UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

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HYDRAULIC LABORATORY REPORT NO. 186

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STUDY OF AIR INJECTION INTO THE FLOW IN THE BOULDER DAM SPILLWAY TUNNELS - BOULDER CANYON PROJECT

By

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Denver, Colorado

October 24, 1945

UNITED STATES
DEPARTMENT OF THE INTERIOR
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Branch of Design and Construction
Engineering and Geological Control
and Research Division
Denver, Colorado
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Laboratory Report No. 186
Hydraulic Laboratory
Compiled by: J. N. Bradley
Reviewed by: J. E. Warnock

Subject: Study of air injection into the flow in the Boulder Dam Spillway Tunnels - Boulder Canyon Project.

1. Introduction. The spillway on the Arizona side at Boulder Dam was first placed in operation on August 6, 1941. Operation of the spillway was continued until December 1, 1941. During the four months of continuous operation, the average discharge was approximately 13,555 second-feet, except for several hours on October 28, when one of the drum gates dropped and the maximum flow was 38,000 second feet.

During a routine inspection of the spillway tunnels on December 12, 1941, an eroded area was discovered in the invert of the curve connecting the inclined and horizontal portions of the spillway tunnel. The hole was approximately 115 feet long and 30 feet wide, with a maximum depth of 45 feet below invert grade. Details of the damage are described in various Denver office correspondence from December 1941 to March 1942 inclusive, and in technical publications*.

It is the general concensus of opinion that misalinement of the tunnel invert, a few feet upstream from the eroded area, initiated the trouble. The misalinement actually was in the form of a hump in the invert of the tunnel. With the extremely high velocities involved, approximately 150 feet per second, separation occurred downstream from the hump reducing the pressure in this area to the vapor pressure of water. The result was cavitation and pitting. Although opinions vary

*"Erosion Causes Invert Break in Boulder Dam Spillway Tunnel", Kenneth B. Keener, Engineering News-Record, November 18, 1943.
"Symposium: Cavitation in Hydraulic Structures. Experiences of the Bureau of Reclamation", Jacob E. Warnock, Proceedings Am. Soc. C.E., September 1945.

as to the initial action responsible for the erosion, this fact is certain: That once the surface of the lining has become roughened in the invert of the vertical bend, the combination of high-velocity flow and centrifugal force present will scale the surface of the concrete by impingement alone. Once the surface has been roughened, erosion will proceed rapidly as was evidenced in the short flood of 1941.

It appears therefore, that the most effective means of preventing a reoccurrence of the 1941 incident would be to maintain the tunnel lining as smooth as possible. As an additional precaution Mr. J. L. Savage suggested that some means be devised to introduce air into the spillway flow with the expectation that the air first, would act as a cushion between the high-velocity water and the tunnel lining, and secondly, that the same air would aid in relieving any subatmospheric pressures which may occur along the surface of the tunnel invert. Experiments were made in an attempt to accomplish this end.

2. The model. These experiments were performed on a model of the Arizona spillway tunnel constructed on a scale of 1 to 60. A drawing of the prototype spillway is shown on figure 1, and a photograph of the lower vertical transparent bend of the model is included as figure 2A. The side-channel portion of the spillway was not included in the model as it had little bearing on the problem under investigation. Instead, a simple head box was constructed upstream from the tunnel to provide equally distributed flow to the tunnel transition. The transition was constructed of concrete poured to conform to metal guides. The remainder of the tunnel, including the constant-diameter vertical bend, was constructed principally of 10-inch diameter plastic pipe. The flow of water was measured through the laboratory venturi meters. The air flow was measured by various means which will be explained subsequently.

3. Record of tests in tunnel transition. The sole purpose of these tests was to develop a method of injecting air into the spillway flow by natural means. In other words, the use of air compressors was out of the question first, as the quantity of air involved would be

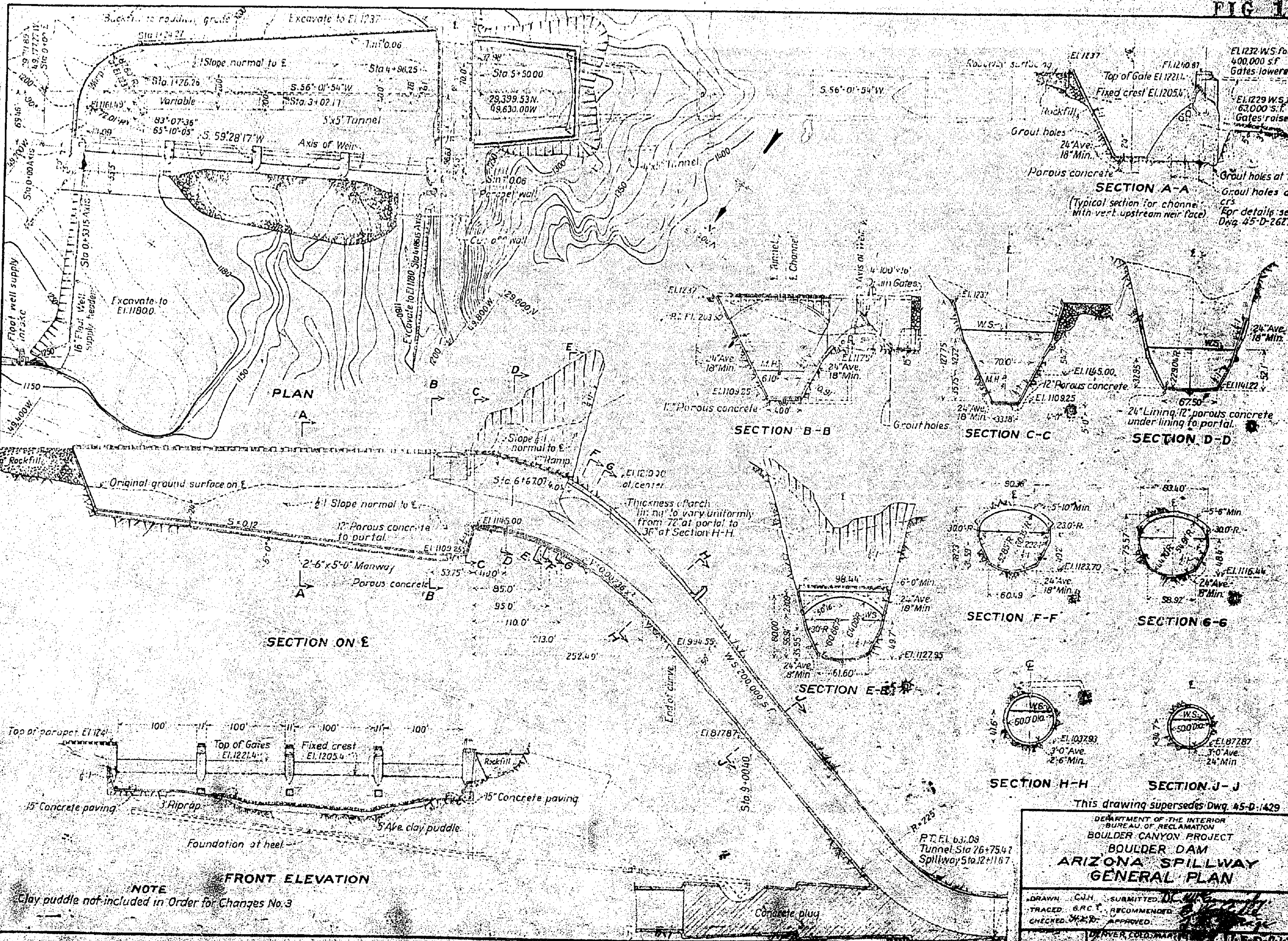
FIG. 1
PLAN
SECTION ON ℄
FRONT ELEVATION
SECTION A-A
(Typical section for channel with vert. upstream weir face)
For details see Dwg. 45-D-2627
SECTION B-B
SECTION C-C
SECTION D-D
SECTION E-E
SECTION F-F
SECTION G-G
SECTION H-H
SECTION J-J
Excavate to El. 1237
5'x5' Tunnel
Axis of Weir
Excavate to El. 1180.0
Float well supply intake
16" Float Well supply header
Rockfill
Original ground surface on ℄
½:1 Slope normal to ℄
12" Porous concrete to portal
2'-6"x5'-0" Manway
Porous concrete
Thickness of arch lining to vary uniformly from 72" at portal to 36" at Section H-H
W.S. 200,000 s.f.
End of curve
Top of parapet El. 1241
Top of Gates El. 1221.4
Fixed crest El. 1205.4
15" Concrete paving
3' Riprap
5' Ave. clay puddle
Foundation at heel
Concrete plug
NOTE
Clay puddle not included in Order for Changes No. 3
This drawing supersedes Dwg. 45-D-1429
DEPARTMENT OF THE INTERIOR
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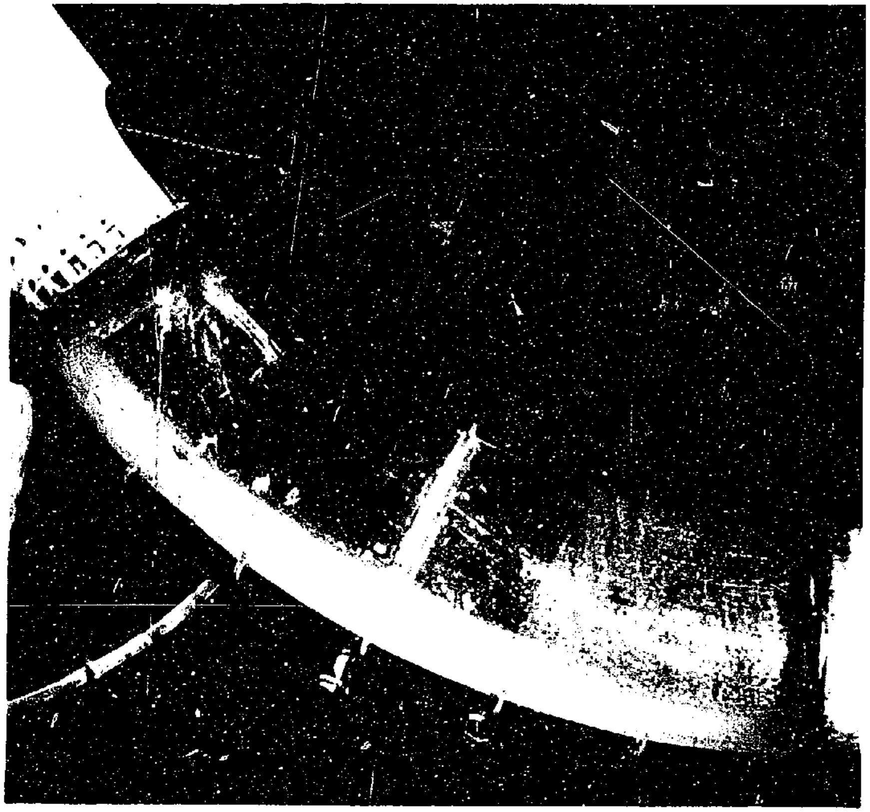
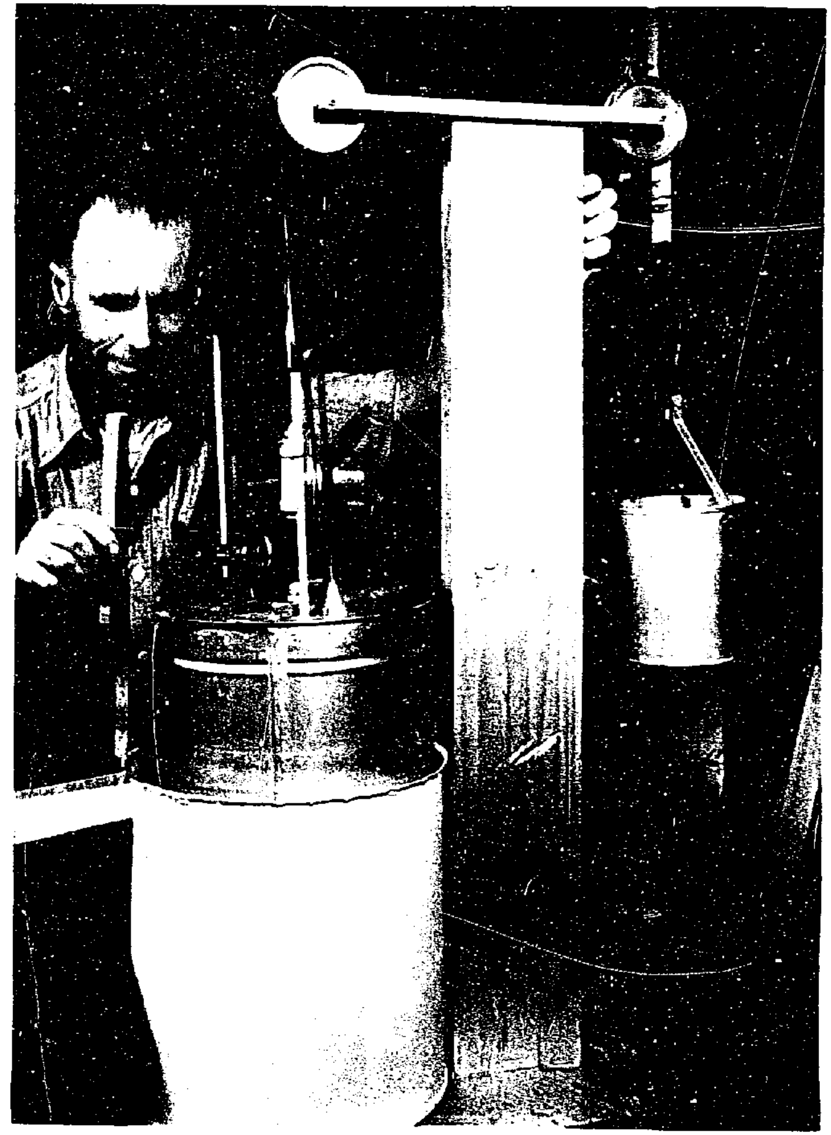
BOULDER CANYON PROJECT
BOULDER DAM
ARIZONA SPILLWAY
GENERAL PLAN
DENVER, COLO.
45-D-1442



A - Side view of flow in vertical bend



B - Device for measuring air content of water

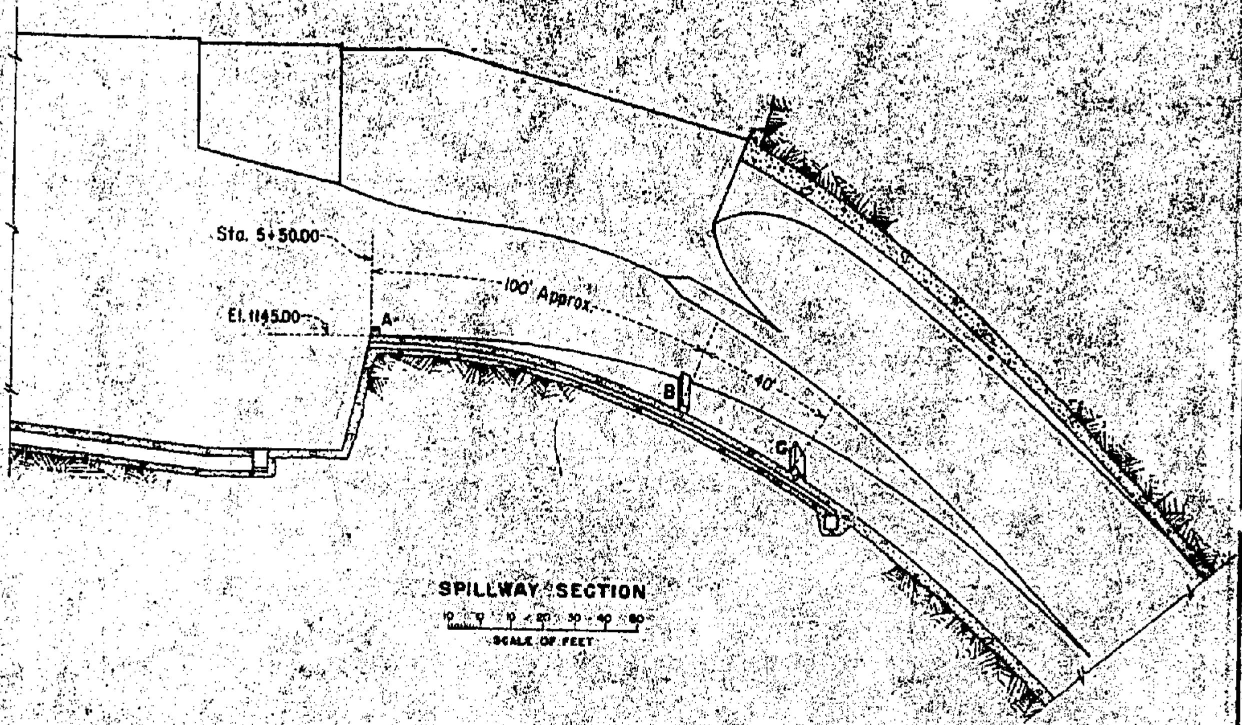
MODEL EQUIPMENT USED IN BOULDER DAM SPILLWAY AIR INJECTION TESTS

Figure 2

tremendous and secondly, because compressors would be economically infeasible due to the fact that they would operate perhaps once in five years. As it was desired not to interfere with the flow in the spillway any more than necessary, the first experiments were performed in the tunnel transition where velocities were not excessive. It was early learned that to implant air in the lower surface of the sheet in quantity, a lowered pressure under the jet was required. An appreciable differential pressure must exist to create this flow of air in quantity. To accomplish this air flow, sills and other devices were installed on the floor of the tunnel transition to cause the jet to spring free of the floor for a short distance. In most cases this created a subatmospheric pressure immediately downstream from the sill thus producing a continuous flow of air from the atmosphere to the space under the jet.

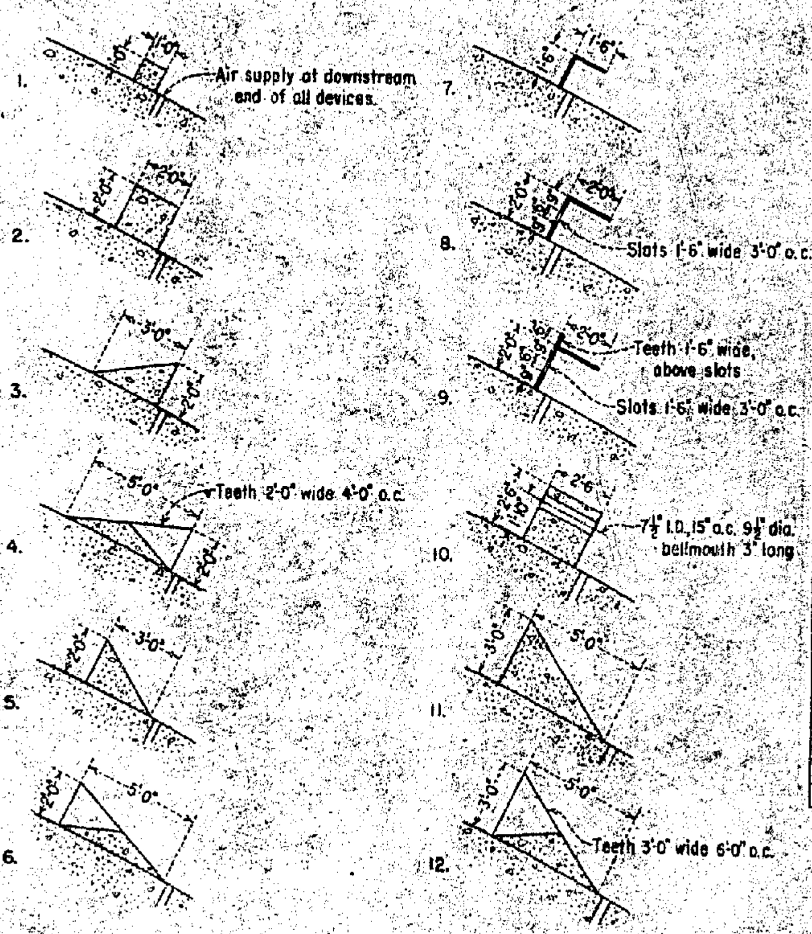
A few of the sills and devices and the locations in which they were installed are shown in section on figure 3. These included solid sills, sills with dentates, and devices incorporating orifices and short tubes. It is evident from the table on figure 3 that some installations possessed merit while others did not. The table shows a comparison in percentage of air to water for the sills and devices used separately and in combinations for water discharge of 60,000 second-feet. In all cases however, the air inflow was surprisingly small in comparison to the water discharge. The best results were obtained for test 12 with a combination of sills 10 and 11 in which case $\frac{Q_a}{Q_w}$ equalled 3.00 percent. The air in this case was admitted and measured through seven $\frac{1}{4}$-inch orifices located in the floor immediately downstream from the upper sill. The results of this design for a range of water discharges are shown as test 12 on figure 4. Test 11, on the same figure, shows the results with the lower sill removed. The curves for tests 15 and 16 show the effect of placing the lower sill upstream and downstream, respectively from the position shown on figure 3.

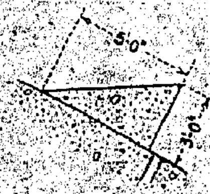
The orifice arrangement was advantageous for the measurement of air flow but not practical for the prototype structure. From the standpoint of the prototype, a vertical deflector sill was installed on each side of the transition in line with the upper floor sill as shown



SPILLWAY SECTION

10 0 10 20 30 40 50
SCALE OF FEET

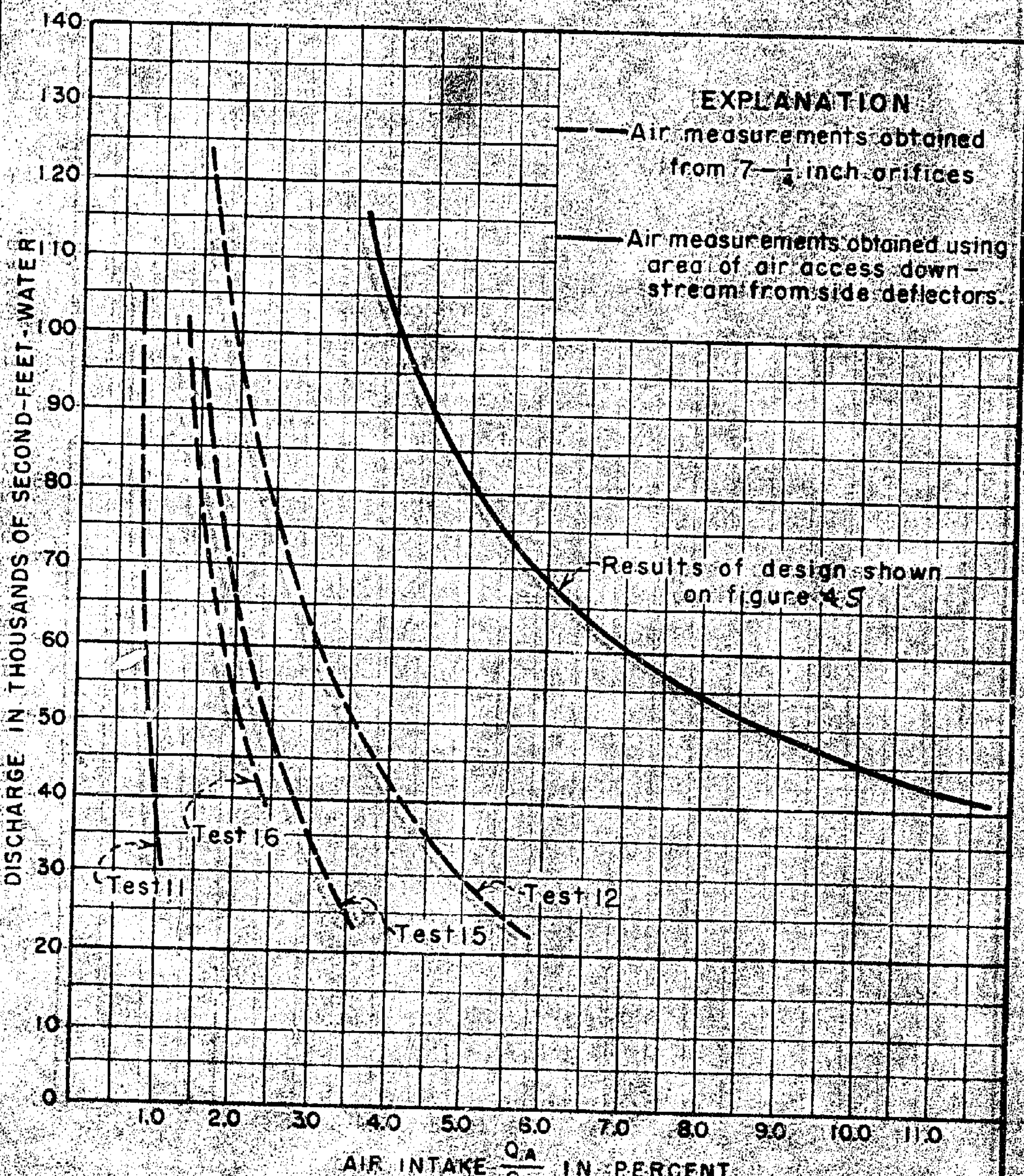




TEST No.	LOCATION A	LOCATION B	LOCATION C	$\frac{Q_A}{Q_W}$ IN %‡
	DEVICE USED			
1	1	—	—	0
2	—	1	—	0.50
3	—	2	—	0.60
4	—	3	—	0.50
5	—	4	—	0
6	—	5	—	0
7	—	6	—	0
8	—	7	—	0.70
9	—	8	—	0.80
10	—	9	—	0.85
11	—	10	—	0.85
12	—	10	11	3.00
13	—	10	12	2.80
14	—	10	13	AERATES NATURALLY
15	—	10	11*	2.10
16	—	10	11†	1.80
17	—	—	11	AERATES NATURALLY
18	—	—	10	AERATES NATURALLY

* Located 5'-0" downstream from C.
† Located 5'-0" upstream from C.
All locations are to upstream edge of device except as noted.
‡ Percent of air at discharge of 60,000 sec. ft.

BOULDER DAM
1:60 SCALE MODEL
STUDIES FOR AERATION OF SPILLWAYS
SUMMARY OF DEVICES TESTED IN THE ARIZONA SPILLWAY TRANSITION



BOULDER DAM

STUDIES FOR AERATION OF SPILLWAYS

RESULTS OF DEVICES INSTALLED IN SPILLWAY TRANSITION
AIR CONTENT MEASURED AT SAME POINT

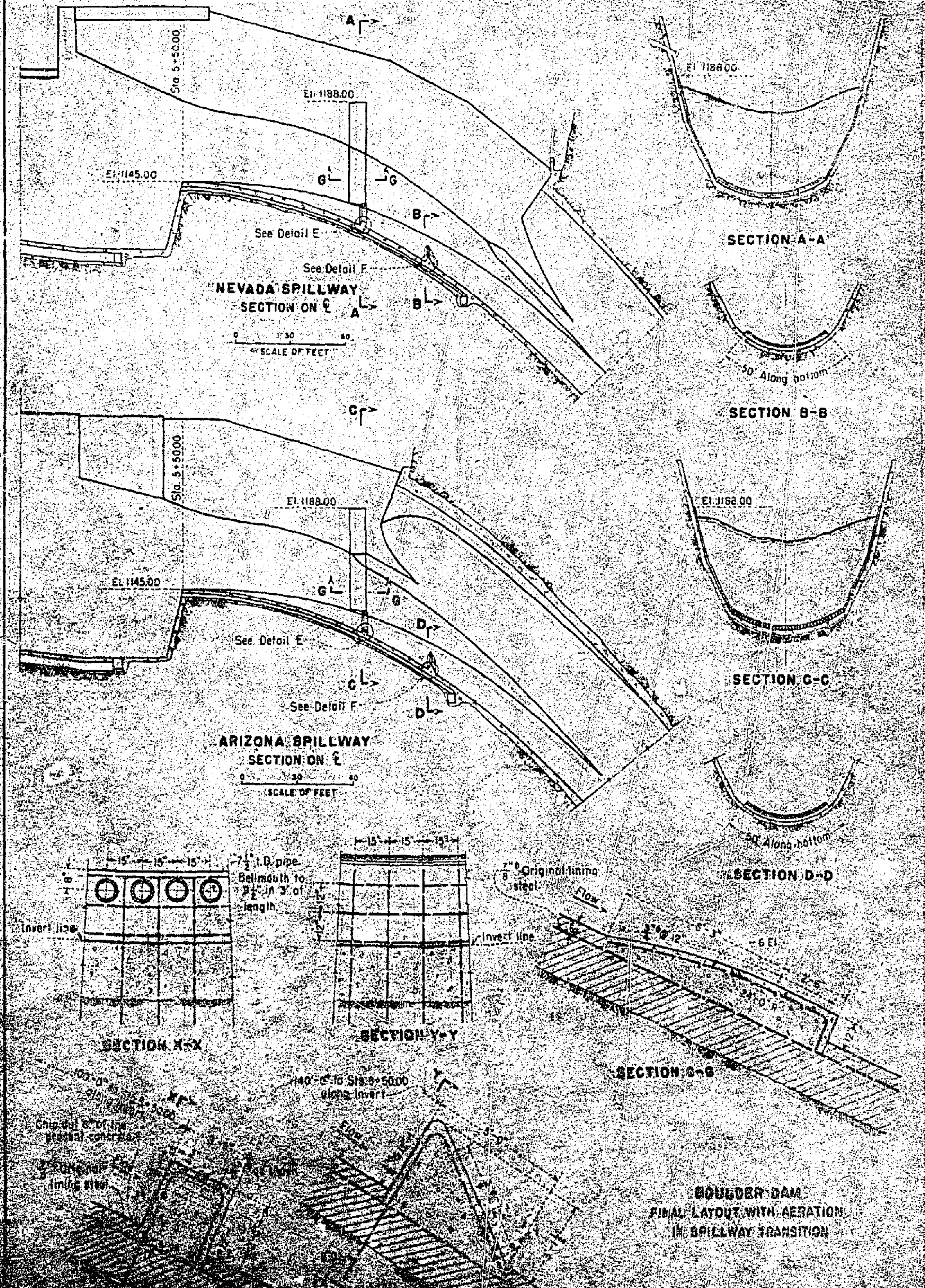
on figure 5. In this case the flow of air was measured using the area of the air gaps adjacent to the side wall deflectors and the differential pressure measured immediately downstream from the upper sill. The results of this design over a range of water discharges are shown by the solid line on figure 4. This indicates a maximum of 11.5 percent of air for a water discharge of 40,000 second-feet reducing to 4.0 percent for a discharge of 100,000 second-feet. For discharges less than 40,000 second-feet, the flow no longer filled the tunnel transition, thus it was no longer possible to measure the air flow. The arrangement in figure 5 produced the most favorable results for areation of the transition section.

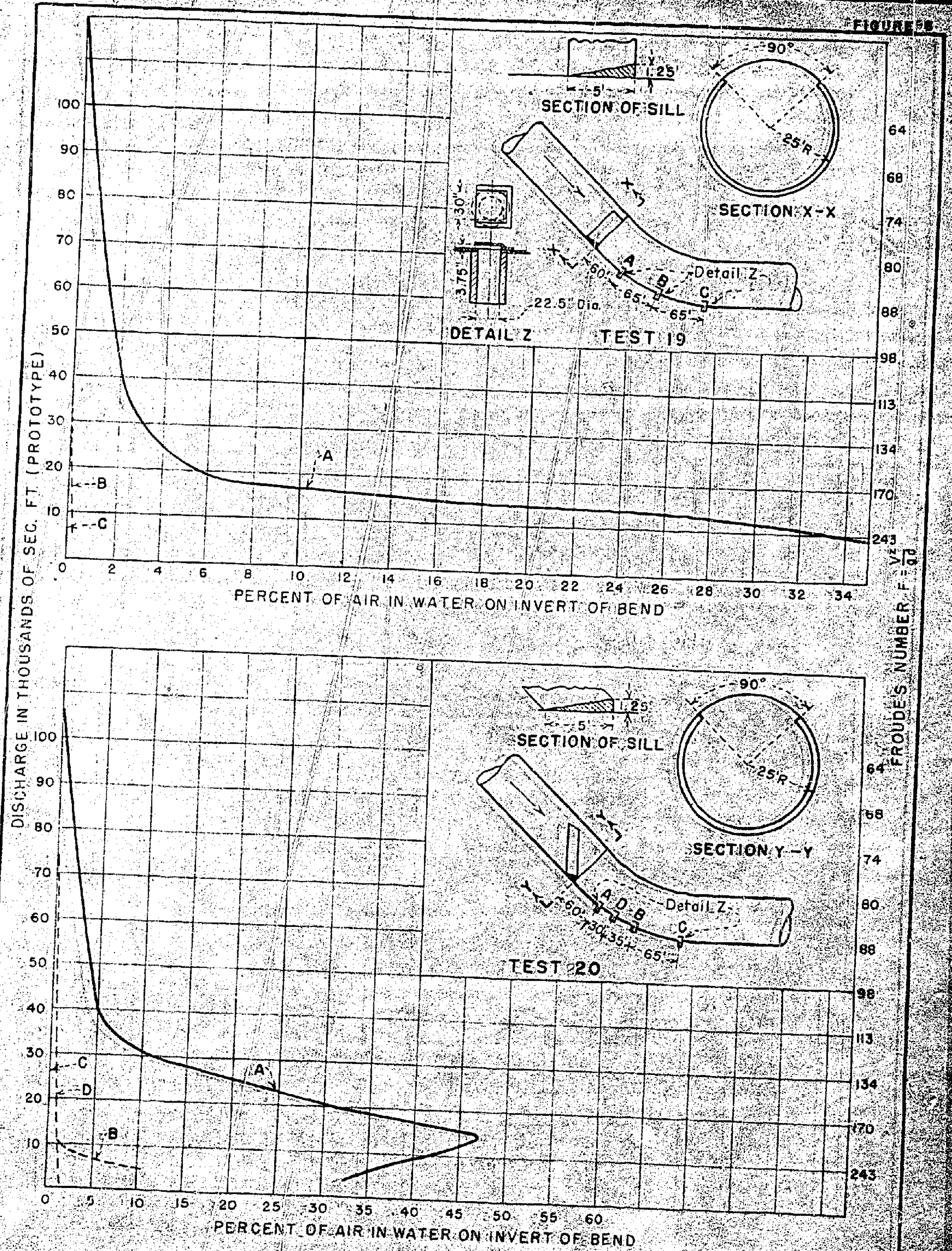
It was found that moving the sills a short distance downstream in the transition caused the jet of water to leave the invert of the 45-degree tunnel for its entire length. This was not considered an advisable condition of operation, as impingement resulted downstream.

4. Method of obtaining air measurements in vertical bend. Some doubt existed as to whether the air injected into the water at the transition remained entrained in the flow down the spillway tunnel. To study this condition, sampler connections were installed in the 50-foot diameter vertical bend as shown in figure 6. These were made to skim a layer of fluid approximately 1/16-inch in thickness from the invert of the tunnel. The sample flowed under pressure to the volumetric measuring device shown on figure 2B. This consisted of an air chamber and a water container. The air chamber was counter-balanced by a bucket of shot such that atmospheric pressure was maintained inside the air chamber regardless of its vertical position. A thermometer and a manometer were attached to indicate the temperature and pressure within the air chamber.

A measurement was obtained by connecting a ½-inch I.D. rubber hose from the air chamber to a sampler connection on the vertical elbow of the spillway tunnel and allowing the air and water mixture to flow until a stable condition prevailed. At this time the vertical position of the air chamber was measured, the time observed, and

FIGURE 5


NEVADA SPILLWAY
SECTION ON ℄
SCALE OF FEET
Sta. 5+50.00
El. 1188.00
El. 1145.00
See Detail E
See Detail F
SECTION A-A
SECTION B-B
50' Along bottom
ARIZONA SPILLWAY
SECTION ON ℄
SCALE OF FEET
SECTION C-C
SECTION D-D
Invert line
SECTION X-X
SECTION Y-Y
SECTION G-G
Flow
BOULDER DAM
FINAL LAYOUT WITH AERATION
IN SPILLWAY TRANSITION



BOULDER DAM

STUDIES FOR AERATION OF SPI...

collection of the water flowing over the spout of the water container was commenced. A run usually required ten minutes. During this period air was trapped in a gas chamber, while the water portion of the mixture flowed over the spout of the water container. At the end of the ten-minute interval, the position of the air container was again measured and the change in air volume computed, while the water which flowed over the spout in the same period of time was weighed. From these two measurements the ratio of air to water in the inflowing mixture was determined.

5. Record of tests on vertical bend. The first objective in these tests was to determine the percentage of air remaining in the water at the vertical bend, as a result of entrainment by the sill arrangement shown on figure 5. Measurements were made at samplers A, B, and C for discharges of 40,000, 60,000, 80,000 and 100,000 second-feet, but not a trace of entrained air could be recovered at these points in any case. Visual observations confirmed these results as the only air visible in the vertical bend was on the surface of the flow. After these observations, further attempts at air introduction at the upstream transition were abandoned.

As an alternative, a triangular sill encircling three-fourths of the pipe circumference was installed immediately upstream from the vertical bend as shown in test 19, figure 6. Samples were taken at connections A, B, and C for various water discharges and the results are shown on the same figure. For discharges of less than 20,000 second-feet the air content at sampler A was considerable, but for greater discharges the air content decreased rapidly. The curves show that only a trace of air was measured at B and no air could be detected at sampler C. The vertical bend at these velocities acted similar to a centrifuge in that the water, or heavier fluid, was forced toward the invert of the bend, while the air, or lighter fluid, was forced to the surface of the flow.

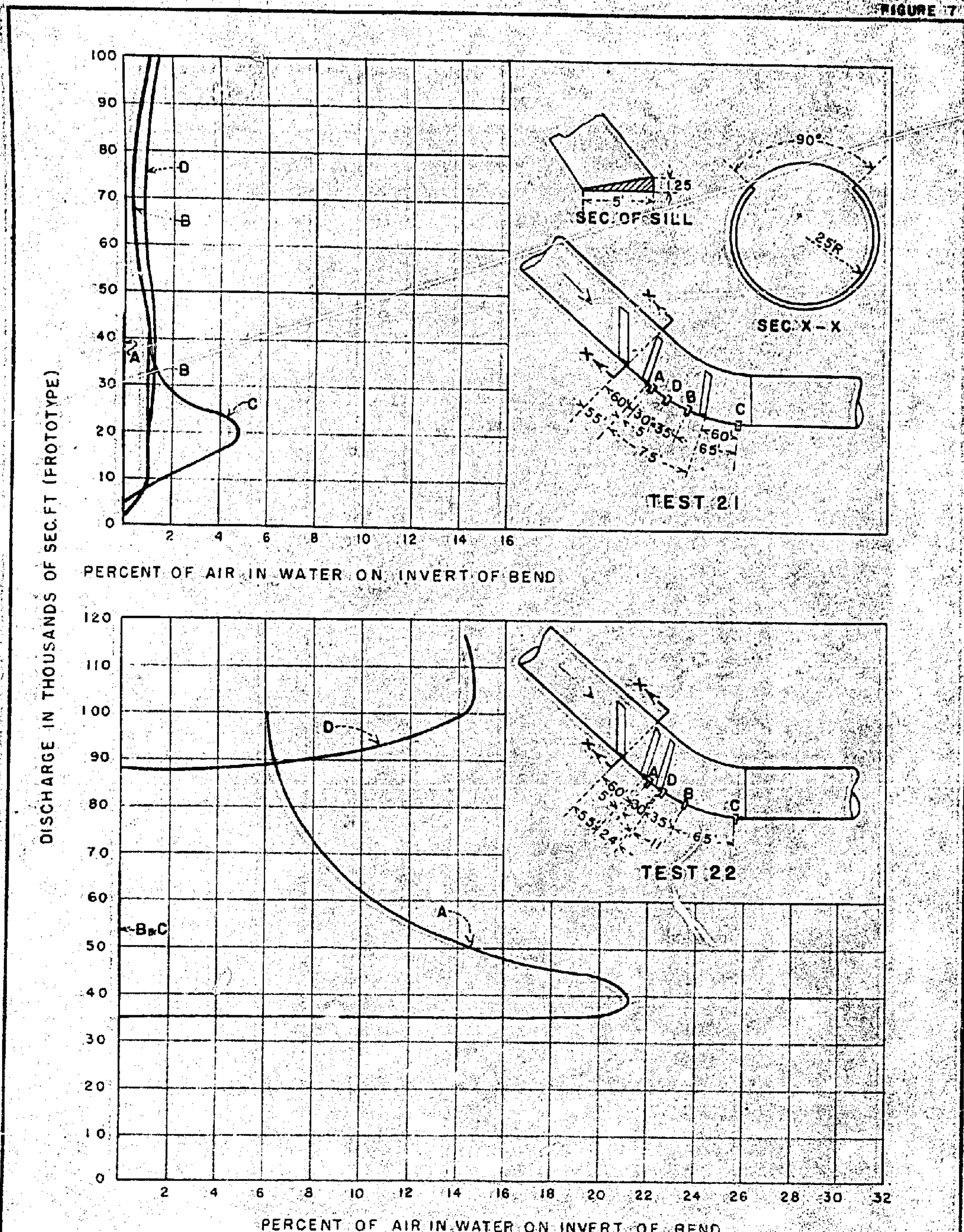
Another attempt was made to inject air into the water by the triangular sill arrangement shown for test 20, figure 6. The results, shown on the same figure, are similar to those for test 19 in that an encouraging air measurement was obtained at sampler A, while only a trace of air was observed at D and B and no air was detected at sampler C.

Additional sills were then installed in the bend in an effort to repeat the areation process at intervals along the invert. The arrangements and results are shown for tests 21 and 22 on figure 7. As is evident from the results the objective was not accomplished. These were merely experiments made with no practical application in mind. Had the sills entrained air throughout the bend as desired, their use in this high-velocity flow would have constituted another problem requiring solution. The sills would add to the problem of impingement in the bend proper and it is doubtful whether devices of this nature could be anchored sufficiently to keep them in place in the prototype.

In an effort to overcome these disadvantages, an abrupt notch was constructed in the tunnel immediately upstream from the vertical bend as shown for test 23, figure 8. The results, on the same figure, show this design to be ineffective.

As a final trial, a design (test 24, figure 8) using dentates spaced over three-fourths the circumference of the pipe was tested. Air was supplied through a square vent located at the downstream end of each dentate. From visual observation the flow appeared milky throughout the bend giving the impression that this device was quite effective. On the contrary, the measurements show that a maximum of less than two percent of air was measured on the invert of the bend for this design. Because of discouraging results and the lack of promising ideas, the tests were discontinued at least for the present.

6. Conclusions. The results of this investigation were negative in character. The plan for areation of the Boulder Dam spillways by devices constructed on the tunnel invert, to aid in preventing a reoccurrence of the damage encountered in 1941, does not appear encouraging. Tests made on devices in the upper tunnel transition indicated that a limited amount of air could be injected into the flow at this location, but none of this air could be detected on the invert of the vertical bend downstream. Similar results were obtained when air was introduced



BOULDER DAM

STUDIES FOR AERATION OF SPILLWAYS

DEVICES TESTED IN VERTICAL BEND

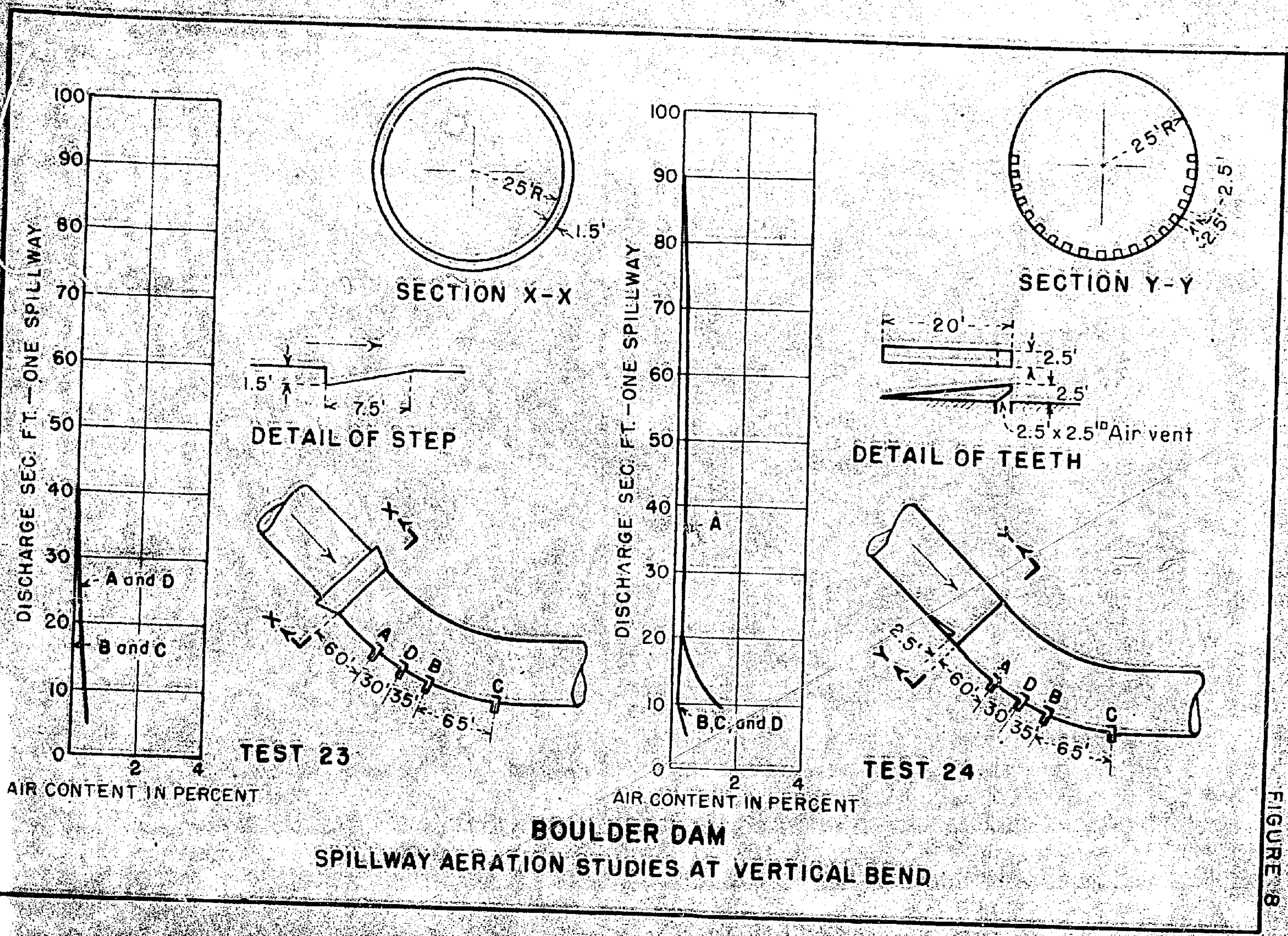


FIGURE 8
DISCHARGE SEC. FT.—ONE SPILLWAY
100
90
80
70
60
50
40
30
20
10
0
2
4
AIR CONTENT IN PERCENT
A and D
B and C
TEST 23
SECTION X-X
25'R
1.5'
DETAIL OF STEP
1.5'
7.5'
X
A
D
B
C
60'
30'
35'
65'
A
B,C, and D
TEST 24
SECTION Y-Y
2.5'
DETAIL OF TEETH
20'
2.5'x2.5'' Air vent
Y
BOULDER DAM
SPILLWAY AERATION STUDIES AT VERTICAL BEND

into the flow at the beginning of the 50-foot diameter vertical bend. The air, in this case, did not remain near the invert of the bend but rapidly rose to the surface a short distance downstream. In no case was aeration throughout the vertical bend sucessful. An air supply is needed throughout the invert of the vertical bend, as providing relief in one section of the bend will in no way insure against a reoccurrence of the damage at other points downstream.

It is difficult to estimate the accuracy involved in the above experiments. Inaccuracies in measuring the flow of air through the very small orifices and short tubes in the tunnel transition tests may have amounted to 50 percent plus or minus. Also, the method employed in measuring the air supply to the arrangement shown on figure 5 was not precise. The volumetric measurements of air in the vertical bend, on the other hand, were very accurate from the standpoint of the model. The model results were converted to prototype by Froude's Law which should apply within limits to this type of open channel flow. The errors lie in the fact that the viscosity of the water and air are the same in both model and prototype, and that entrainment of air from the surface will be much more pronounced on the prototype. Had these factors been to scale in the model, the prototype results may have been more favorable, but this is not certain as a number of factors are involved. In spite of the inaccuracies, it would be necessary for the model results to be many times better for the foregoing plan of areation to be feasible.