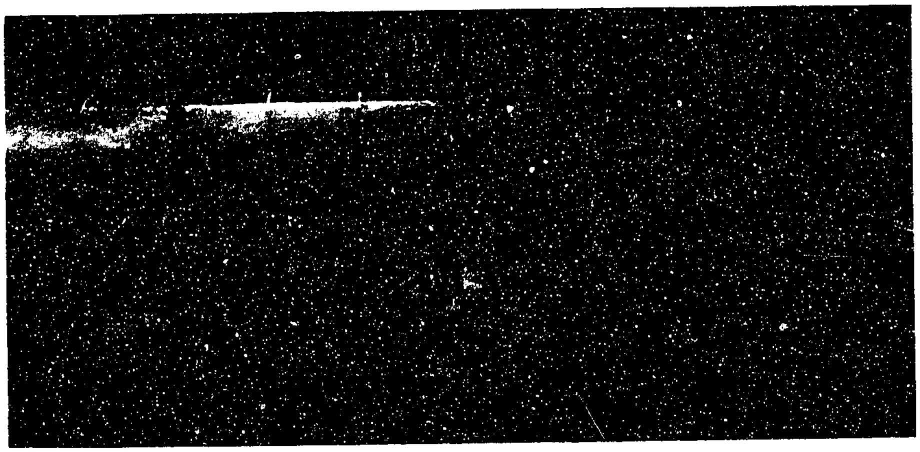
Operation of conduit without elbow. In the procedure of the outlet tests related in this report, studies were made at various stages of completion of the model. The first investigation was made without the exit elbow in place to determine the flow conditions in the conduit downstream from the control gate. The conduit was of 6-inch height and width corresponding to 102-inch in the prototype. The maximum prototype head of 288 feet on the outlets corresponded to a model head of 16.94 feet. With full gate opening at maximum head the prototype discharge of 4,800 second-feet was represented by 4.03 second-feet in the model. Heads up to 41 feet in the model were used corresponding to 697 feet in the prototype.

The flow through the gate and in the conduit downstream was observed for various gate openings, Figure 47. Pressure measurements were not made because the design of the gate had been checked in prior tests, and the form of the horseshoe-shaped conduit was not expected to cause subatmospheric pressures. With the gate 100 percent open, wisps of water appeared to leave the jet at the gate giving it a ragged appearance. This condition, believed due to turbulence created by the expanding section upstream from the gate, had been noted in previous tests and was not considered important. For the lesser gate openings, a small amount of water was deflected into the gate slot. The jet leaving the gate struck the sidewalls of the conduit for openings between 50 and 75 percent and the bottom for openings less than 50 percent; however, this did not result in any adverse conditions. At these lower openings the jet was deflected from the bottom and created a wave on each side of the conduit about four diameters downstream from the gate. The two waves were of sufficient height to meet at the top of the conduit, but being thin sheets of water, they offered little resistance to the flow of air through the outlet. The conduit was not completely filled with water for any gate opening in which the model head was 16.94 feet or less. Thus open-channel flow at supercritical velocity existed in the model for all prototype ranges of operation.

FIGURE 47



A. Gate 25 percent open.



B. Gate 50 percent open.

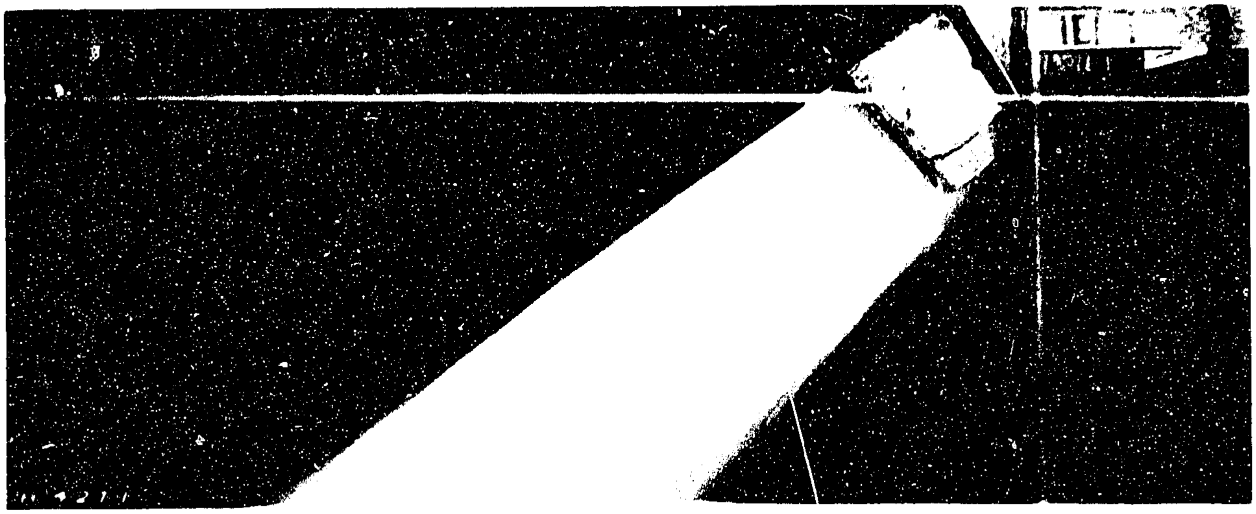
C. Gate 100 percent open.

FLOW IN CONDUIT ABOVE ELBOW, DIRECTION OF FLOW TO LEFT
BHAKRA DAM 1:17 MODEL

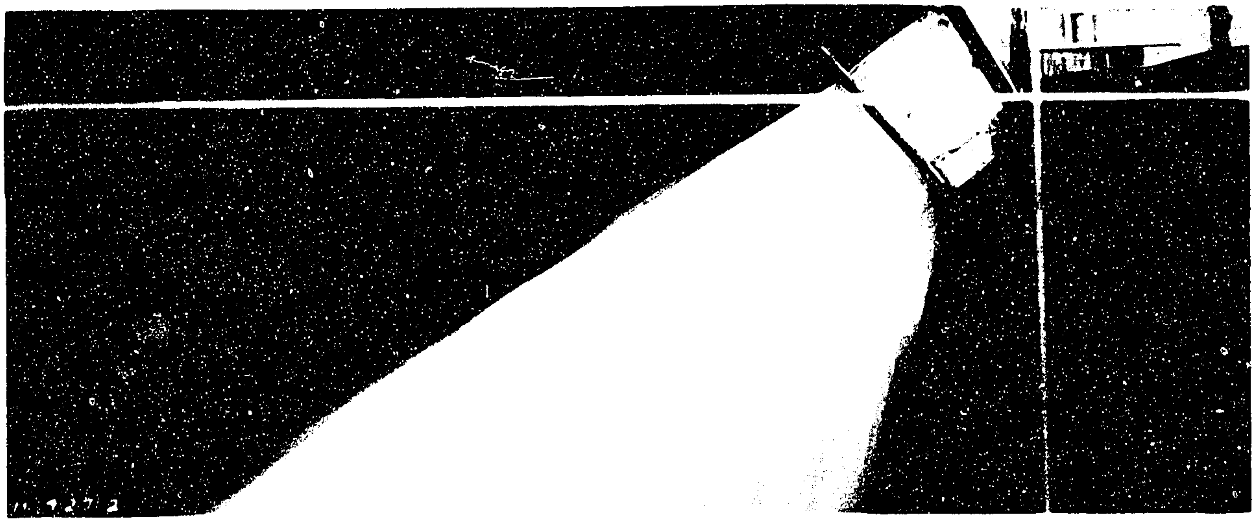
Investigation of partial elbow. A 41-degree 19-minute elbow was installed at the end of the conduit with the radius at the centerline corresponding to 38.5 feet in the prototype. It was of square cross-section 6 inches on a side (model), with the bottom omitted. The radius and angle through which the elbow turned was the same as that used on Shasta Dam. No restriction was used at the end of the elbow as in former practices, since this would not be effective at the partial discharges. The new design was selected for study since the flat top appeared best to turn jets of various depths caused by regulation of the outlet. A transition section was not used in changing from the arch of the conduit to the rectangular elbow. No adverse pressure conditions were anticipated from this discontinuity, but, if necessary, correction could be provided by the use of air vents.

Flow in the elbow was observed for various gate openings and heads. At 100 percent opening, the elbow was virtually filled and the jet was turned downward in the desired direction, Figure 48A. As anticipated the bottom section was not necessary to confine the flow in the elbow. The step formed at the junction of the conduit and elbow roof surface was filled with water under pressure; hence no adverse conditions were produced at this point. At partial gate openings, the upper part of the elbow was not filled, as the jet, having a horizontal trajectory, impinged on the top surface of the elbow. It then flowed downward along the top boundary of the elbow with a portion of the flow being deflected down the sides of the elbow to form the fan-shaped jet shown in Figure 48B. The fins were only thin sheets of water. At small openings they virtually disappeared resulting in the jet shown in Figure 48C. At constant gate openings, variation in the head on the outlet had little effect on the appearance of the flow, except at very low heads when the trajectory of the jet was such that it failed to strike the roof of the elbow.

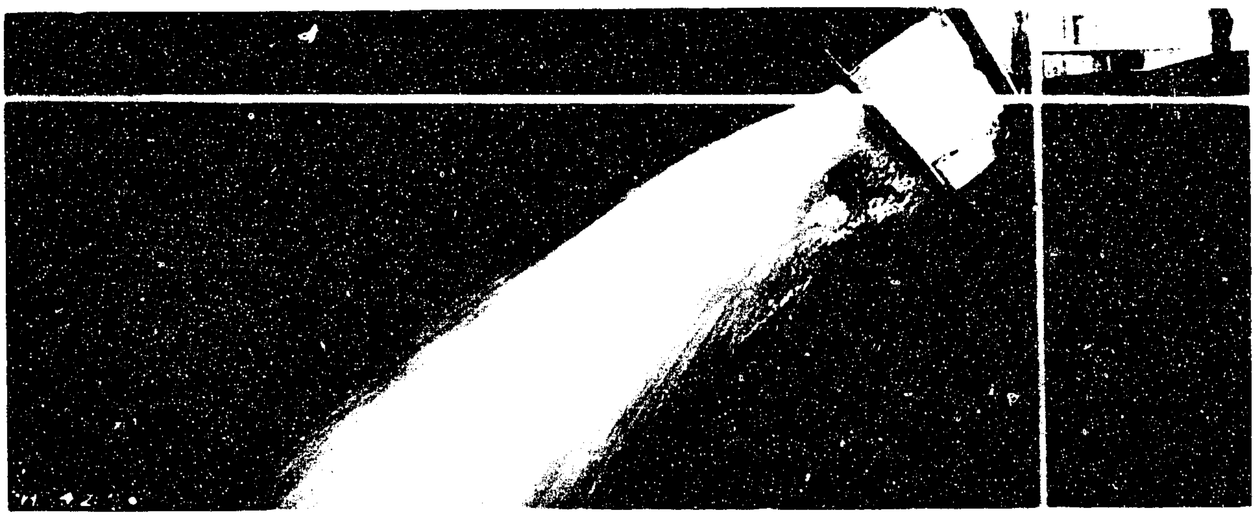
To observe the effect of turning the jet through greater angles, sections were added to the existing elbow to give bends of 50, 60, and 70 degrees. In all tests the flow was satisfactorily turned as shown in Figure 49 (70-degree elbow). In fact, at the larger angles the fan shape of the jet at the intermediate gate openings was less pronounced.



A. Control gate 100 percent open.



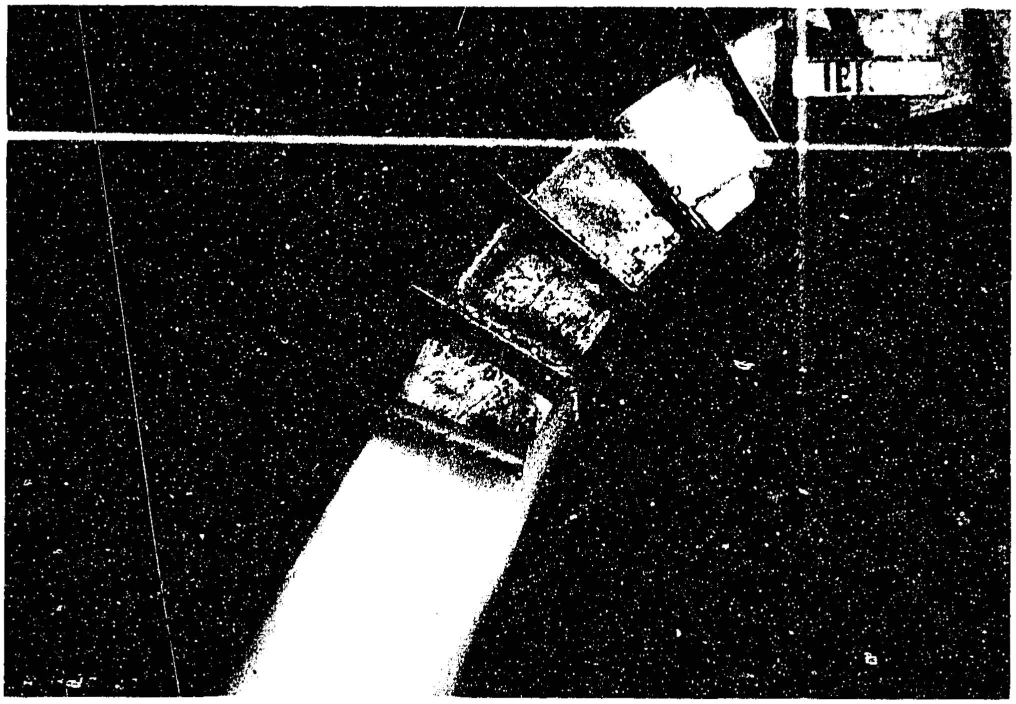
B. Gate 40 percent open.



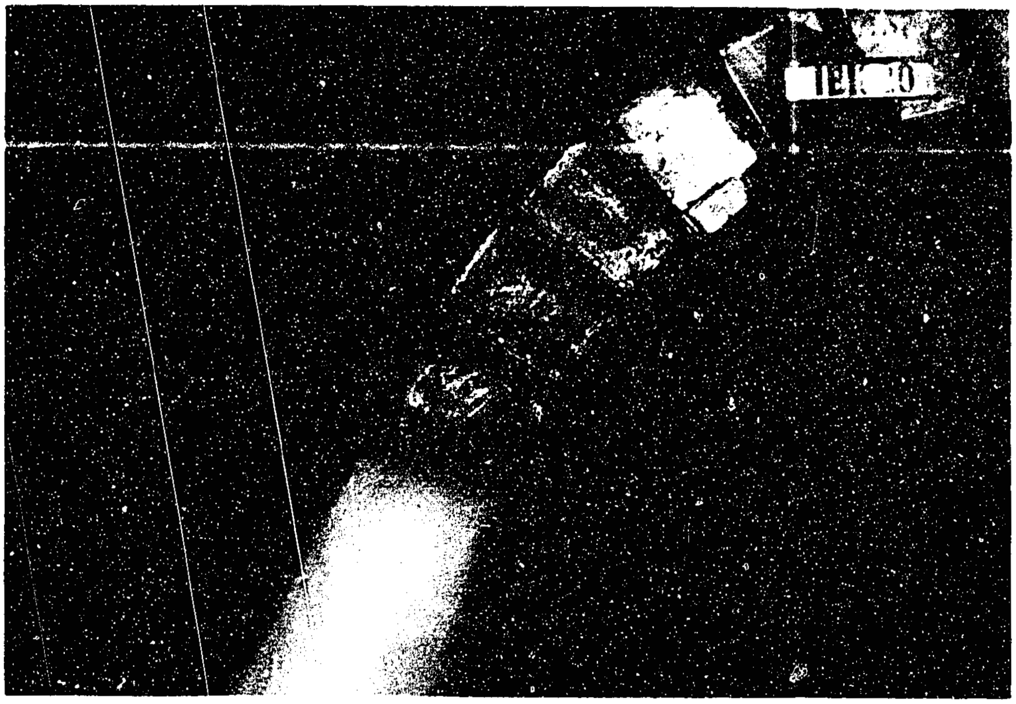
C. Gate 15 percent open.

FLOW FROM 41 DEGREE-19 MINUTE ELBOW
BHAKRA DAM 1:17 MODEL

FIGURE 49



A. Gate 100 percent open.



B. Gate 40 percent open.

FLOW FROM 70-DEGREE ELBOW
BHAKRA DAM 1:17 MODEL

Investigation of partial elbow with spillway trough. A sheet metal trough and wooden spillway face were next added to the model as shown in Figure 50A. This addition was necessary since the required elbow angle could not be determined without observation offlow down the face of the spillway. The lower end of the top of the elbow was placed flush with the spillway face and construction was such as to permit changes in the elbow angle or trough length. The trough was of rectangular cross-section instead of circular as in the Shasta design.

Observation of flow conditions were first made using a 41-degree 19-minute elbow, Figures 50B and 51. The appearance of the jet did not vary greatly for different gate openings and high fins did not form as observed on the model and prototype of the outlets for Shasta Dam.

A 45-degree elbow was next studied. There was no appreciable difference in the appearance of the jet from that of the previous elbow. Figures 52A and 52B show the discharge from the 45-degree elbow, while Figure 52C is a high-speed photograph of the 41-degree 19-minute elbow.

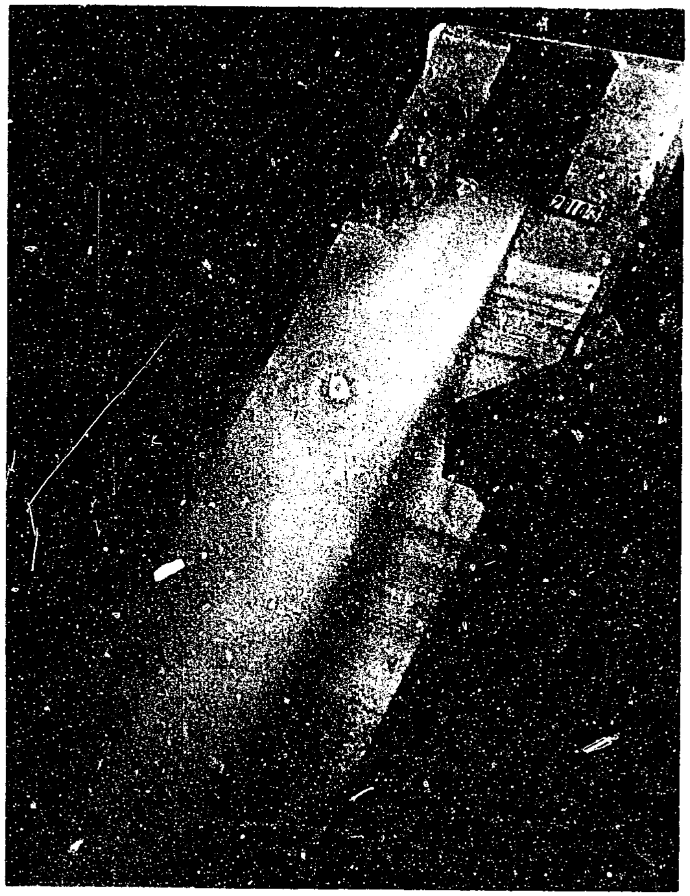
Investigation of complete outlet. The 41-degree 19-minute elbow was selected for further study. Flow down the spillway face was satisfactory for either elbow, but the 41-degree 19-minute elbow was more desirable since it resulted in a shorter trough length. A new sheet metal elbow, trough, and spillway face were installed on the model. The bottom of the elbow was constructed as shown in Figure 46. By using a shorter radius of curvature the bottom of the elbow was not concentric with the top and joined the conduit 1.06 inches below the floor, corresponding to 18 inches in the prototype. It was expected the step thus formed, when supplied with an air-vent, would prevent negative pressures in this region. Air-vents were also placed in the face of the spillway immediately below the intersection of the lower end of the trough. In a trial run, the lip across the top of the elbow exit materially improved the appearance of the jet at partial gate openings by directing the flow downward into the trough. Various lip designs were investigated with the one selected consisting of a 24-inch extension, prototype, to the top of the elbow in the plane of the spillway face. With this addition the model, Figure 53A, was considered ready for the final tests.

A. The model.

B. Discharge with control gate 100 percent open.

BHAKRA DAM 1:17 MODEL

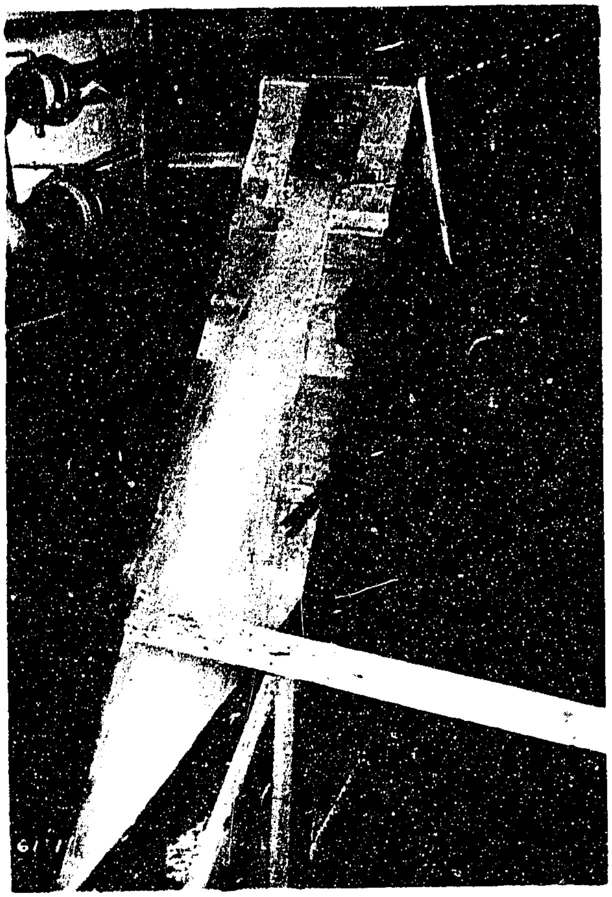
FIGURE 50



A. Control gate 50 percent open.

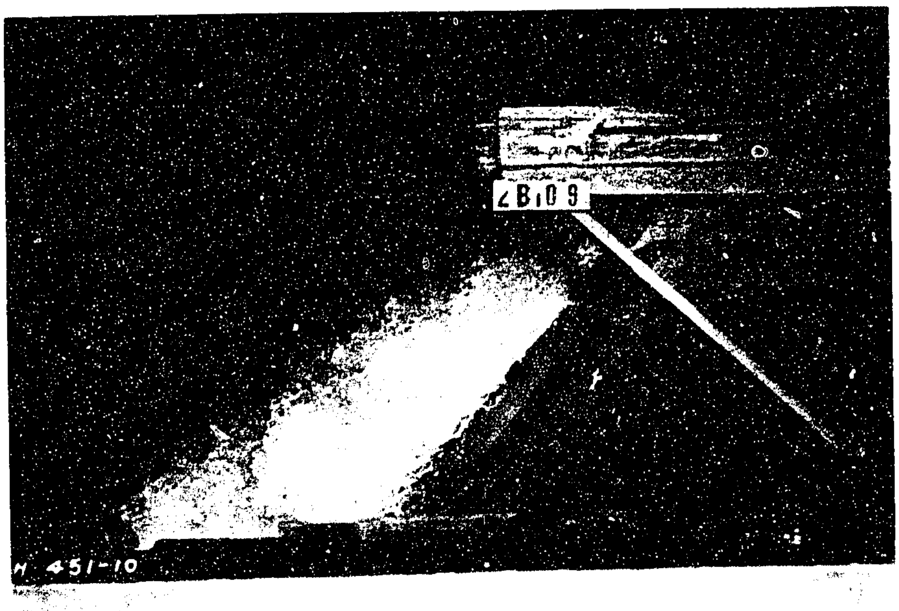
B. Control gate 25 percent open.

DISCHARGE ON FACE OF SPILLWAY WITH 41 DEGREE-19 MINUTE ELBOW
BHAKRA DAM 1:17 MODEL



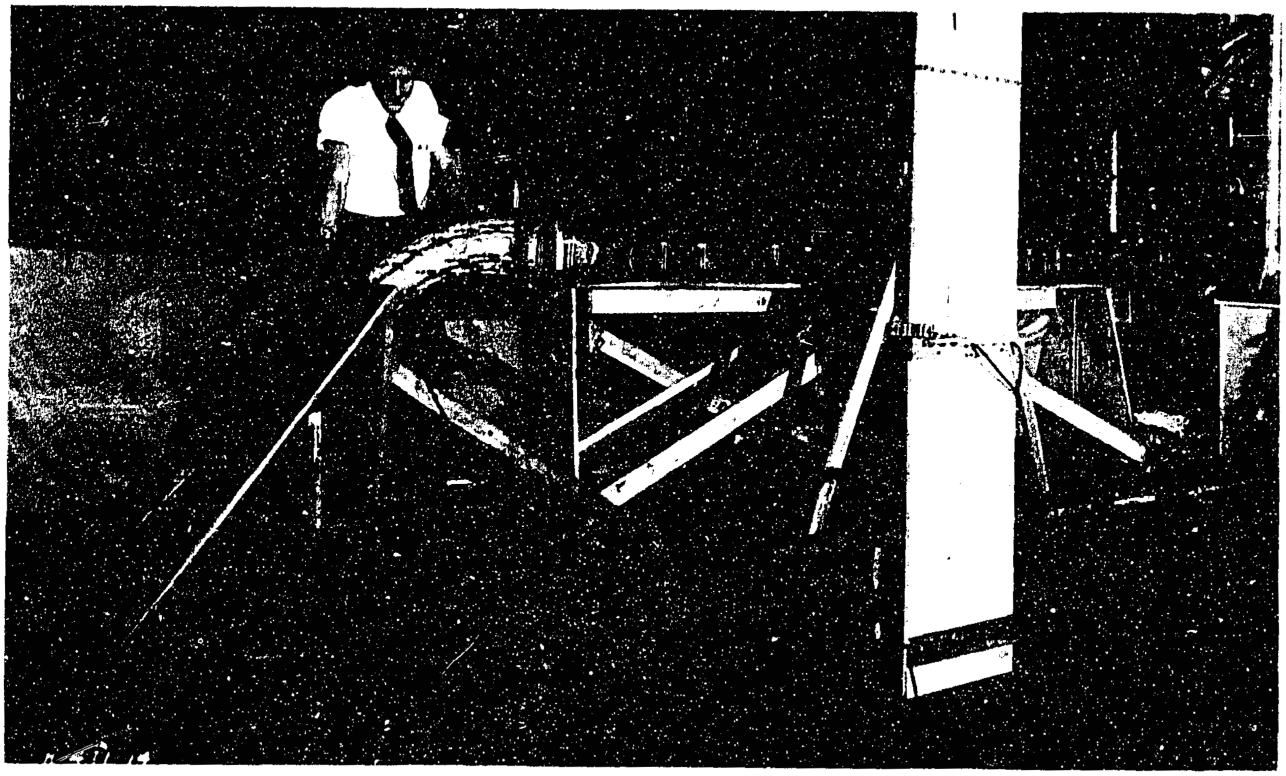
A. Control gate 100 percent open; 45-degree elbow.

B. Control gate 25 percent open; 45 degree elbow.

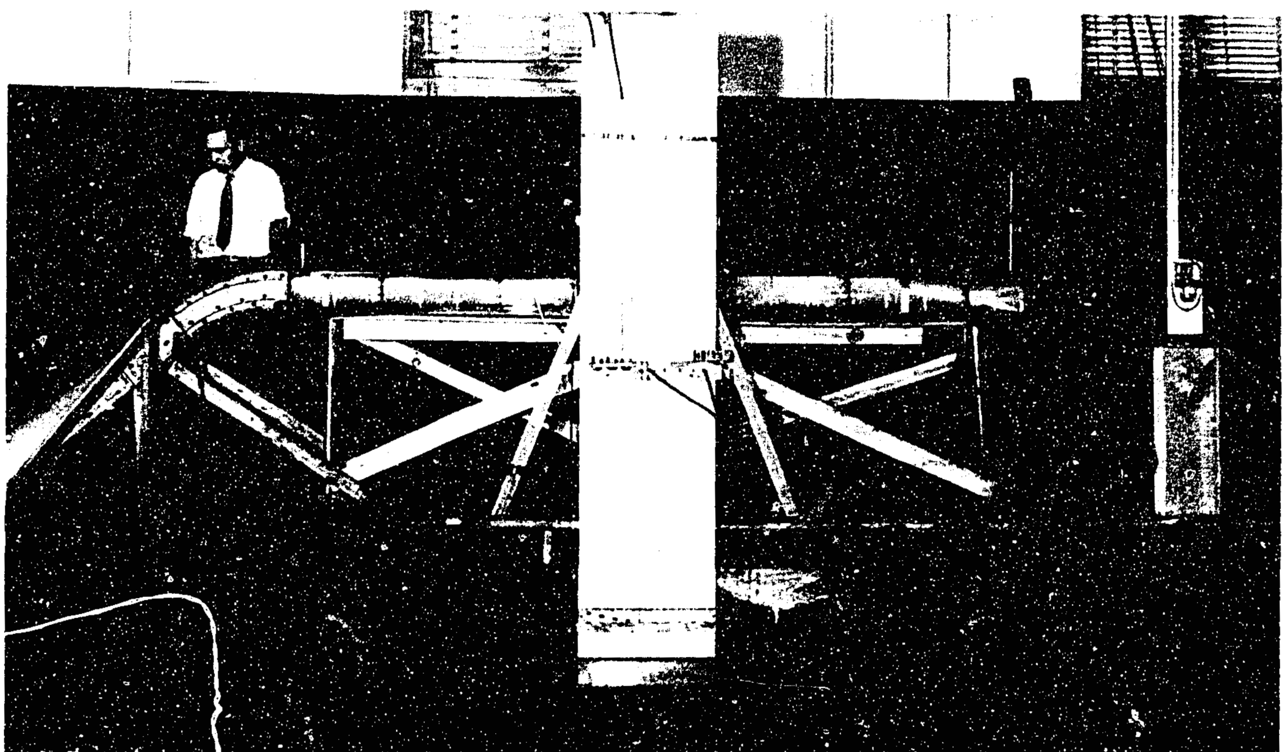


C. Discharge stopped by high speed photography. Gate 100 percent open; 41 degree-19 minute elbow.

BHAKRA DAM 1:17 MODEL



A. The model showing exit elbow.



B. Discharge through outlet with gate 80 pecent open.

BHAKRA DAM 1:17 MODEL

Flow from the exit and down the spillway, Figures 53B and 54A, appeared satisfactory developing no fins under all operating conditions except with the control gate less than 15 percent open. For gate openings less than 15 percent, a small fin and splash occurred in the center of the trough, caused by the jet striking the floor of the trough and also by flow along the sides of the trough turning inwards to form the fin. This condition was not objectionable because of the small flows involved. Figure 54B shows the flow on the face of the spillway taken with a high-speed camera. With the motion stopped, the appearance of the jet was more like the prototype outlets in Grand Coulee Dam than observed on the model by eye alone. This would suggest increased use of high-speed photography in future model tests. It must be pointed out, however, that the model head of 41 feet of water at which the photographs were taken was considerably above the maximum scale head of 10.94 feet.

Negative pressures occurred in the upstream portion of the conduit directly downstream from the gate as anticipated, but the positive pressures occurring near the elbow was unexpected. These positive pressures showed that the exit was sealed. This resulted in the suggestion that air be taken from the top of the conduit at the elbow and diverted into the offset at the bottom of the elbow, since there was considerable air demand at this point. Accordingly, the standpipe at the end of the straight conduit was opened (shown in Figure 46A), and some air was ejected through this pipe which, it was thought, might be used to vent the offset at the bottom of the elbow. However, when the head of the model was increased beyond the maximum scale head, insufflation of air into the water increased and considerable water was ejected from the standpipe, which indicated similar water ejection might occur in the prototype, so this method of providing air to the step was abandoned.

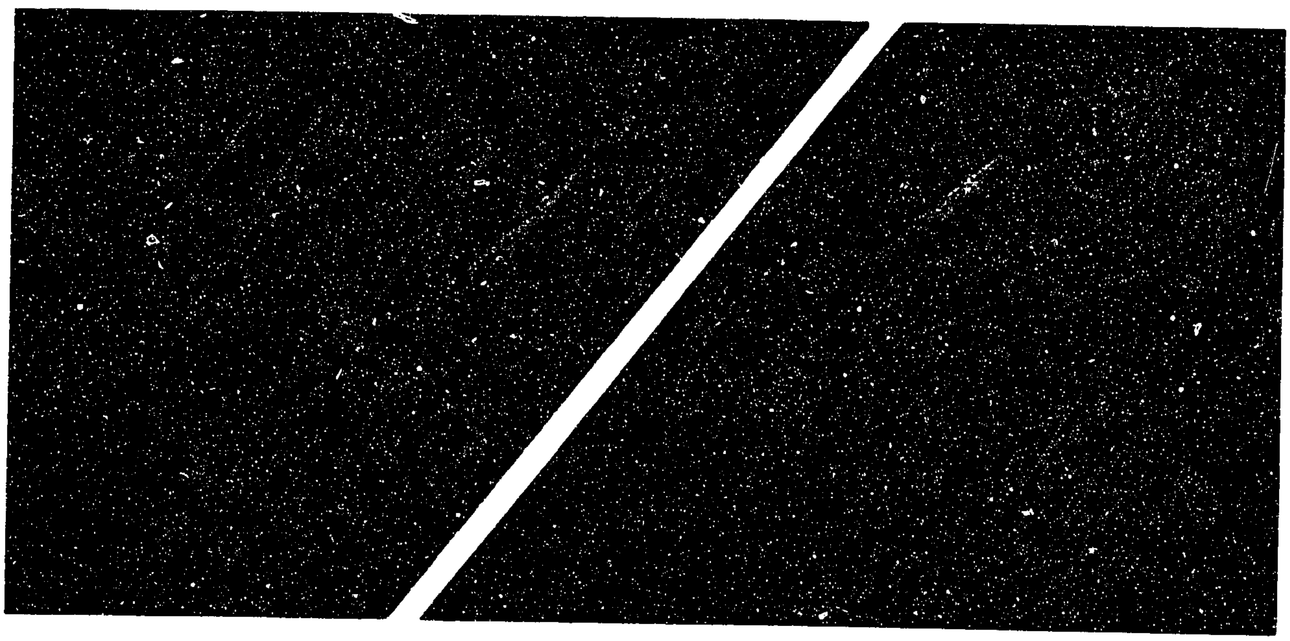
Pressure readings were made on the piezometers in the conduit, elbow, trough, and spillway face. Figure 55A shows the piezometer locations. The results of these tests, based on a design head of 288 feet prototype, are shown in Figures 55B through 55F. The minimum pressure on the bottom of the elbow was found to be less than 6 feet

Gate 100 percent open.

Gate 50 percent open.

Gate 25 percent open.

A. Flow as observed.

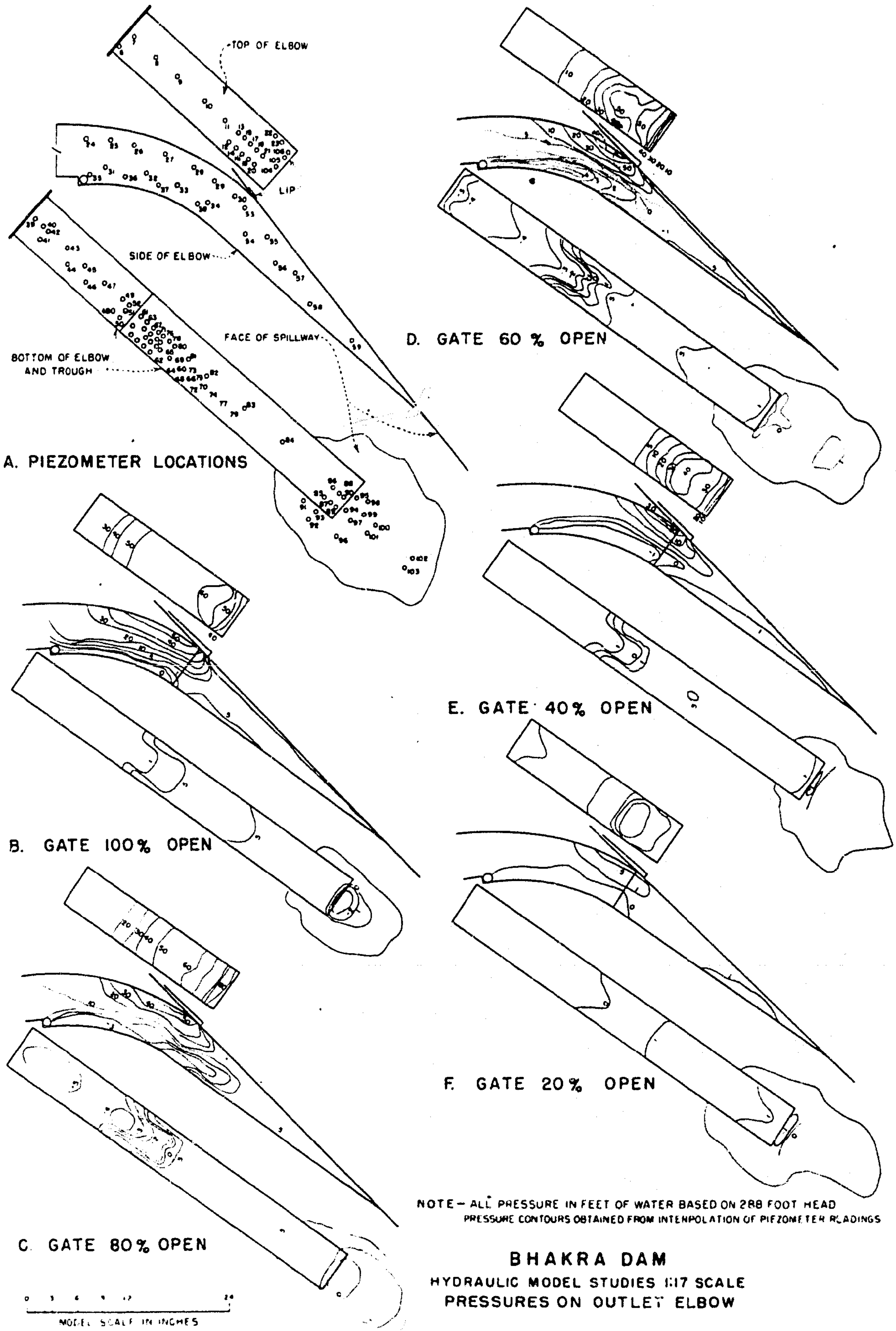


Gate 80 percent open.

Gate 40 percent open.

B. Flow stopped by high speed photography.
(Exposure 1/20,000 second; velocity 50 feet per second.)

BHAKRA DAM 1:17 MODEL



NOTE — ALL PRESSURE IN FEET OF WATER BASED ON 288 FOOT HEAD
PRESSURE CONTOURS OBTAINED FROM INTERPOLATION OF PIEZOMETER READINGS

BHAKRA DAM
HYDRAULIC MODEL STUDIES 1:17 SCALE
PRESSURES ON OUTLET ELBOW

below atmospheric. At no point in the exit section was there subatmospheric pressures sufficiently intense to cause cavitation in the prototype. In addition to the bottom of the elbow, subatmospheric pressures existed on the face of the spillway immediately below the intersection with the trough. Both of these regions were vented, the bottom of the elbow by an 18-inch pipe, and the face of the spillway by three 8-inch pipes as shown in Figure 46D. Past experience on both model and prototype structures have always shown low pressures on the spillway face below the intersection of the trough. To prevent destructive action because of these low pressures venting of this region is essential. In the preliminary design of the elbow roof, the assumed pressures were greater than those found in the model studies, so verification of the pressures was desirable. This was possible by calculating the force required to turn the jet since its mass and velocity were known. The close agreement of these calculations with the model values was considered satisfactory confirmation of the tests.

A test was next run to determine if the offset at the junction of the elbow floor and conduit could be eliminated. The joint between elbow and conduit was made flush by filling the offset with wax. Piezometers were installed and pressures again measured. Severe negative pressures were found and after the third run, the wax was loosened and carried away by the water. It was concluded that this design was unsatisfactory. With the wax filler removed the air-vent to the offset was plugged and pressures were again measured. Although negative pressures were more intense than with the vent open, they were not sufficiently severe to be considered detrimental. While this test indicated that it would be possible to eliminate the vent, it was decided that it should be installed in the prototype to obtain a safe design. A similar stopping of the air-vents to the spillway face below the junction with the trough resulted in severe negative pressures conducive to cavitation. This demonstrated that these air-vents were essential.

1:32 MODEL OF RIGHT DIVERSION TUNNEL

Model Construction

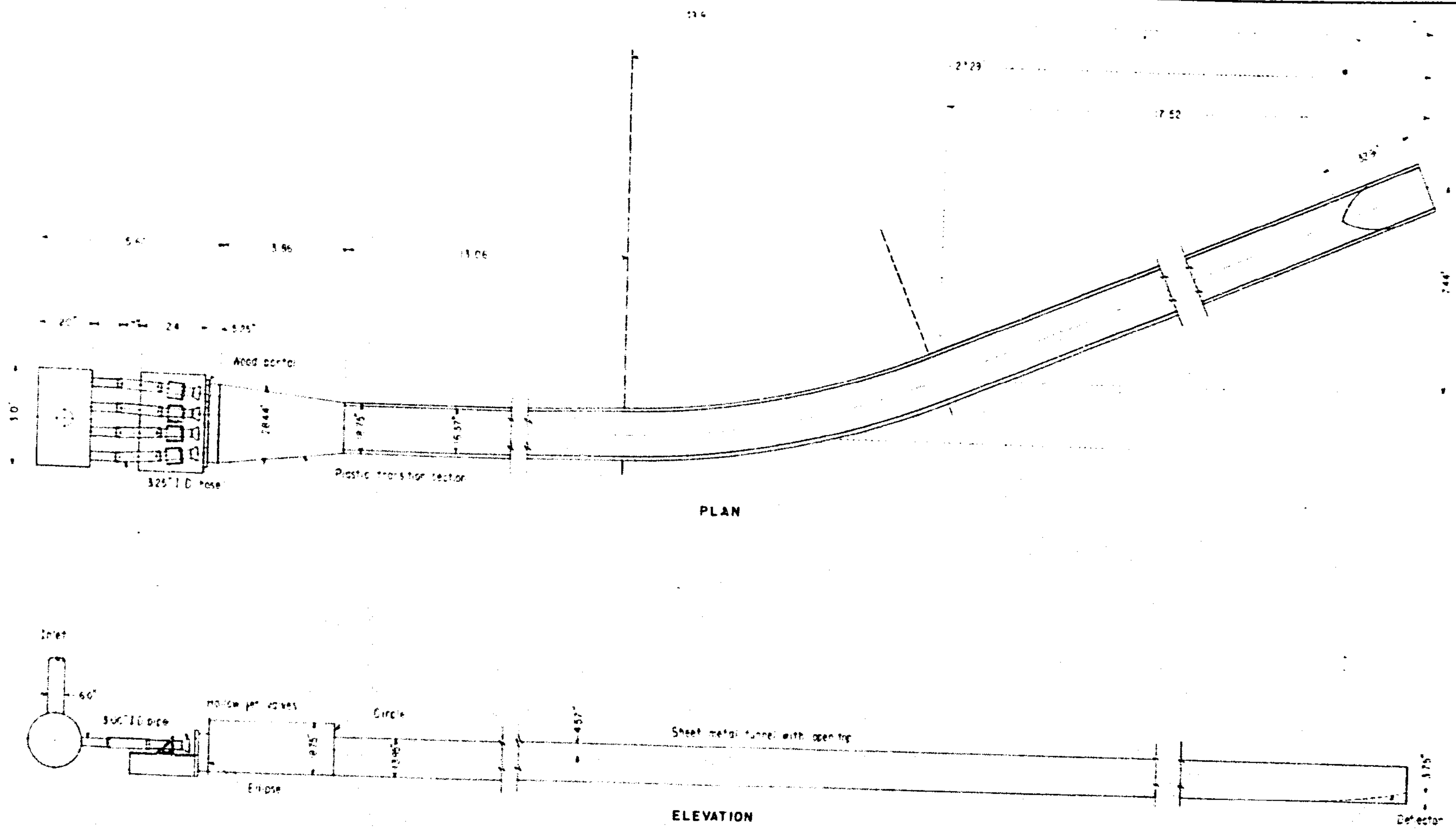
Description of model. This model on a scale of 1:32 was of the portion of the right diversion tunnel starting with the valves and ending with the tunnel portal. The transition section below the valves was made of transparent plastic while the tunnel from the transition to the portal was made of sheet iron with an open top. There were four 3-inch hollow-jet model valves at the upper end of the transition section. These valves were mounted with brackets to a metal covered platform and connected by sections of rubber hose to a 20-inch diameter head tank. This arrangement permitted adjustment of the horizontal angle of the valves. For vertical angle adjustment wedge-shaped filler pieces were used between the ends of the pipe and the valves. The extent of this model is shown in Figure 56. Flow of water through the model was measured by venturi meters and pressure readings were made in the pipe upstream from one of the valves.

Results

Alinement of valves. The prototype plan and sections of the right diversion tunnel are shown in Figure 5. The maximum discharge of the model for 4 valves operating was 3.68 second-feet, corresponding to a discharge of 21,300 second-feet in the prototype with reservoir elevation of 1573 feet. With all 4 valves fully open and the reservoir elevation at 1400, the minimum elevation for operation of the right tunnel, the discharge was 2.76 second-feet in the model, or 16,000 second-feet in the prototype. The first test was to determine the proper angles at which the valves should be set for best distribution of flow in the tunnel. In the original design the two outside valves converged toward the center, each with a horizontal angle of 6 degrees and with no vertical angle. The two inside valves each converged toward the center with a horizontal angle of 1 degree and an upward vertical angle of 2-1/2 degrees.

The model was operated with the valve angles set as in the original design. With all 4 valves open the distribution of flow appeared

FIGURE 56



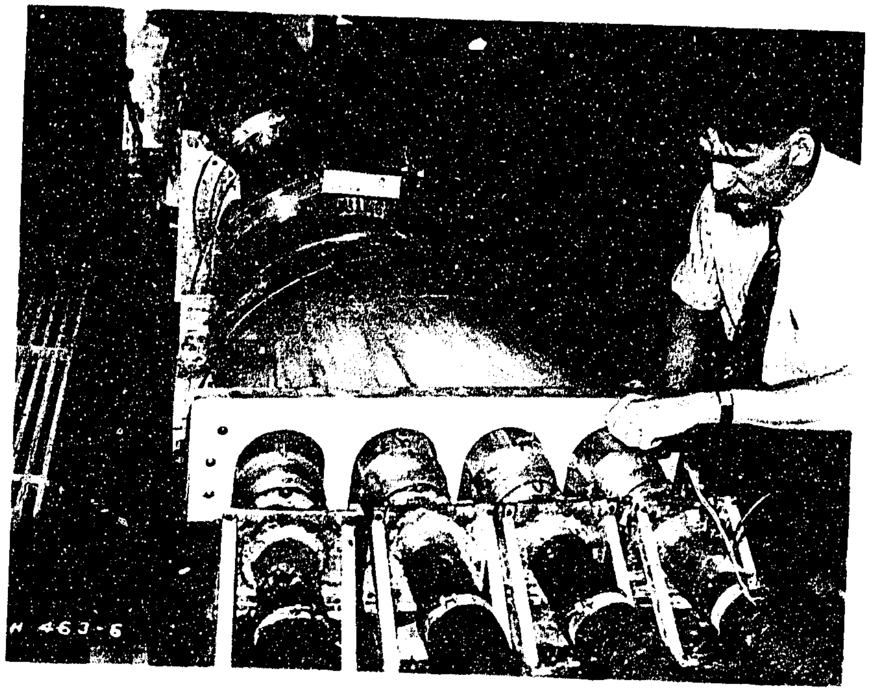
BHAKRA DAM
RIGHT DIVERSION TUNNEL
1:32 MODEL– ORIGINAL DESIGN

satisfactory. The jets from the 2 outside valves were parallel to the sides of the transition section and struck the floor at the end of this section for maximum discharge. The 2 inner jets carried farther downstream before striking the tunnel invert producing a more or less uniform depth to the water in the tunnel. The next operation was with 1, 2, and 3 valves in various combinations. Satisfactory flow down the tunnel was obtained except when operating either outside valve alone. In these cases the water climbed the wall of the tunnel on the opposite side from the valve, but not sufficiently to overtop the side of the open tunnel. In all operations the elbow in the tunnel caused the water to rise to some extent on the right side of the tunnel below the elbow, then deflect back to the left side and again to the right side just before reaching the end of the tunnel. Figures 57 through 59 show the flow at various conditions as explained under the photographs.

The next operation was with several different angle settings on the valves to determine whether improvement could be made in the alinement of the jets. The outside valves were limited to a small change in the horizontal angle because of their close proximity to the transition walls. It was desirable to decrease the horizontal angle of these valves, but to do this would have required an increase in the length of the transition section. Since this change was not warranted the studies were made with the original transition section. If improvement resulted in any of these tests it was too slight for detection by visual observation. Accordingly, the original design was considered satisfactory.

Deflector at portal. A deflector was installed at the tunnel portal to lift the issuing jet to improve the flow in the river channel and decrease the scour of the riverbed. The flow without a deflector, in the 1:80 model, is shown in Figure 60. The scour below the portal after 2 hours operation, Figure 12, caused a hole about 25 feet deep. The first deflector design tried is shown in Figure 61A, which was the same as that used on Tunnel No. 4 at Boulder Dam. Figure 62 shows operation of this deflector at discharges of 10,000 and 21,300 second-feet. The 18-foot rise of this design was too high because it was difficult

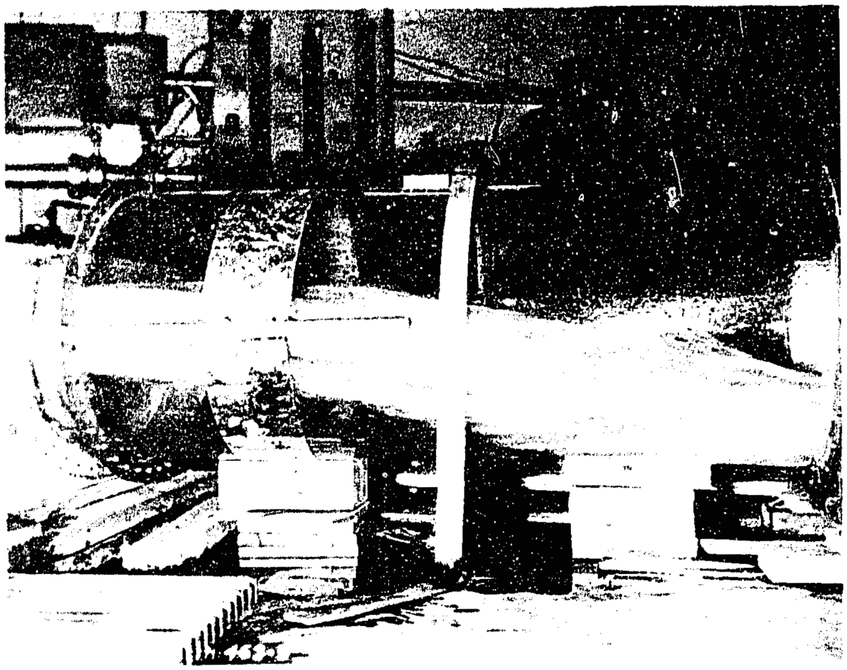
FIGURE 57



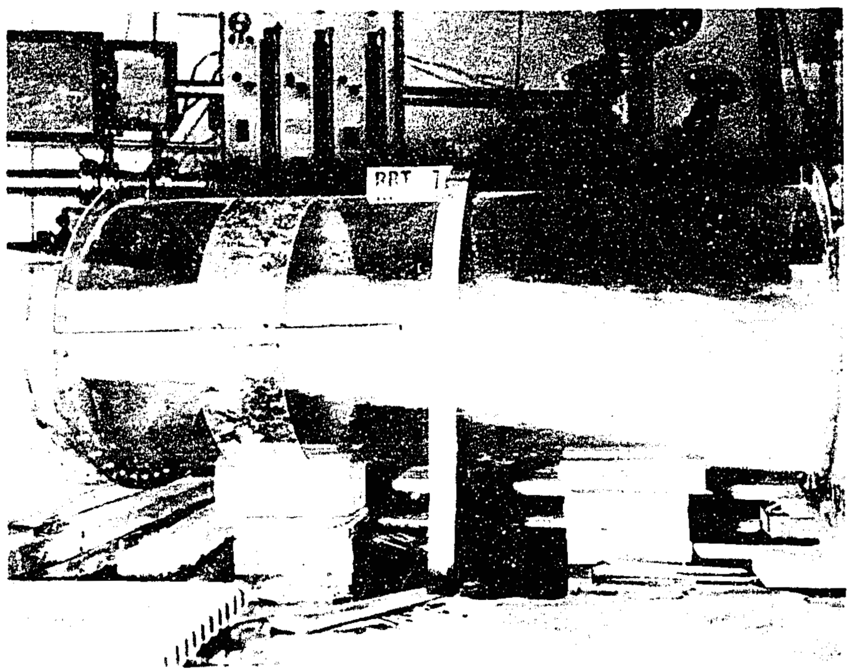
A. Looking downstream into transition section.

B. Looking upstream into transition section.

OPERATION OF FOUR TUNNEL OUTLET VALVES
DISCHARGE 21,300 SECOND-FEET
BHAKRA DAM 1:32 MODEL



A. Discharge 16,000 second-feet.

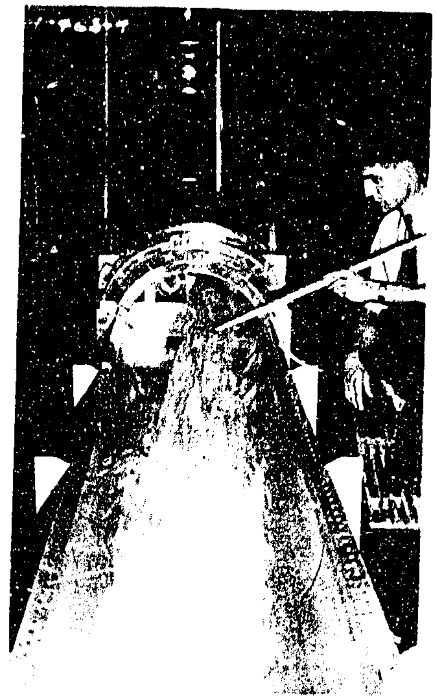


B. Discharge 21,300 second-feet.

FLOW THROUGH TRANSITION SECTION WITH
OPERATION OF FOUR TUNNEL OUTLET VALVES
BHAKRA DAM 1:32 MODEL

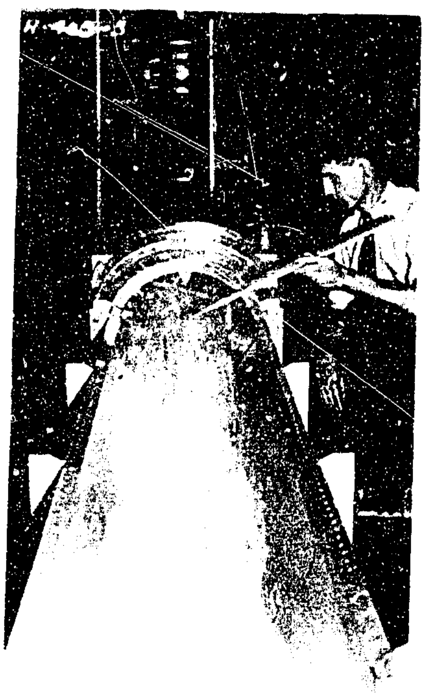
FIGURE 59

A. No. 1 valve operating.



B. No. 2 valve operating.

Discharge 5,375 second-feet



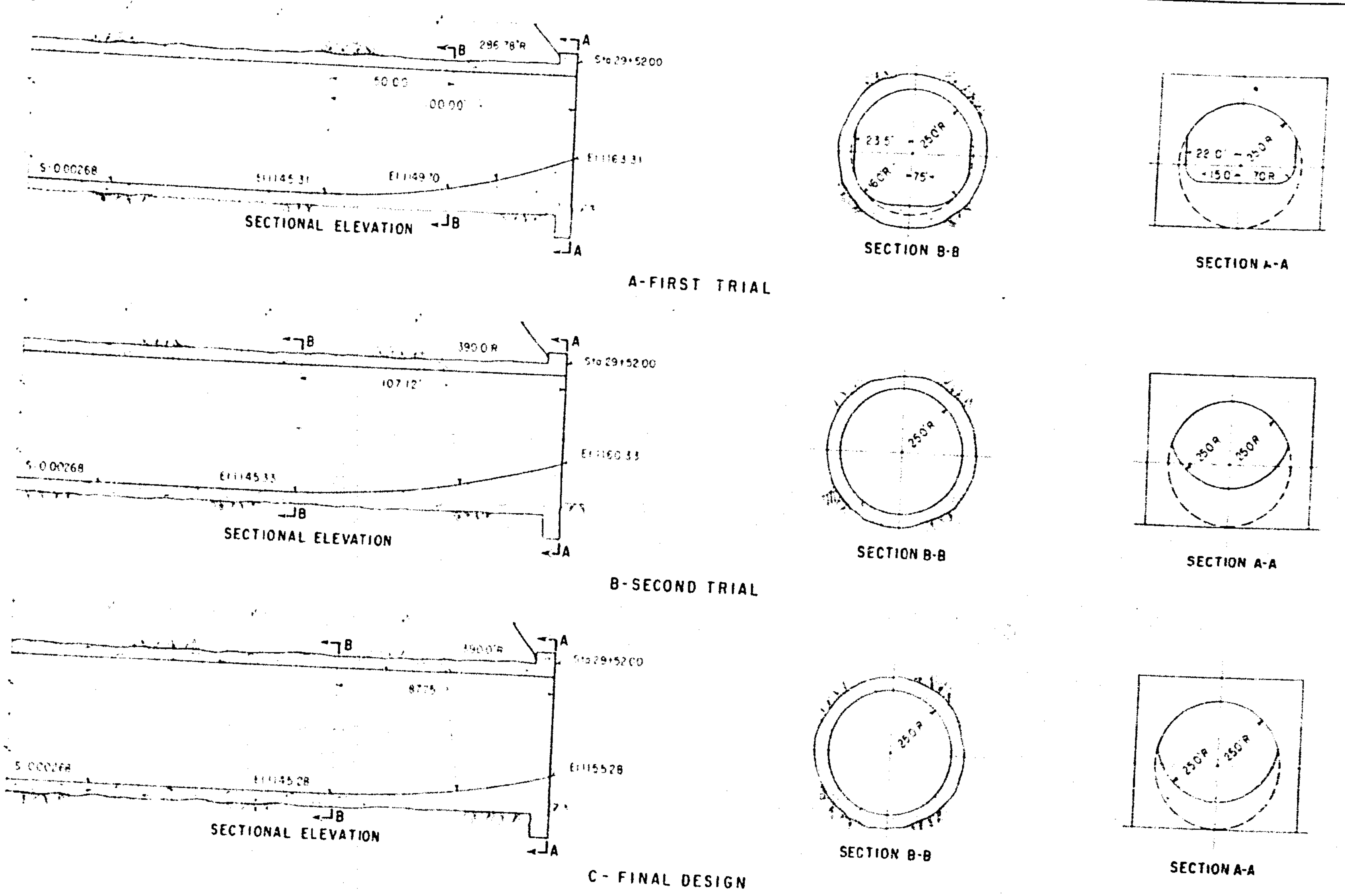
C. Nos. 2 and 3 valves operating.

D. Nos. 1 and 4 valves operating.

Discharge 10,650 second-feet

FLOW LOOKING INTO TRANSITION SECTION
BHAKRA DAM 1:32 MODEL

RIGHT DIVERSION TUNNEL—DISCHARGE 21,300 SECOND-FEET, NO DEFLECTOR
BHAKRA DAM 1:80 MODEL



BHAKRA DAM

RIGHT DIVERSION TUNNEL DEFLECTOR

FIGURE 61

A. Discharge 16,000 second-feet.

B. Discharge 21,300 second-feet.

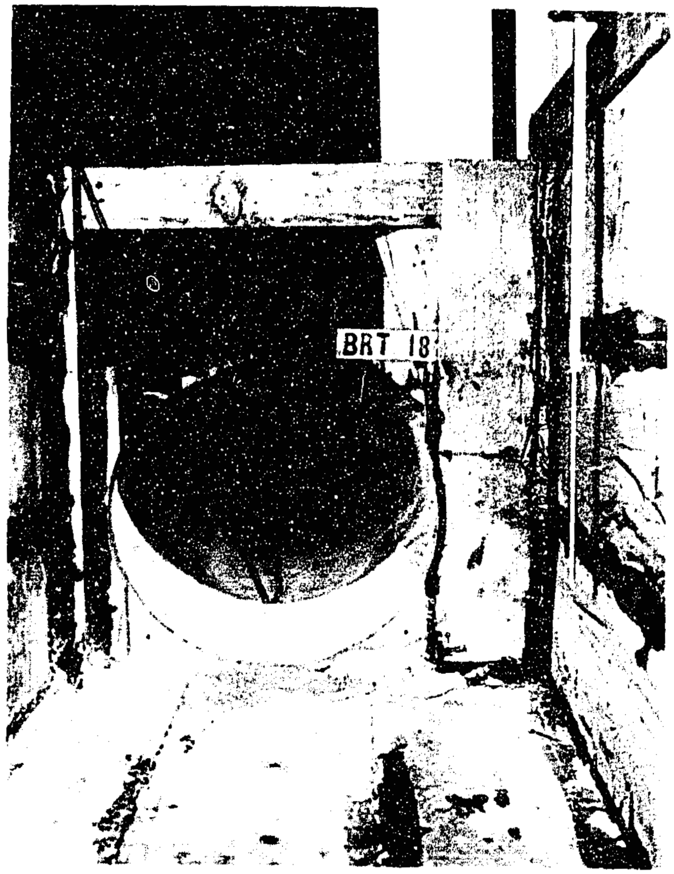
DEFLECTOR RIGHT DIVERSION TUNNEL, FOUR VALVES OPERATING—FIRST DESIGN
BHAKRA DAM 1:32 MODEL

to sweep the hydraulic jump out of the tunnel. The horizontal lip of this deflector section was undesirable since the concentrated flow in the bottom of the circular tunnel did not distribute uniformly across the opening. At maximum discharge the flow at the lip was concentrated on the left side due to the deflection of the flow from the right side of the tunnel. This deflector was also installed in the 1:80 model, but operation was not successful. The velocity of the jet was insufficient to sweep the hydraulic jump out of the tunnel for some conditions of flow. One large valve was employed for regulation in this tunnel instead of four of the proper size as the latter would have been too small to produce dependable results. The accuracy of the reproduction using the single valve was also questionable so it was decided to abandon the 1:80 model for these deflector studies.

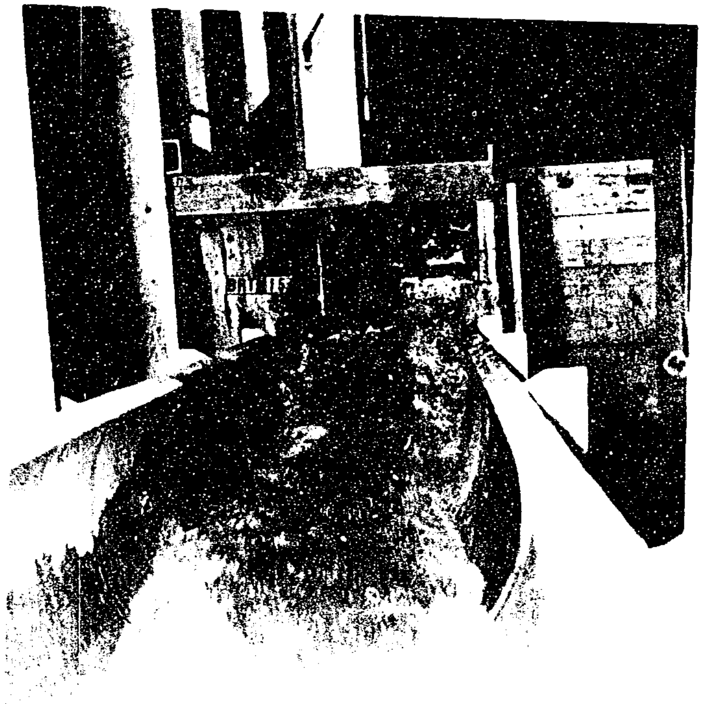
In the second deflector design on the 1:32 model, Figure 61B, the circular tunnel section was maintained throughout and the lift was reduced to 15 feet. Distribution of flow at the end of the deflector was better than in the previous design for all discharges, but difficulty was still experienced in moving the jump out of the tunnel. It was decided that acceptable flow conditions in the river channel appeared obtainable with less rise of the jet. This reduction would also make it easier to sweep the hydraulic jump out of the tunnel. No photographs were taken of this installation.

The third design, Figure 61C, and illustrated in Figure 63, was the same as the previous one except that a rise of 10 feet was used instead of 15 feet. The operation of the deflector at various discharges, Figure 64, showed satisfactory distribution of flow across the lip. To sweep out the tunnel required less energy than in the 2 earlier designs. The jet was lifted sufficiently to give good flow conditions in the river channel, but this was considered to be the minimum rise that should be used. From these studies this third deflector was selected as the final design.

Operation characteristics. With the final deflector design at the tunnel portal, additional studies could be made to determine conditions



DEFLECTOR ON RIGHT DIVERSION TUNNEL
FINAL DESIGN—LOOKING UPSTREAM
BHAKRA DAM 1:32 MODEL

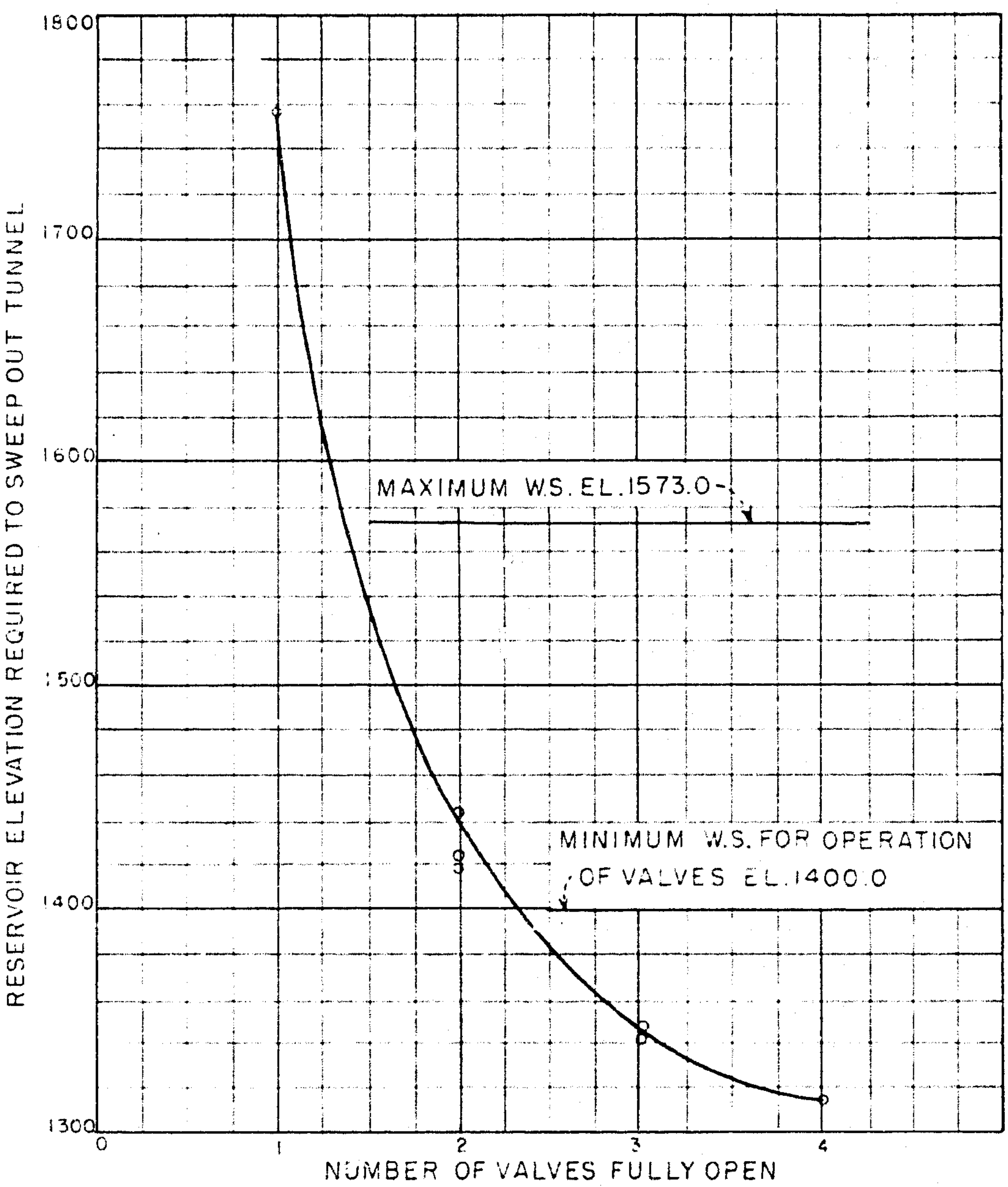


A. Discharge 16,000 second-feet.

B. Discharge 21,300 second-feet.

DEFLECTOR RIGHT DIVERSION TUNNEL, FOUR VALVES OPERATING—FINAL DESIGN
BHAKRA DAM 1:32 MODEL

necessary to prevent the existence of a hydraulic jump in the tunnel. In starting the valves, a jump will form due to the action of the jet against the tailwater. If the energy of the jet is sufficient the jump will move downstream until it is swept out of the tunnel. Various combinations of valves from 1 to 4 in number were operated and measurement was made of the minimum reservoir elevation required to sweep out the tunnel with a constant tailwater of elevation 1169. This data is shown plotted in Figure 65. From the curve it is apparent that with 3 or 4 valves fully open the jump will be swept out of the tunnel for any reservoir elevation in the operating range of 1400 to 1573 feet. With 2 valves fully open the reservoir should not be below elevation 1450 and at no time will the reservoir elevation be sufficient with only 1 valve operating. The required discharge was greater at the lower heads. This was to be expected since the velocity of the jets was lower, and additional energy needed to sweep out the tunnel could only be supplied by an increase in discharge. It is preferable that a jump not be allowed to exist in the tunnel during operation of these outlets. Very little difference in head requirement was found due to the combination of valves for any given number operating.



BHAKRA DAM

RESERVOIR ELEVATION REQUIRED TO MOVE
HYDRAULIC JUMP OUT OF RIGHT DIVERSION TUNNEL

1:100 MODEL OF RIGHT DIVERSION TUNNEL

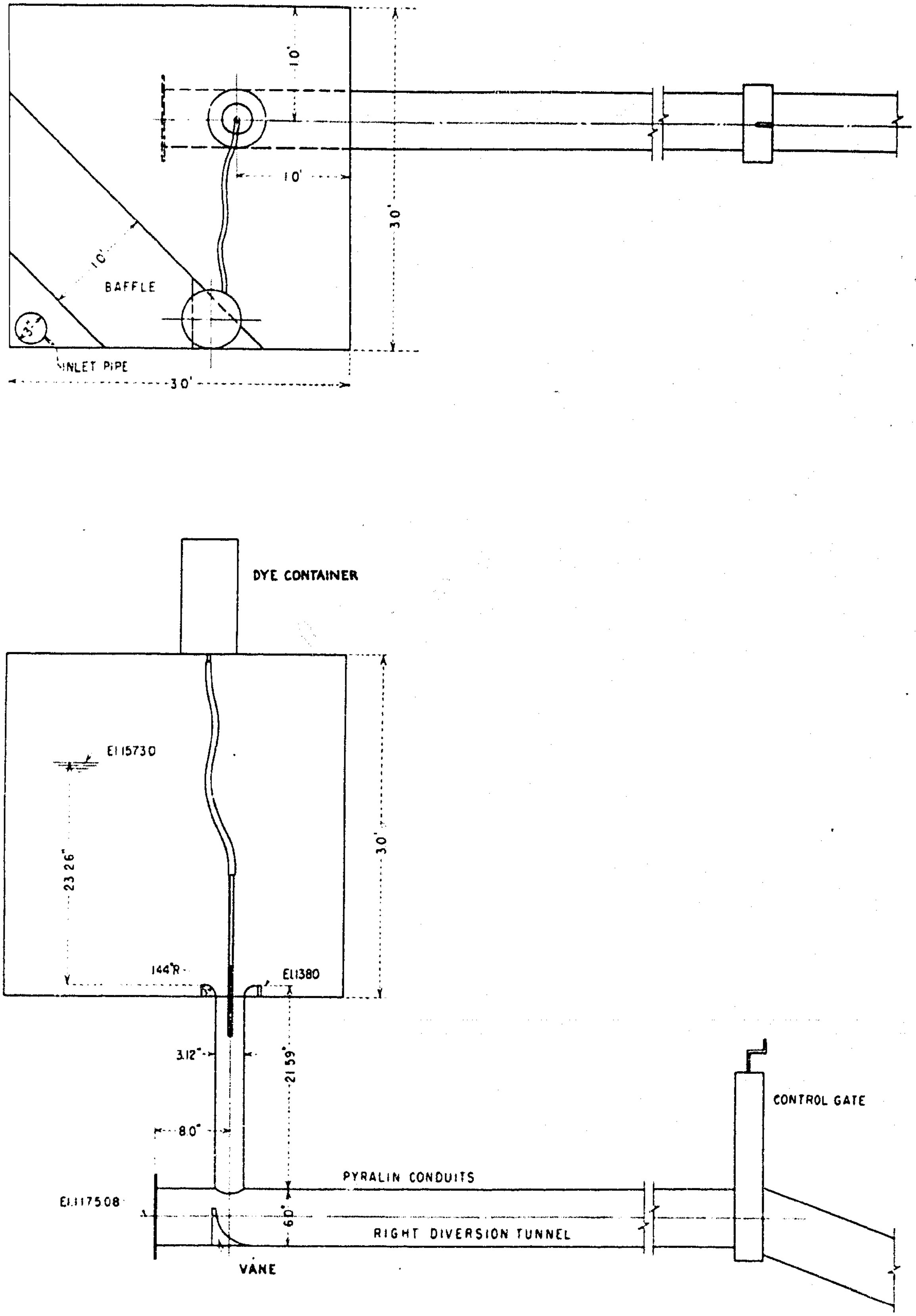
Model Construction

Description of model. A model on a scale of 1:100 was made of the right diversion tunnel upstream from the hollow-jet control valves because this section was not accessible in the 1:80 model for observation of flow. It was desired to learn if a vane was necessary at the junction. The 26-foot diameter shaft from the reservoir to the diversion tunnel and the 50-foot diameter tunnel were made of transparent plastic. The reservoir was simulated by a 3- by 3-foot wooden head box lined with sheet metal. The shaft was connected to the bottom of this box. A glass tube connected through rubber hose to a container was located at the shaft entrance for the introduction of dye into the flow. Numerous piezometers were placed at the elbow formed by the shaft and tunnel. For regulation of the flow a 6-inch control gate was placed at the location of the hollow-jet valves. A plan and section of this model is shown in Figure 66.

Results

Junction with vane. The design of the right diversion tunnel outlet system is shown in Figure 5. This investigation was concerned with study of the flow in the elbow at the intersection of the 26-foot vertical shaft with the 50-foot diversion tunnel, to determine if the proposed junction design was necessary for satisfactory flow at this point. A curved vane with 30-foot radius was placed at the junction in the bottom of the tunnel. The intake structure at the shaft entrance was omitted in these studies since the outlet would not be operated below a reservoir water surface of elevation 1400. This would give a 20-foot depth of water over the crest, so no problem would be encountered with the entrance flow.

In the operation of the model the critical flows were considered to be the maximum flow obtainable at the upper and lower reservoir elevations, which were 21,300 second-feet in the prototype at elevation 1573, and 16,000 second-feet at elevation 1400. This maximum discharge of 21,300 second-feet gave a prototype velocity of 40 feet per second in the 26-foot



BHAKRA DAM

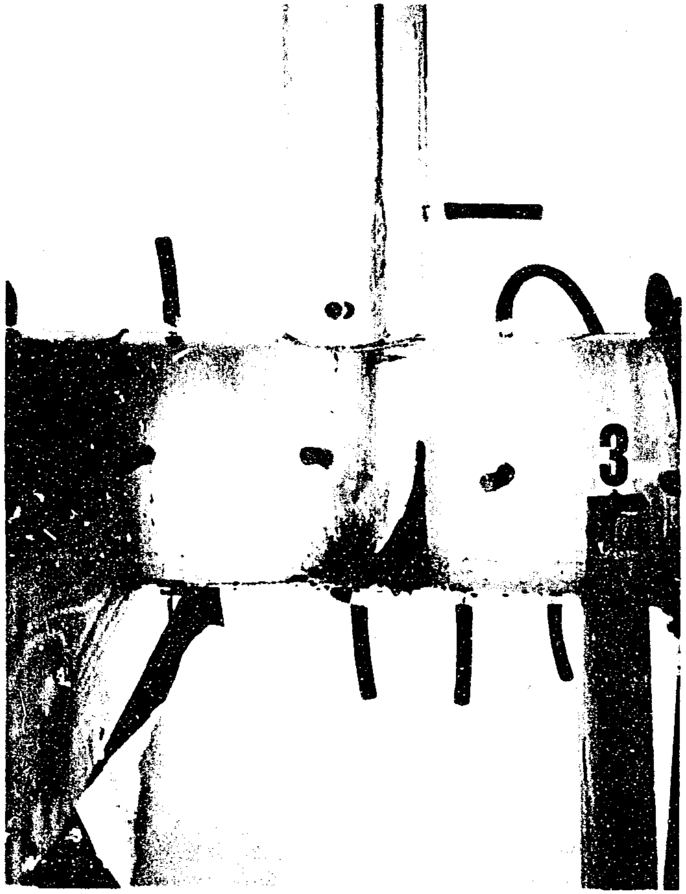
INTAKE SHAFT JUNCTION - 1:100 MODEL

vertical shaft while the lower discharge produced a velocity of 30 feet per second. With these velocities unfavorable flow conditions were expected at the shaft junction. It was necessary to observe this flow to take corrective action. Dye was introduced into the flow at the shaft entrance, and photographs, Figure 67, were taken at the above 2 discharges. In addition, pressure measurements were made under these conditions of flow. The results of the readings are shown in A and B of Figure 68 plotted as lines of constant pressure in feet of water, with scales showing the pressure for static head at the same reservoir elevation also indicated for purposes of comparison. The lines of constant pressure shown on these sections are along the periphery of the tunnel.

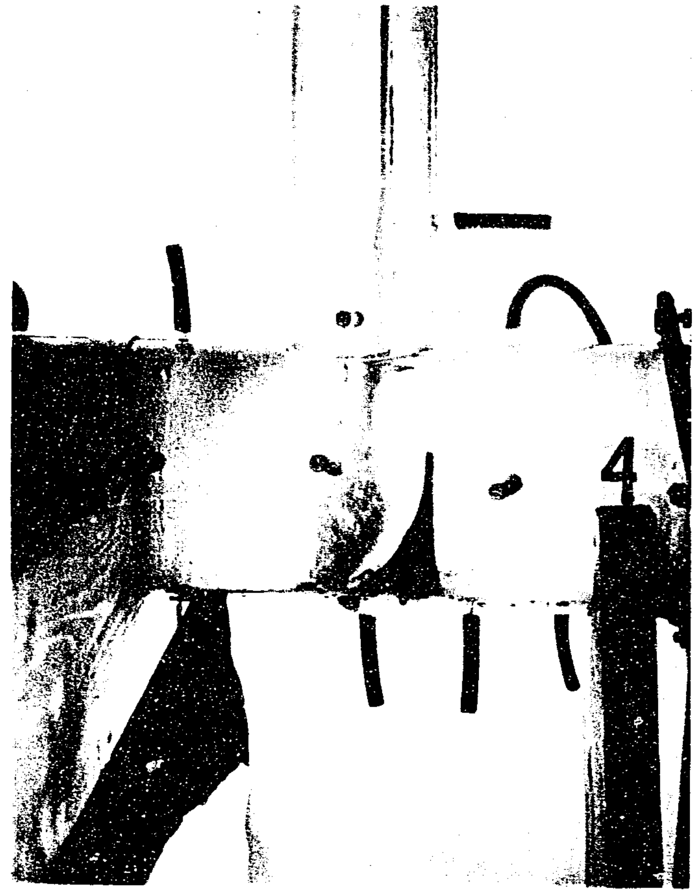
Referring to the photographs, it is seen that the vane caused a greater turning of the flow than planned. Instead of moving horizontally downstream the water was deflected upward against the roof of the tunnel where it was again deflected in a downward direction. This condition created a very turbulent flow that tended to smooth out as the water proceeded down the tunnel. Upstream from the vane no movement of the water occurred with the result that the pressure distribution was very uniform in this section. The pressure distribution from the vane downstream was surprisingly uniform considering the turbulence of the flow. The greater intensity of pressure over the vane was expected and is not considered as an unfavorable condition.

Junction without vane. The vane in the elbow was removed from the model and studied again at the same conditions of flow. Photographs and pressure measurements were made at the discharges of 21,300 and 16,000 second-feet corresponding to the reservoir at elevations of 1573 and 1400. These photographs are in Figure 69, and the results of the pressure readings, plotted as in the first studies on the original design, are shown in Figures 68C and 68D.

With the vane removed the water was not turned until the floor of the tunnel was reached resulting in most of the flow being confined to the lower section of the 50-foot tunnel. However, this flow was very uniform, without the noticeable turbulence that existed in the previous design. It should be mentioned here that the photographs do not show

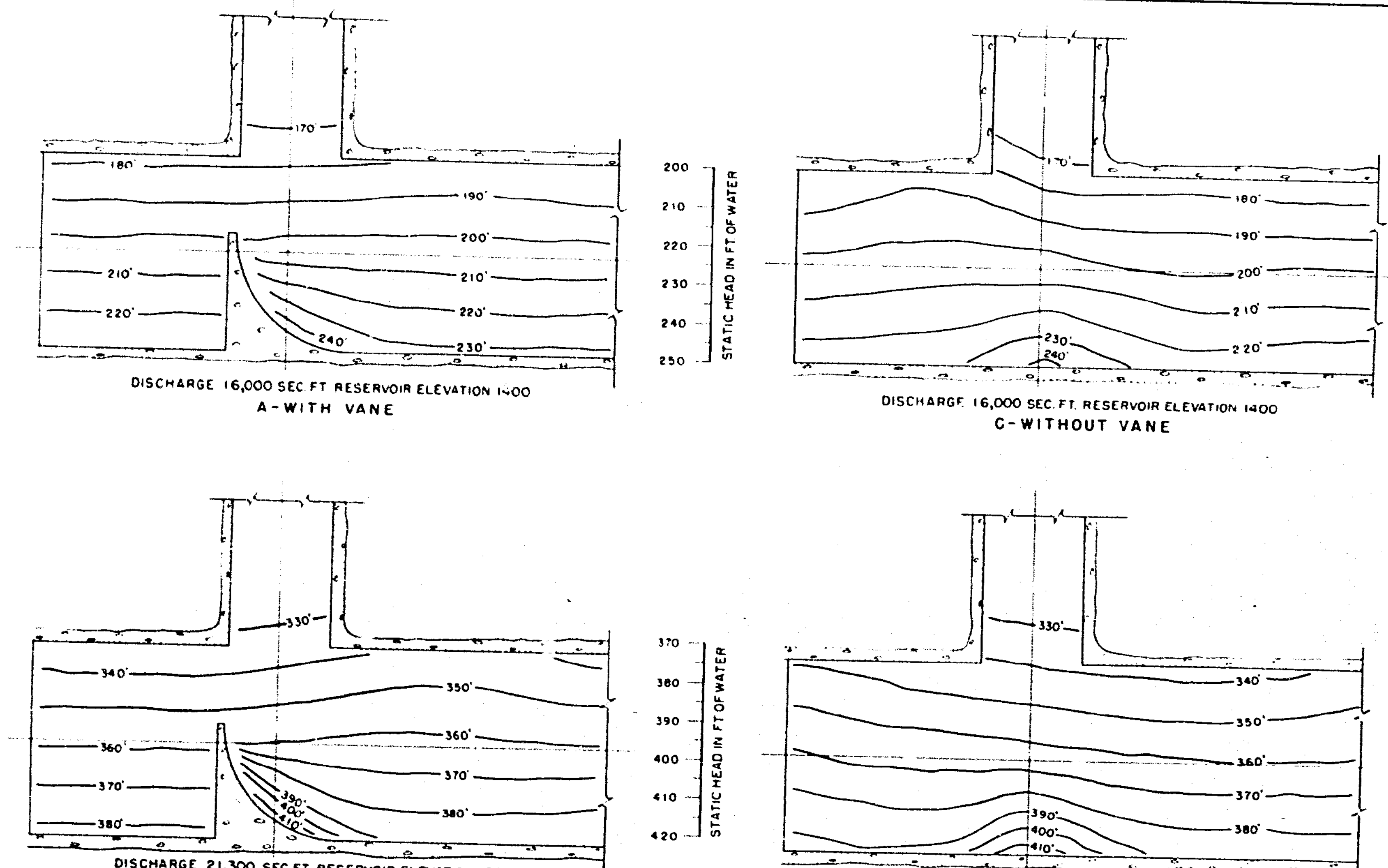


A. 21,300 second-feet; reservoir elevation 1573.



B. 16,000 second-feet; reservoir elevation 1400.

FLOW IN INTAKE SHAFT JUNCTION—WITH VANE
BHAKRA DAM 1:100 MODEL



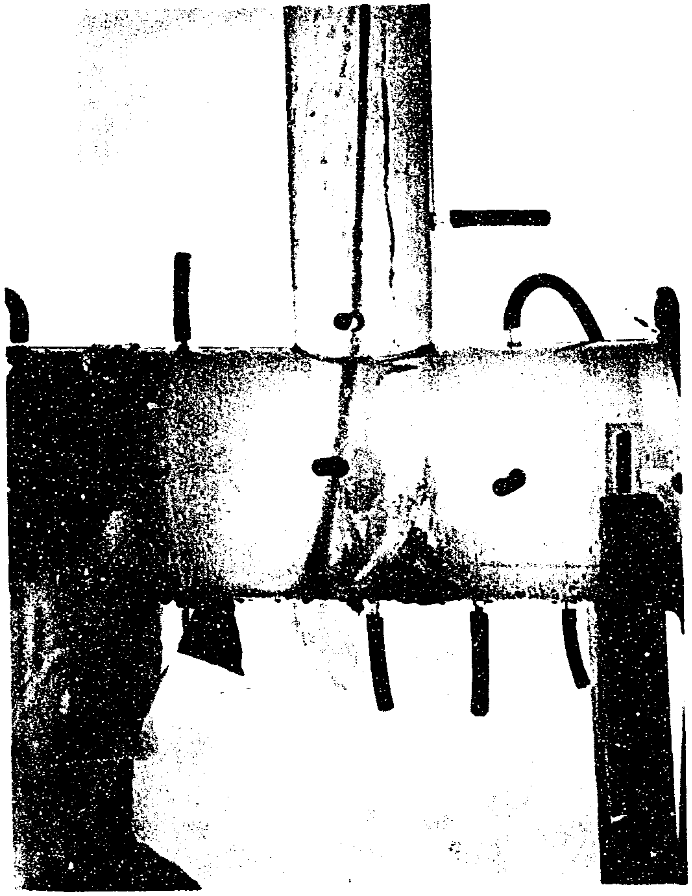
DISCHARGE 16,000 SEC.FT. RESERVOIR ELEVATION 1400
A-WITH VANE

DISCHARGE 16,000 SEC.FT. RESERVOIR ELEVATION 1400
C-WITHOUT VANE

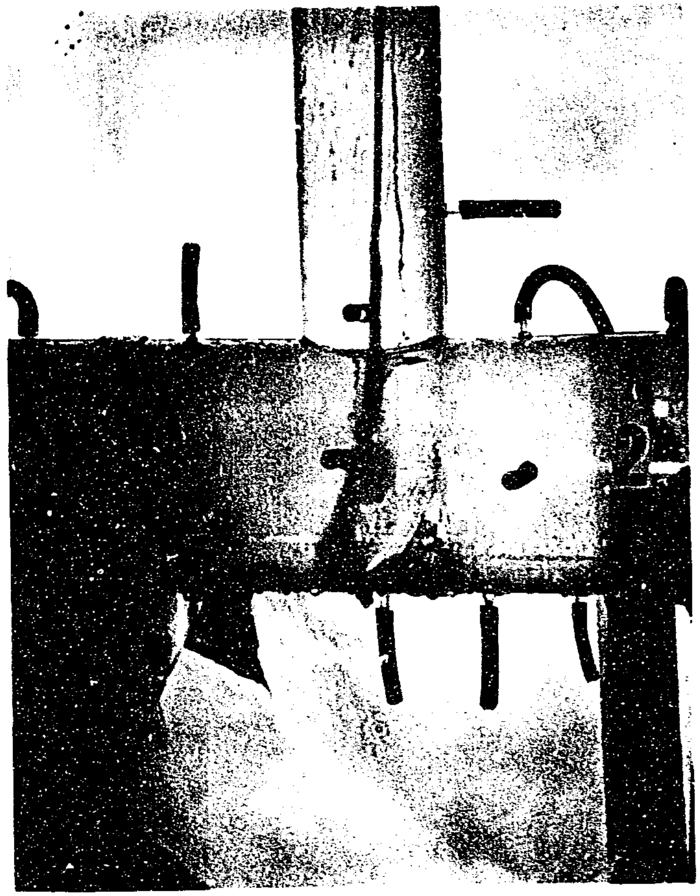
DISCHARGE 21,300 SEC.FT. RESERVOIR ELEVATION 1573
B-WITH VANE

DISCHARGE 21,300 SEC.FT. RESERVOIR ELEVATION 1573
D-WITHOUT VANE

BHAKRA DAM
CONSTANT PRESSURE LINES IN FEET OF WATER
INTAKE SHAFT JUNCTION



A. 21,300 second-feet; reservoir elevation 1573.



B. 16,000 second-feet; reservoir elevation 1400.

FLOW IN INTAKE SHAFT JUNCTION—WITHOUT VANE
BHAKRA DAM 1:100 MODEL

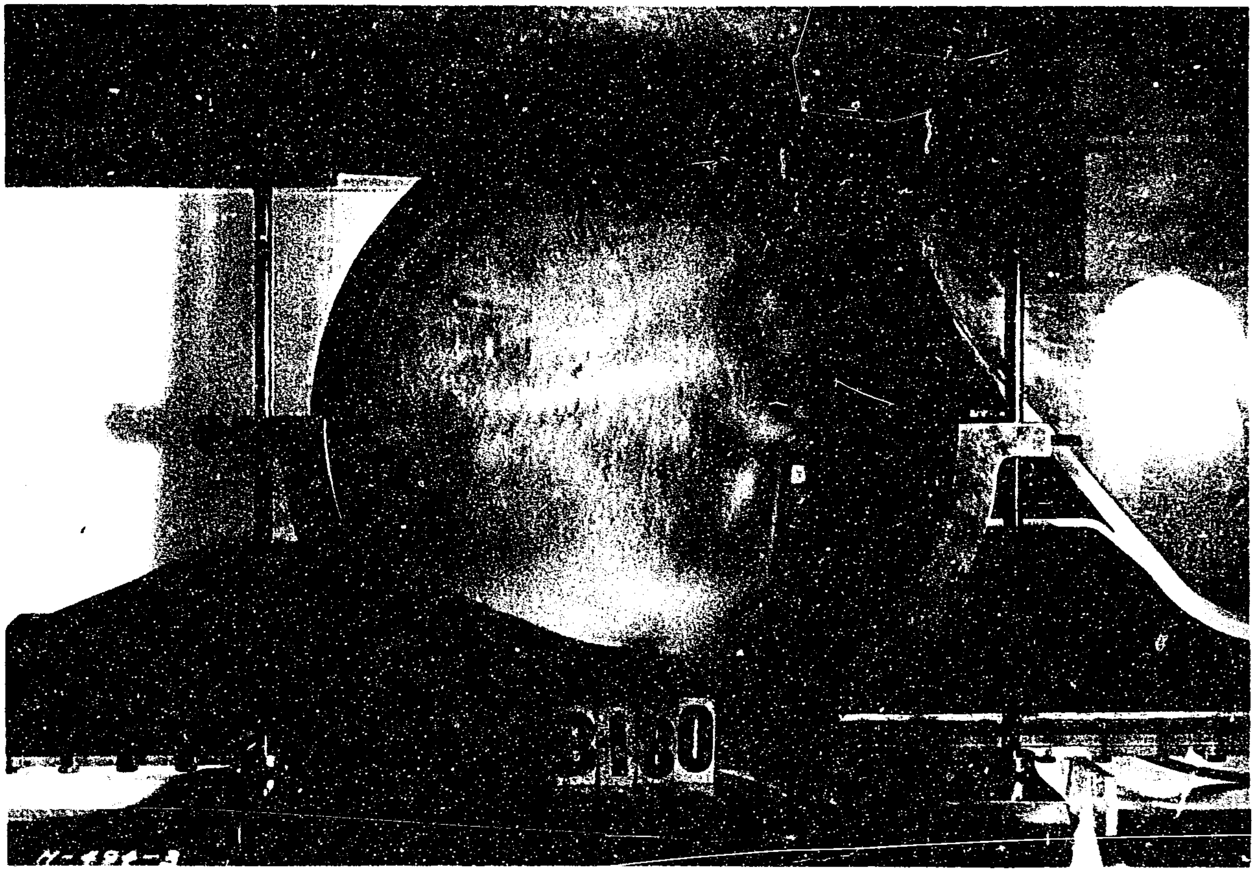
the difference in the 2 designs clearly. The movement of water upstream from the intersection of the shaft and tunnel made it appear that part of the flow was being deflected upstream. Actually, this movement did not represent any substantial flow since it was only a continuous rotation of the water confined to this region, induced by the passing of the jet from the shaft across the end of this section. The lines of equal pressure did not vary greatly from that found in the original design except over the vane. Here the constant pressure lines were less dense than with the vane in place, but the maximum intensity was about the same in both cases.

The pressure distribution and conditions of flow in the elbow are the 2 factors governing the selection of design. However, in making a choice, the first consideration can be neglected since only minor pressure changes resulted from removal of the vane. From the second consideration, the design without the vane is superior and will result in a small saving in construction costs. Accordingly, it is recommended that the structure be built without a vane.

Results

Fluid polariscope model. The conditions of flow upstream from the dam were desired to learn if suspended solids, especially colloids, would be carried from the lower levels of the reservoir through the lower tier of outlets and into the river downstream. The Indian engineers maintain that to store this material in a reservoir is to starve the irrigable lands downstream. The outlets were designed to achieve this condition as far as possible. None of the previous models were constructed such that the outlet operation could be observed in this region. For this particular study of a small 2-dimensional model was built of the main spillway section on a scale of 1:480. The model of 1/2-inch width was mounted between 2 plates of transparent plastic. Fluid used in the model was a solution of optically active bentonite and distilled water. A plane-polarized lens and a quarter-wave plate was placed between one face of the model and a diffused light source, with a second polarizer and a quarter-wave plate on the opposite or viewing side of the model. The polarized light passing through the stream was modified by the bentonite solution making visible colored bands or fringes where a particular rate of change in speed of the fluid prevailed.

In the operation of the model, studies were limited to visual observations of flow conditions. A small motor-driven pump circulated the fluid, but no measurement of the flow was attempted. The speed of the pump was regulated to give flow through the outlets and over the spillway while maintaining such tailwater as to give a satisfactory jump on the apron. Flow at appreciable velocities occurred throughout the entire depth and length of the reservoir section of the model. The flow entering the bottom of the trashrack structure came directly from the reservoir floor which is the region of solids concentration. Of course, the 2-dimensional model indicated higher velocities in the reservoir at appreciable distances upstream from the dam than will actually occur in the prototype. The width of flow will be greater in the reservoir of the prototype with consequent lower velocities. Figure 70 shows flow in the section of the model upstream from the dam. The dark fringes on the



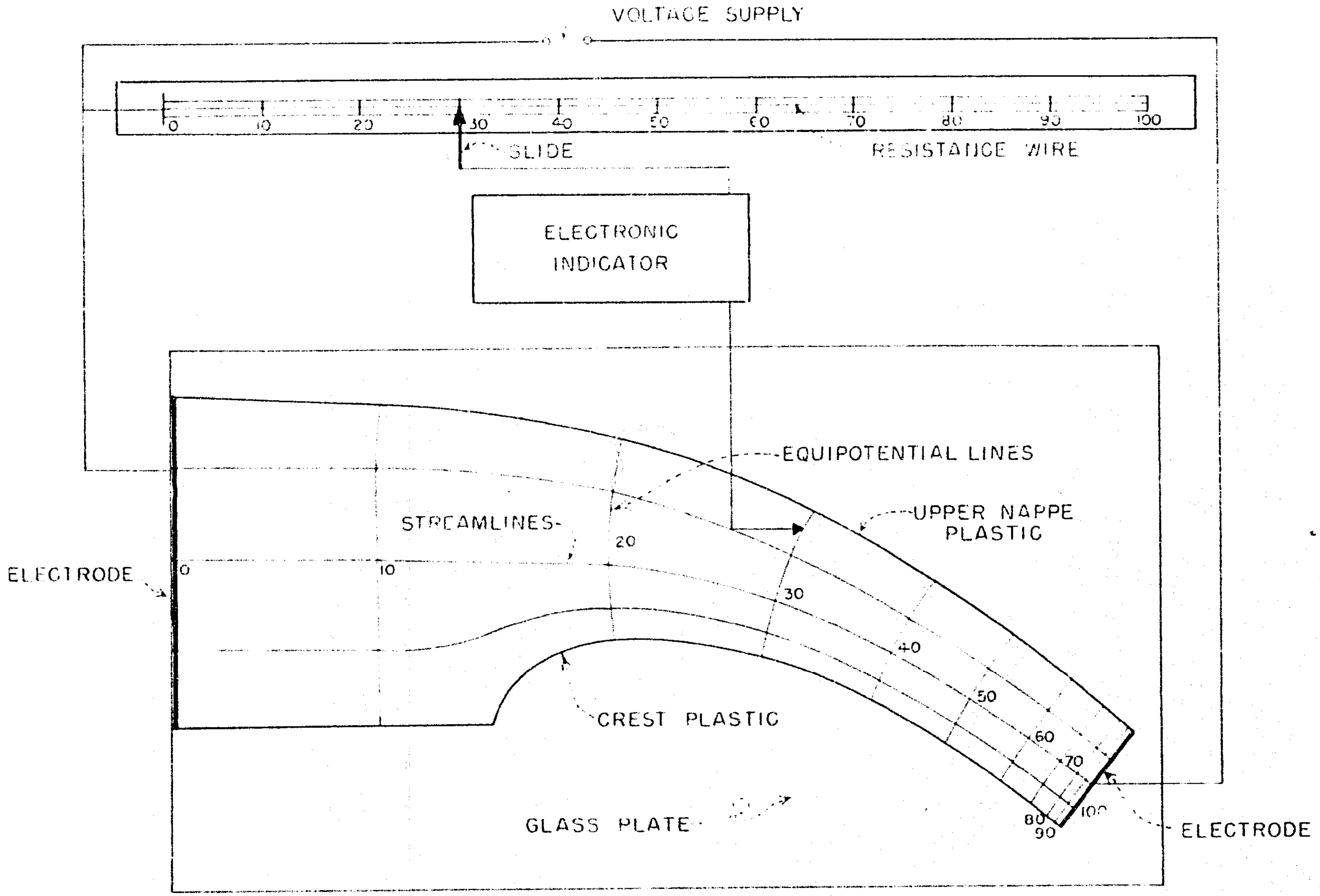
FLOW THROUGH FLUID POLARISCOPE SHOWING FRINGES
BHAKRA DAM 1:480 MODEL

FIGURE 70

upstream face of the dam are lines of equal acceleration; they do not indicate velocities. The Kodachrome moving pictures more nearly show the movement of the fluid in all sections of the model. The dark spots in the trashrack section of Figure 70 do, however, indicate the turbulent flow condition in this part of the structure. After consideration of the model limitations, it appears from observations of the flow that the desirable movement of colloidal solids through the lower tier of river outlets will take place in the prototype.

Electric analogy model. Prior to the construction of the hydraulic models it was necessary, in the design of the tunnel spillway, to determine the maximum water surface downstream from the crest to locate the hinge brackets for the radial gates. Resort was therefore made to an electric analogy model, Figure 71, on a scale of 1:80, of the spillway crest and a portion of the upstream entrance channel. This model used the principle of the analogy between the flow of water and the flow of electricity in a conductor of similar boundaries. The results from the electric analogy study were used as an aid in the construction of a flow net, which is a graphical representation of the nature of the flow of water. The form of the flow net consists of a system of stream lines, whose tangent at any point represents the instantaneous direction of flow, and a system of line normal to the stream lines.

The 2-dimensional model in Figure 71 consisted of a base of plate glass on which was cemented the lower spillway boundary of clear plastic. The upper water surface boundary, also of plastic, was adjustable. Each end of this section was bounded by a strip of plastic cemented to the glass. This enclosed area was filled with a thin layer of salt water. Metal electrodes were placed at each end of the section and connected to an alternating current source in parallel with a slide-wire bridge. A sliding contact on the bridge was connected through an electronic indicator to a probing pencil. In passing through the solution the current followed the stream lines between the terminals. The lines crossing the stream lines represented lines of equal potential. The purpose of the model was to determine the position of the potential lines. To



BHAKRA DAM

1:80 ELECTRICAL ANALOGY MODEL

FIGURE 71

locate any desired potential line, the sliding contact on the resistance wire of the bridge was placed at the point giving the desired potential. The probing pencil was then moved about in the salt solution until the tuning eye of the electronic indicator showed no flow of current between the sliding contact and the probing pencil. This point was plotted and the process repeated until enough points were located to determine the equal potential line. Potential lines at 10 percent increments were determined for the model, then stream lines normal to the potential lines were drawn. From this flow net, calculations were made to determine the discharge. If the computed discharge did not agree with the assumed maximum, the upper water surface boundary was changed and the entire flow net determined again. By this trial and error method the computed discharge finally agreed with the maximum and the water surface profile was considered as final.

The hinge brackets were located to clear the water surface determined by the electric analogy model. Later studies on the hydraulic model showed their location to be satisfactory. However, there was some disagreement between the water surfaces found by the 2 methods. The electric analogy model was limited since it was a 2-dimensional device. Furthermore, it did not represent sufficient approach upstream, consequently it was necessary to assume a velocity of approach. It was found that the assumed velocity was low resulting in a flatter water surface curve than that determined by the hydraulic model. Nevertheless, the results of the electric analogy served the purpose very well.