HYD 126

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HYDRAULIC LABORATORY REPORT NO. 126.

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MODEL TESTS TO INVESTIGATE EXTENT OF RECIRCULATION OF CONDENSER COOLING WATER AT ANTIOCH STEAM ELECTRIC PLANT, CENTRAL VALLEY PROJECT

By

J. N. BRADLEY, ENGINEER

- - -

Denver, Colorado,
May 10, 1943

UNITED STATES

DEPARTMENT OF THE INTERIOR

BUREAU OF RECLAMATION

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MEMORANDUM TO CHIEF DESIGNING ENGINEER

SUBJECT: MODEL TESTS TO INVESTIGATE EXTENT OF RECIRCULATION OF CONDENSER COOLING WATER AT ANTIOCH STEAM ELECTRIC PLANT, CENTRAL VALLEY PROJECT

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By J. N. BRADLEY, ENGINEER

- - - - -

Under Direction of

J. E. WARNOCK, ENGINEER
and
R. F. BLANKS, SENIOR ENGINEER

- - - - -

Denver, Colorado
May 10, 1943

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MEMORANDUM TO CHIEF DESIGNING ENGINEER
(J. N. Bradley)

Subject: Model tests to investigate extent of recirculation of condenser cooling water at Antioch steam electric plant, Central Valley project.

DESCRIPTION AND SCOPE OF INVESTIGATION

1. The plant. A steam electric plant is proposed on the San Joaquin River near Antioch, California, to firm up the hydroelectric power which will be generated at Shasta and Keswick dams. The Shasta and Keswick plants are scheduled to generate a maximum of 450,000 kilowatts, and the tentative capacity of the steam electric plant is 150,000, with provision for an additional 150,000 should the additional capacity be justified by future demands.

This report deals entirely with model studies in connection with the cooling water for the steam-electric plant condensers.[1] For the ultimate installation of 300,000 kilowatts, preliminary computations indicated that a discharge of 1,000 second-feet will be required for single-pass condensers allowing a rise of 6.5 degrees (Fahrenheit) above river water temperature; or, 480 second-feet will be needed for double-pass condensers permitting a 16.5-degree temperature rise. Twelve pumps of 85-second-foot capacity each are proposed for the maximum installation if 1,000 second-feet of cooling water is required, or twelve pumps of 40-second-foot capacity should 480 second-feet of cooling water be desired. A tentative layout

[1] Kerr, S. L., and Moyer, Stanley, "Hydraulic Engineering Problems at Southwark Generation Station," Trans. A.S.M.E., vol. 64, No. 6.

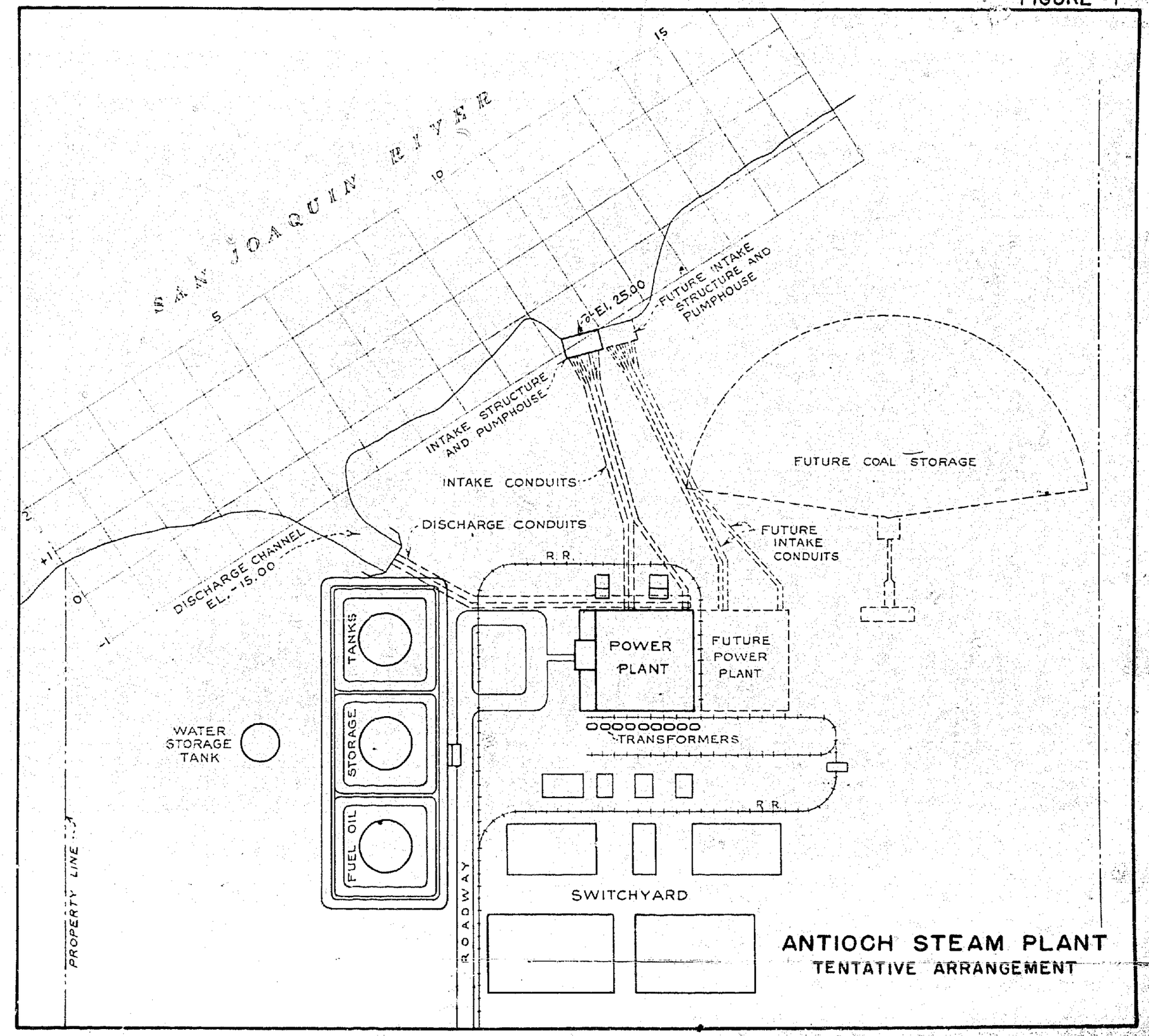
of the plant is shown on figure 1, and the pump house is shown on figure 2. The following model tests were made for the above maximum conditions.

2. The model. The model, constructed on a 1:100 undistorted scale, measured approximately 30 by 14 feet yet included only a small portion of the river adjacent to the steam plant site. The extent of the model and the coordinate system utilized for recording results are shown on figure 3. The pump house and outlet conduits for the ultimate installation, figure 2, were constructed to scale in the model. Thermometers were placed in sections of transparent pipe in the intake conduits for observing any temperature rise which might accompany recirculation of the heated water issuing from the outlet conduits, figure 4. The intake discharge was throttled by two one-inch, calibrated, gate valves and then wasted into the laboratory sump.

A circular tank was provided for mixing hot and cold water to obtain the desired temperature for the outlet discharge water. A motor-driven stirring device was used to obtain a constant temperature throughout the mixing tank. The device lifted the cooler water from the bottom of the tank and discharged it radially near the surface of the liquid with excellent results. The tempered water then passed into the two discharge conduits, in which thermometers were installed, and finally discharged into a trapezoidal outlet channel in the river, figure 4. Flow through the outlet pipes was also controlled by two one-inch, calibrated, gate valves. Although intake water was wasted directly into the sump, compensation for heat lost in this way was made by raising the temperature of the outlet water a corresponding amount.

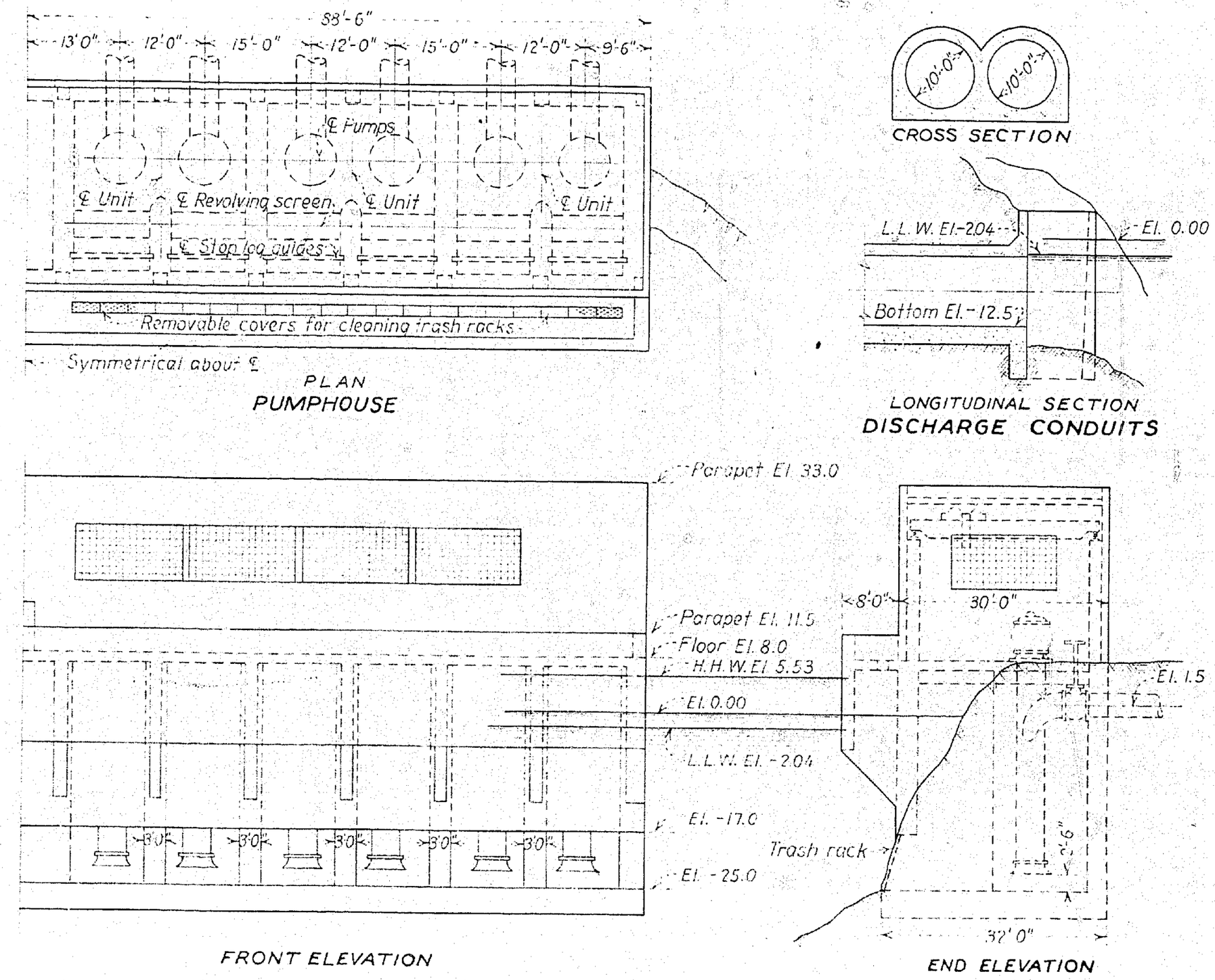
The model river bed, which included approximately one-half the width of the river, was first molded to shape in sand with the aid of metal

FIGURE 1



ANTIOCH STEAM PLANT
TENTATIVE ARRANGEMENT

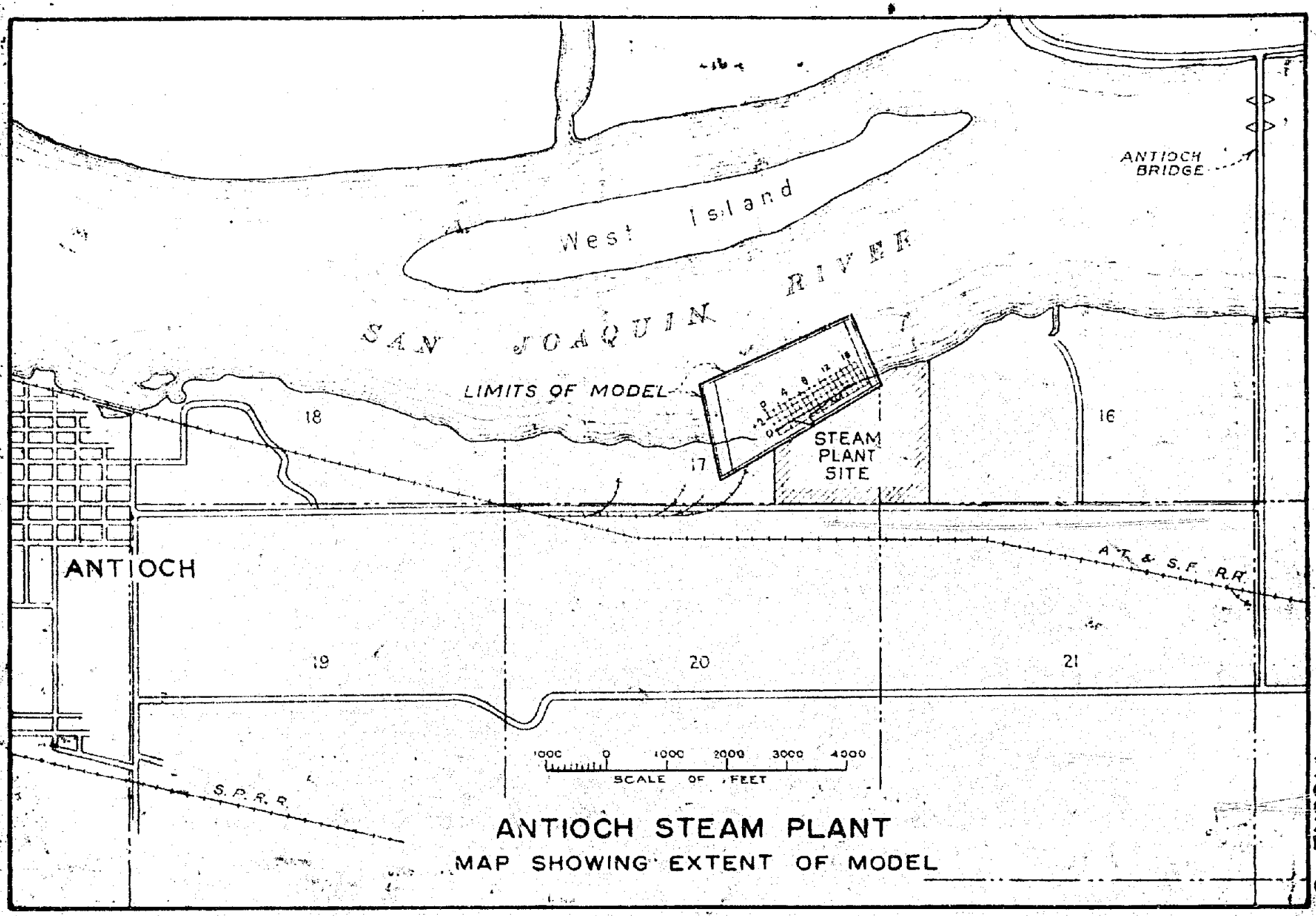
FIGURE 2



ANTIOCH STEAM PLANT

TENTATIVE PUMPHOUSE AND DISCHARGE CONDUIT

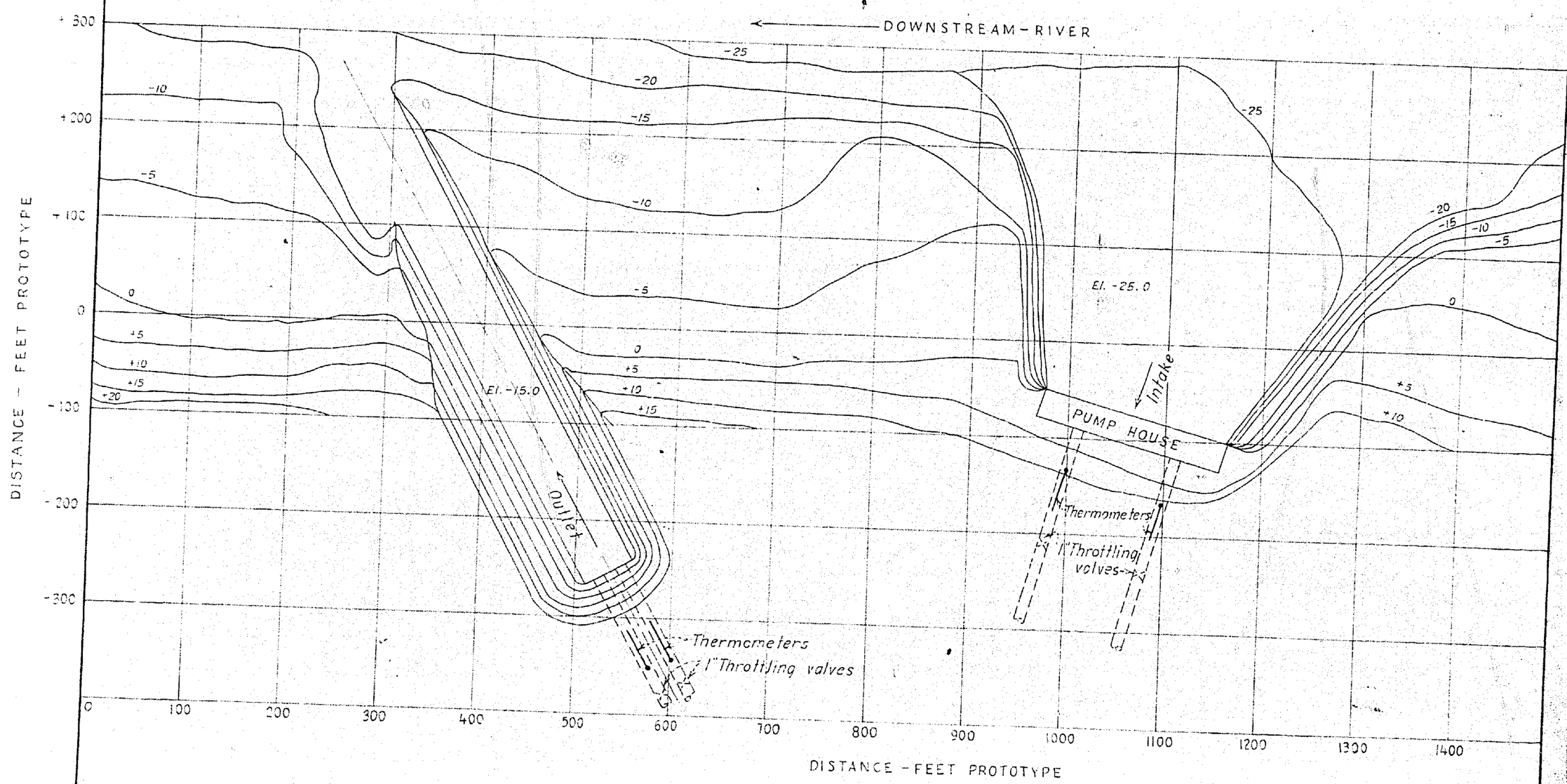
HYD-126



ANTIOCH STEAM PLANT
MAP SHOWING EXTENT OF MODEL

FIGURE 3

FIGURE 4



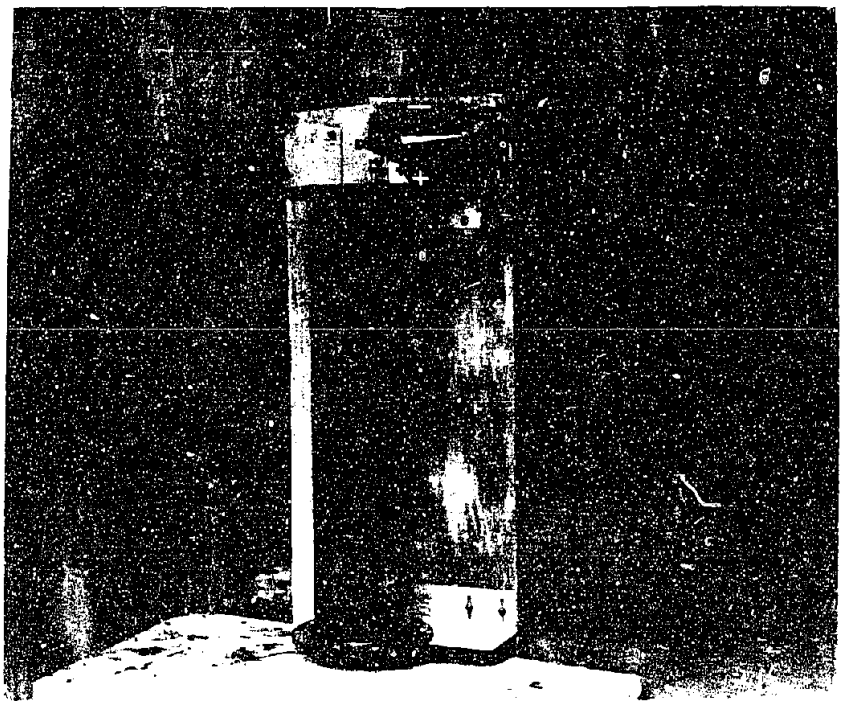
CENTRAL VALLEY PROJECT - CALIFORNIA
DELTA DIVISION

ANTIOCH STEAM PLANT
LAYOUT FOR TEST I
ORIGINAL DESIGN

templates. The shallower portion, including the pump intake bay and outlet channel, on the Antioch side was capped with a thin shell of concrete to stabilize this portion of the bed, while the deeper part of the river channel remained of sand.

As the most extreme condition for heating of the intake water will occur when the tide is flowing up the river with a correspondingly low flow of fresh water down the river, the model was constructed to duplicate only the flood-tide condition. A water supply was provided at the downstream end of the model to create flow up the river, and an adjustable weir was provided at the upstream end by which the tide level could be regulated. The tide level could be observed directly by means of the float gage, shown on figure 5A. A velocity meter reading accurately to 0.4 foot per second was specially developed to calibrate the tidal flow in the model, figure 5B. It consisted of a Lucity sphere possessing a density slightly greater than water. The buoyancy effect of the sphere in water, plus the very minute force produced by the velocity head of the flowing water, resulted in a moderate swing of the needle for extremely low velocities.

To obtain the correct tidal prism flowing upstream on the model, it was necessary to resort to a rather laborious trial process. Commencing with the tide-stage velocity curve for the San Joaquin River at Antioch, shown on figure 6, flood tide was duplicated on the model by setting the tide height with respect to model time by the adjustable weir. Simultaneously the tidal discharge in the upstream direction was regulated to produce corresponding tide velocities with respect to time. Many repetitions were necessary before a discharge curve was developed which was in step with the correct velocity, tide stage, and time. Due to the large volume of the model, a small deviation from the true discharge produced

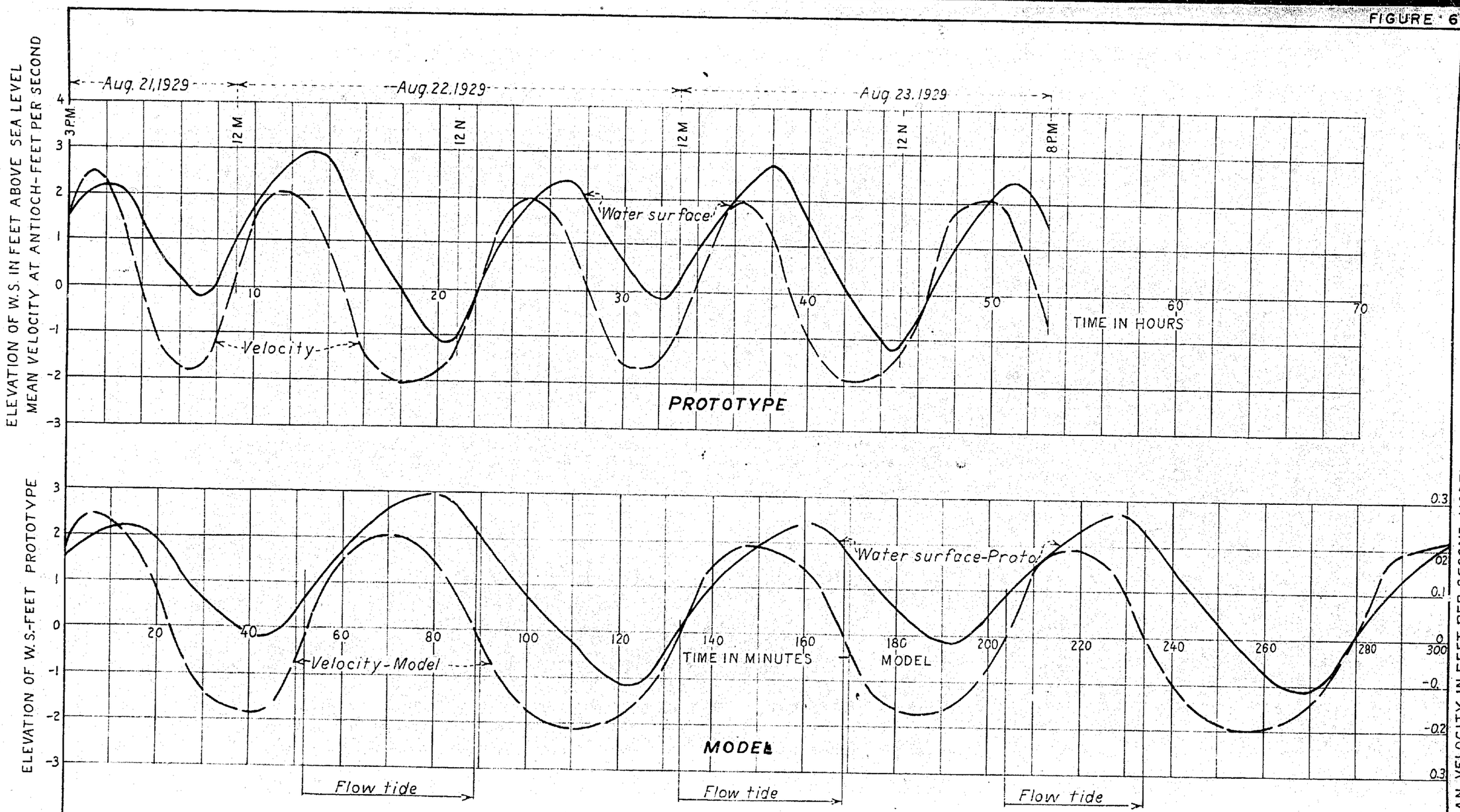


Tide Height Float Gage

Tide Velocity Meter

LABORATORY INSTRUMENTS

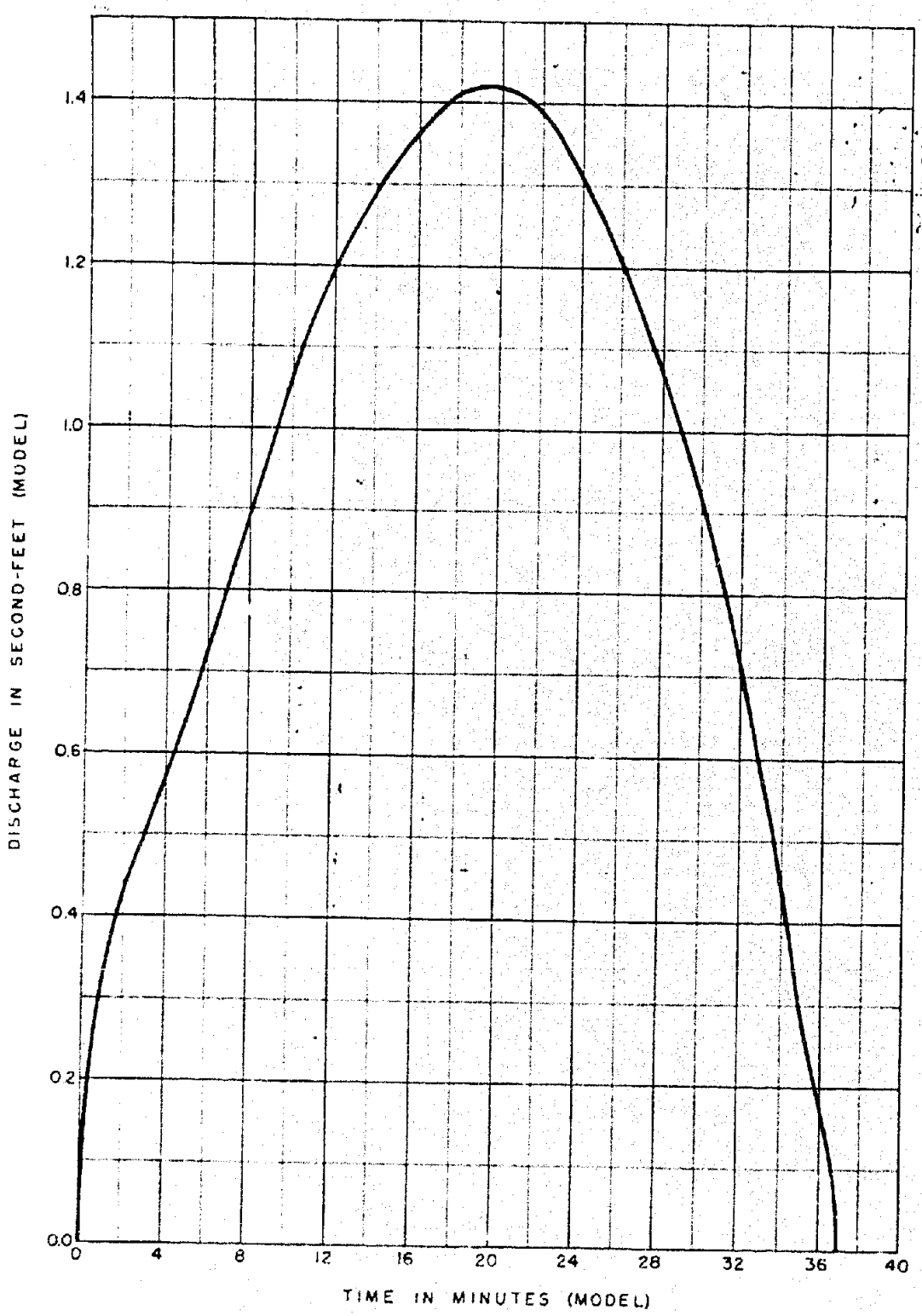
FIGURE 6



CENTRAL VALLEY PROJECT- CALIFORNIA
DELTA DIVISION

ANTIOCH STEAM PLANT
TIDE STAGE AND VELOCITIES FOR SAN JOAQUIN RIVER AT ANTIOCH, CALIFORNIA

FIGURE 7



ANTIOCH STEAM PLANT

FLOW TIDE RIVER DISCHARGE
IN 1:100 SCALE MODEL

a loss or accumulation of storage, causing the remainder of the cycle to be in error. The correct discharge curve as developed for flow tide on the model is shown on figure 7. This tidal prism, however, bears no definite relation to the field data as only a portion of the river width was utilized in the model.

3. Interpretation of results. The primary purpose of the test program was to determine whether recirculation of the heated condenser water would occur during flood tide, and if so, to what extent, as heating of the condenser intake water would be reflected in a reduction in efficiency of the power plant. With the outlet located down river from the intake, recirculation could occur only during flood or slack tide; therefore the study was limited to this portion of the tide cycle. The recirculation problem was considered in two parts: (1) a fluid flow study in which all factors in the model bear a known definite relation to the prototype and (2) a thermodynamic study in which loss of heat and rate of stratification occur at practically the same rate in model and prototype. In the latter, interpretation of model results is less certain than in the former case.

The true similitude relationships which exist between model and prototype are listed below. The letter N denotes scale ratio which, in this case, is 1:100.

Dimension	Prototype	Model	Ratio
Linear feet	L_p	$\frac{L_p}{N}$	1:100
Areas - square feet	L_p^2	$\frac{L_p^2}{N^2}$	1:10,000
Volumes - cubic feet	L_p^3	$\frac{L_p^3}{N^3}$	1:1,000,000

Dimension	Prototype	Model	Ratio
Time - seconds	T_p	$\frac{T_p}{N^{1/2}}$	1:10
Velocity - feet per second	$V_p = \frac{L_p}{T_p}$	$\frac{V_p}{N^{1/2}}$	1:10
Discharge - second-feet	$Q_p = \frac{L_p^3}{T_p}$	$\frac{Q_p}{N^{5/2}}$	1:100,000
Acceleration - ft./sec.^{2}	$a_p = \frac{V_p}{T_p}$	a_p	1:1
Energy - B.t.u.	$H_p = L_p^3 wt$	$\frac{H_p}{N^3}$	1:1,000,000
Power - B.t.u. per hr.	$P_p = Q_p wt$	$\frac{P_p}{N^{5/2}}$	1:100,000

where

w = unit weight of water, and

t = temperature rise in degrees Fahrenheit.

The following thermodynamic relationships exist between model and prototype.

Dimension	Ratio
Density of water (at given temperature).	1:1
Rate of heat loss to air by conduction and convection per square foot of surface (other factors being equal in model and prototype).	1:1
Rate of conduction of heat to adjacent river bed per square foot of contact surface.	1:1 approx.
Rate of transfer of heat to adjacent river water by mixing.	1:1 approx.
Rate of stratification (produced by warmer water of less density rising to surface).	1:1 approx.

With the exception of the first two, all the above ratios are approximate due to numerous factors which influence similarity between model and prototype. Some of the most common of these factors are as follows:

1. Differences in temperature differential between air and water for model and prototype. This factor is difficult to control and would affect rate of heat loss to air.

2. Difference in humidity of air in model and prototype. This factor would influence evaporation rate and thus affect rate of heat loss to air.

3. Difference in rate of heat loss to atmosphere due to variation of wind velocity in model and prototype.

4. Difference in conduction of heat to river bed due to shallowness of model.

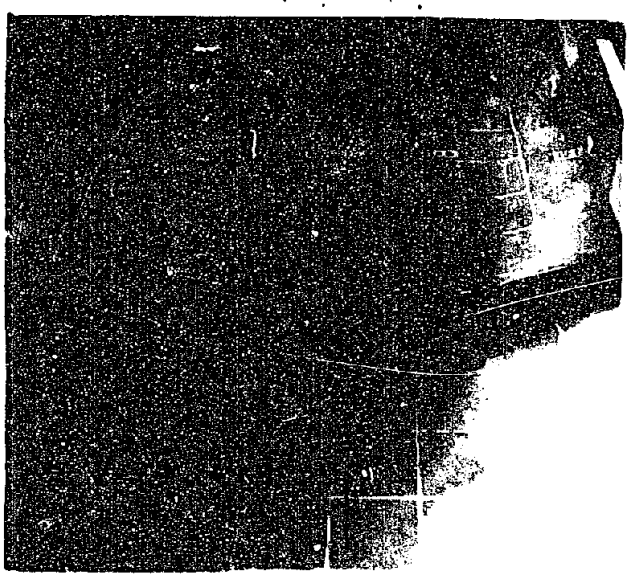
5. Difference in rate of stratification in model and prototype produced by horizontal velocity component of flow which was one-tenth of that in the prototype.

6. Difference in rate of heat transfer to adjacent river water due to variation in mixing. The mixing action would be dimensionally to scale were it not for the fact that the stratification rate is practically the same in model and prototype.

It is apparent from the above ratios that it will be necessary to treat the flow and the heat studies as separate problems. The model was therefore initially operated to observe fluid motion and secondly to study heat flow.

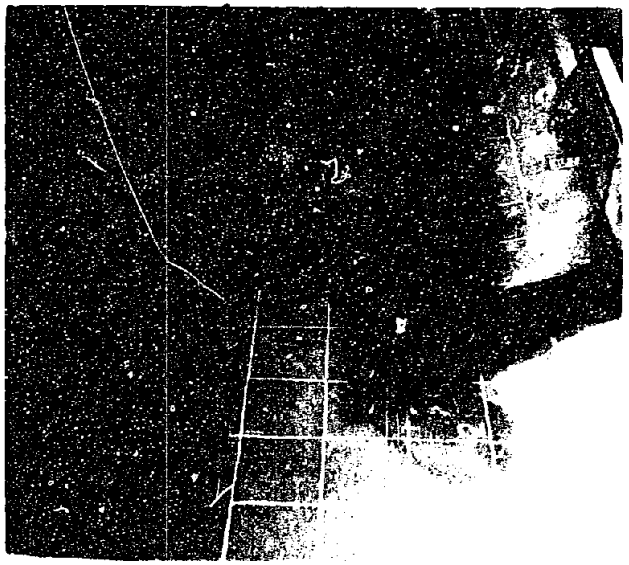
FLOW-STUDY RESULTS

4. Original design (test 1). The original design, figure 4, was first operated to locate predominating currents and determine the extent of recirculation. Two runs were made, and this is true of all following designs: namely, 1,000 second-feet (0.010 second-foot, model) of flow from condensers with 6.5-degree Fahrenheit temperature rise above intake water temperature, and 480 second-feet (0.0048 second-foot, model)



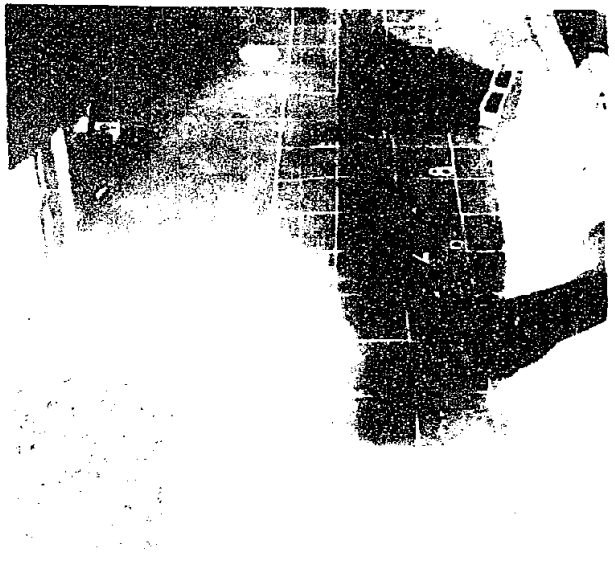
A - 0 Minutes - Beginning of Flow

B - 20 Minutes



C - 180 Minutes

D - 200 Minutes - Maximum Velocity Upstream



E - [illegible] Minutes

F - 380 Minutes - Point at which Current Reverses to Downstream

FIGURE PATH OF WARM WATER CURRENTS PRODUCED BY DISCHARGE CONDENSER WATER DURING FLOW TIDE

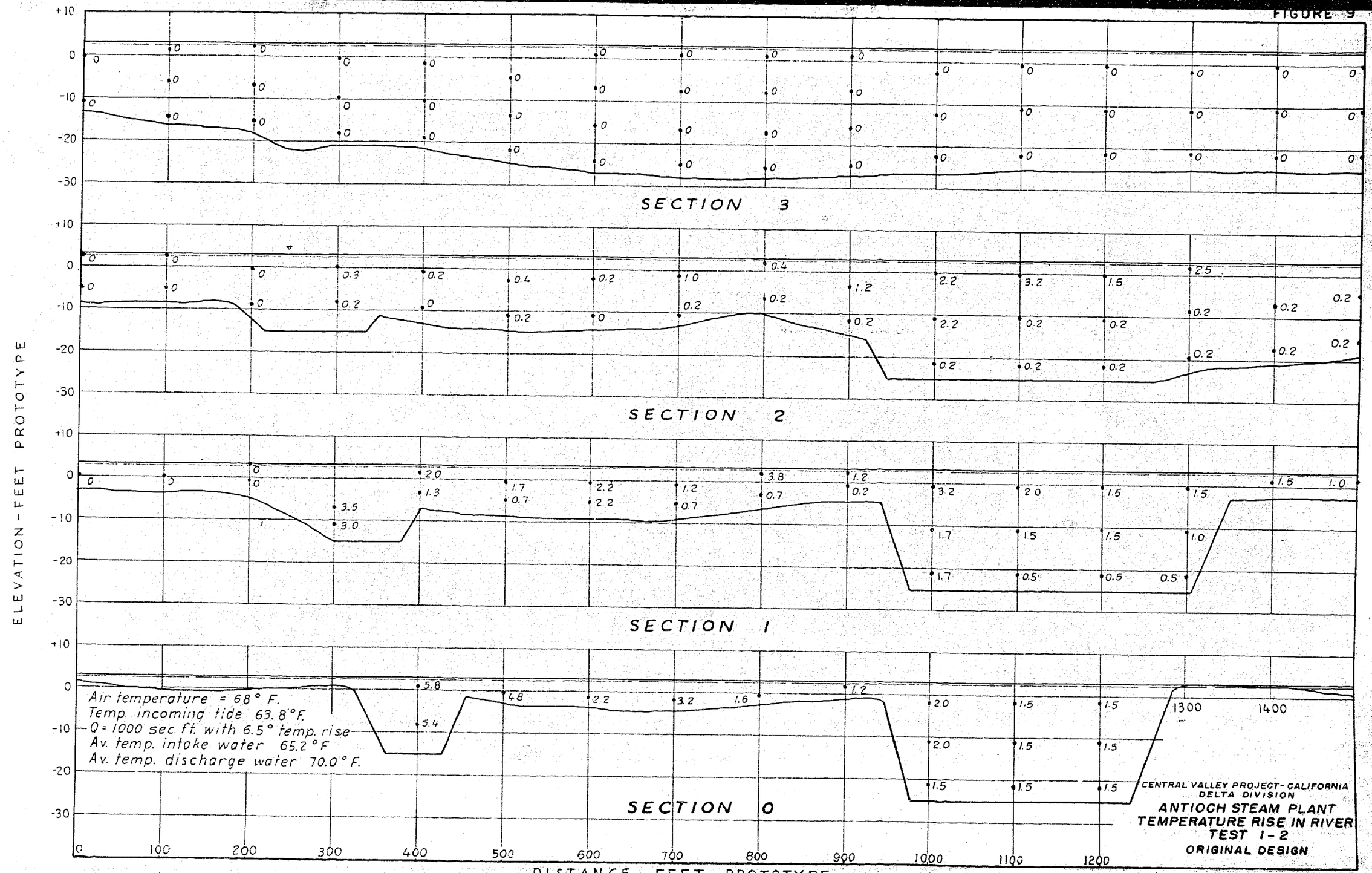
ORIGINAL DESIGN - TEST 1

discharge from condensers with 16.5-degree rise above intake water temperature. Each run was begun at slack tide, extended through the flood-tide portion of the cycle, and concluded at the following slack-tide period, figures 6 and 7. True flow similitude was adhered to throughout these tests, such that time and velocities in the model were one-tenth of those values in the prototype and flow was in the ratio of 1:100,000. It was planned to pump cool water from the river bottom to the condensers and discharge the heated water near the surface, as indicated on figure 2.

The flow pattern for the original design is pictorialized for flood tide on figure 8. Dye was used to color the heated condenser water, and the time indicated on the figure represents prototype minutes after slack tide. During slack tide, figure 8A, the heated water spread out on the surface over a considerable area. Twenty minutes later a slow tide-velocity had forced the condenser discharge water toward the shore, figure 8B. As the tide velocity increased, the flow pattern assumed the forms shown in photographs C, D, and E, during which time the heated water passed directly over the pump intake bay on its course upstream. Photograph F shows the pattern as the heated water commenced to spread again at the following slack-tide period.

During each run, temperature readings were taken at various depths with accurately calibrated thermometers for each intersection point of the grid system, figures 4 and 8. The thermometers were mounted in horizontal racks and were read in a totally submerged position. These readings were recorded during the period of maximum velocity upstream, which was considered the most adverse condition. The grid system bears no significant relation to the plant but merely served as a convenient means of recording

FIGURE 9



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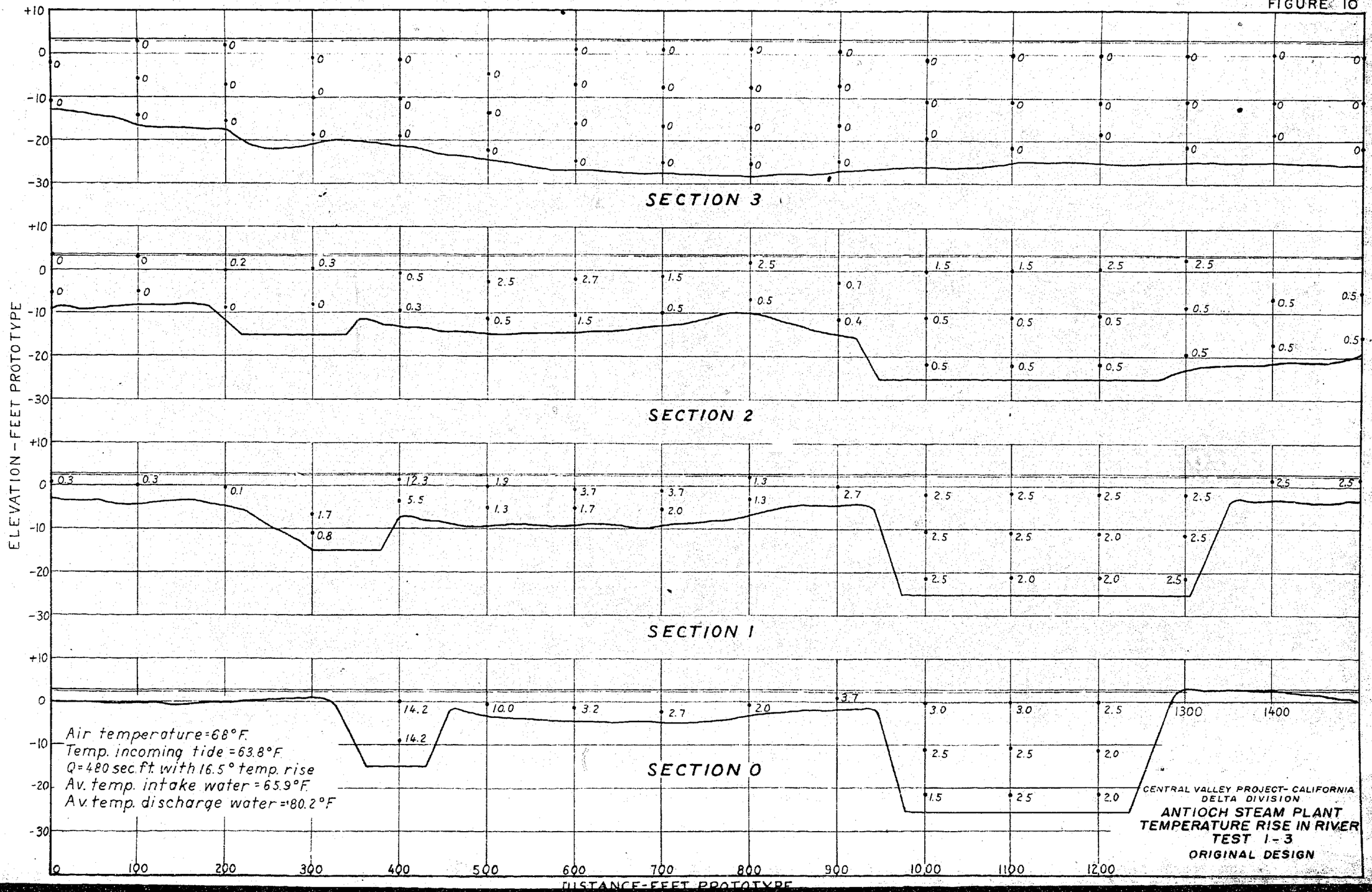
ANTIOCH STEAM PLANT
TEMPERATURE RISE IN RIVER
TEST 1-2
ORIGINAL DESIGN

FIGURE 10



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ANTIOCH STEAM PLANT
TEMPERATURE RISE IN RIVER
TEST 1 - 3
ORIGINAL DESIGN

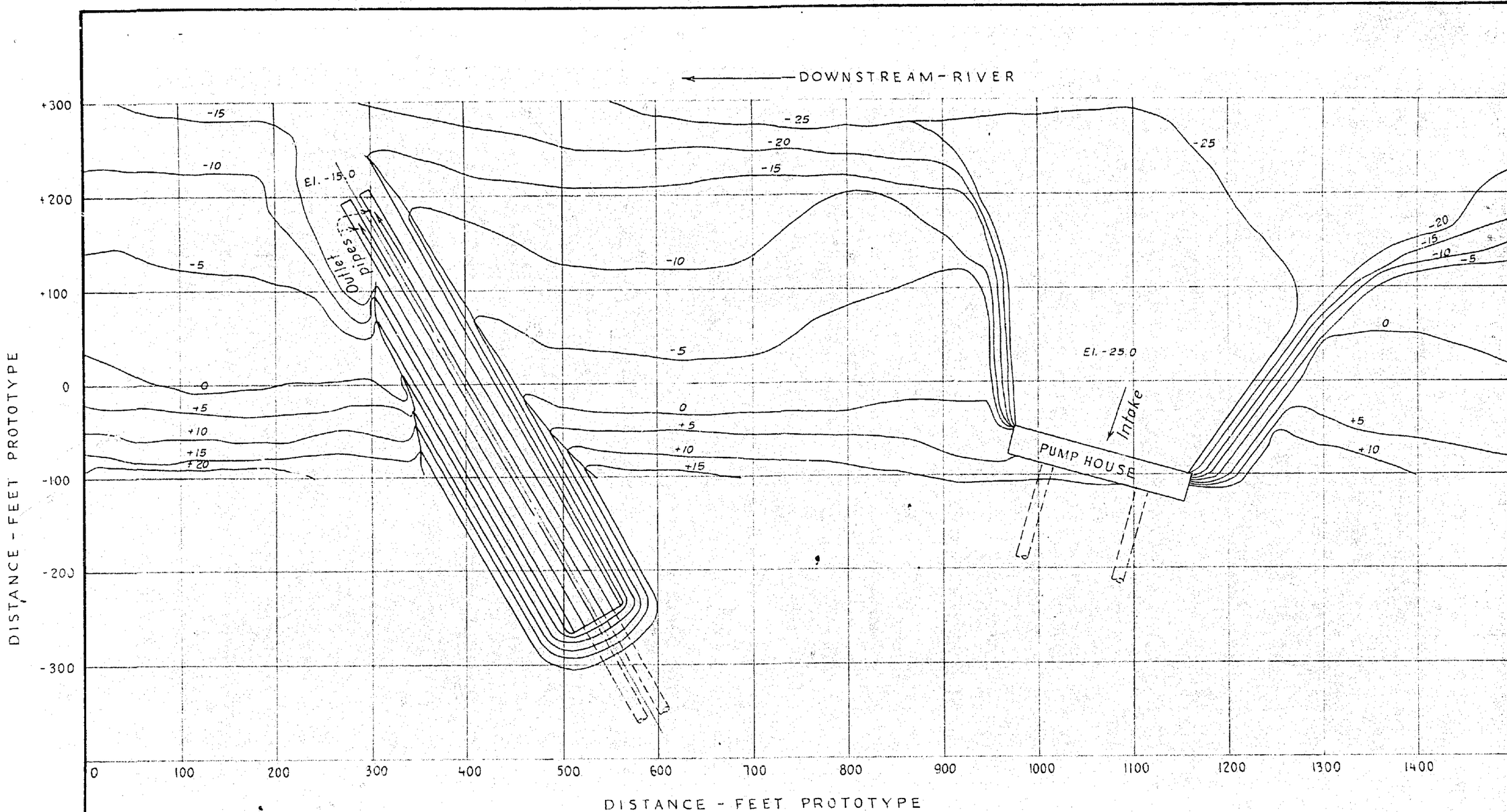
and photographing results. The grid lines as shown were 100 feet apart in each direction, or one foot apart in the model.

Cross sections on figure 9 show the measured temperature rise, above tide-water temperature, at various points throughout the grid system produced by 1,000 second-feet of condenser water, heated approximately 6.5 degrees, discharging into the river. In this case the intake water was heated 1.4 degrees above tide-water temperature by recirculation. The pump bay as located in the original design formed a dead, slowly rotating pool of water in which heat tended to accumulate with time. This is evidenced by the manner in which the colored water remained in the pump bay after slack tide, figure 8F.

Figure 10 shows cross sections of the temperature rise produced by a discharge of 480 second-feet which was heated 16.5 degrees in its passage through the condensers. Recirculation, in this case, heated the intake water 2.1 degrees above tide-water temperature. The B.t.u. content discharged into the river was slightly greater in the latter case, and this is evidenced by a larger temperature rise.

5. Discharge conduits extended 500 feet (test 2). In an attempt to obtain better mixing action with the cooler water in the river, the condenser discharge was conducted 500 feet farther out into the river by extending the two discharge conduits, as shown in figures 11 and 12. The photographs on figure 12 record the heated flow pattern during the flood-tide cycle from slack water to slack water. A comparison of these photographs with those on figure 8 shows that the heated water moved about 100 feet farther out into the river for the outlet extension; however, heat accumulated in the pump bay as in the former case. Confetti floating on the water surface of the pump bay, figure 12E, illustrates the type of slow,

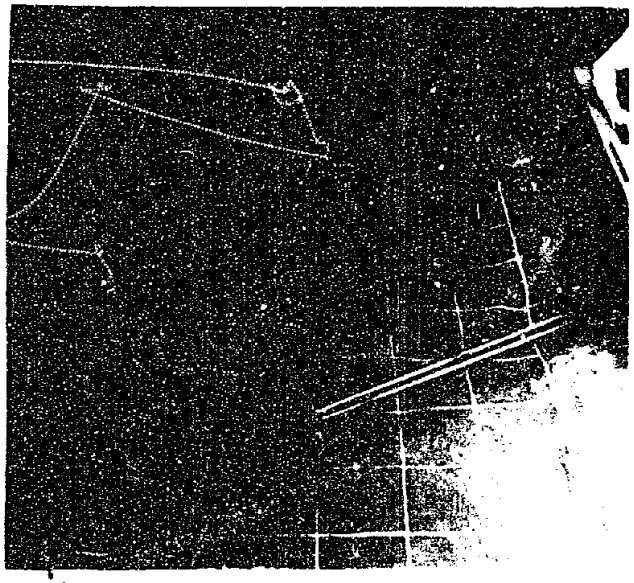
FIGURE 11



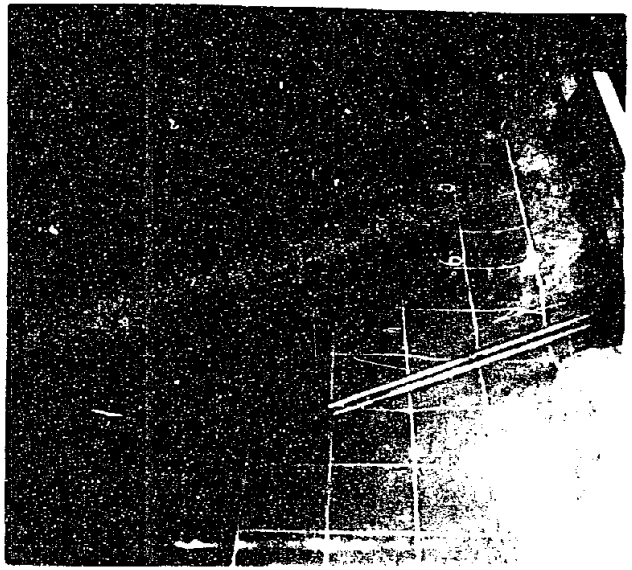
CENTRAL VALLEY PROJECT - CALIFORNIA
DELTA DIVISION

ANTIOCH STEAM PLANT
LAYOUT FOR TEST 2

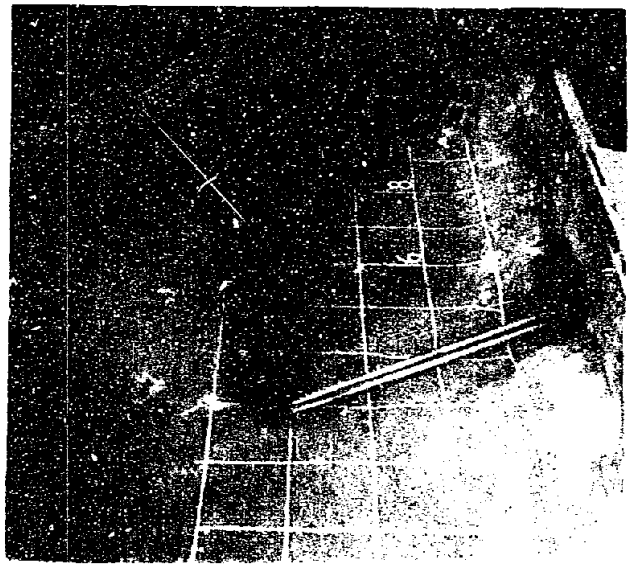
DISCHARGE CONDUITS EXTENDED
500 FEET



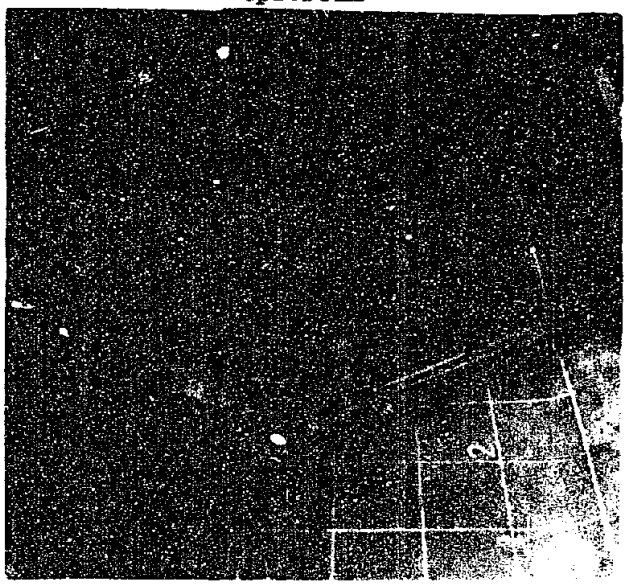
A - 0 Minutes - Beginning of Flow Upstream



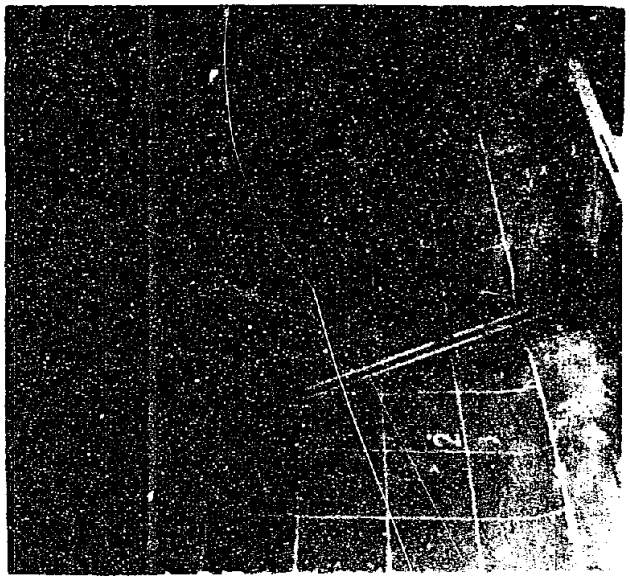
B - 20 Minutes



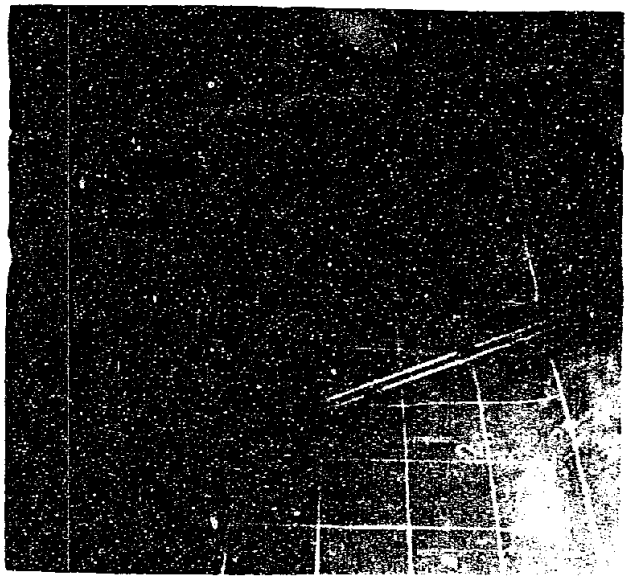
C - 120 Minutes



D - 200 Minutes - Maximum Velocity Upstream



E - 300 Minutes



F - 380 Minutes - Point at which Current Reverses to Downstream

FIGURE 12 PATH OF WARM WATER CURRENTS PRODUCED BY DISCHARGE CONDENSER WATER DURING FLOW TIDE

CONDENSER OUTLETS EXTENDED 500 FEET - TEST 2

FIGURE 13

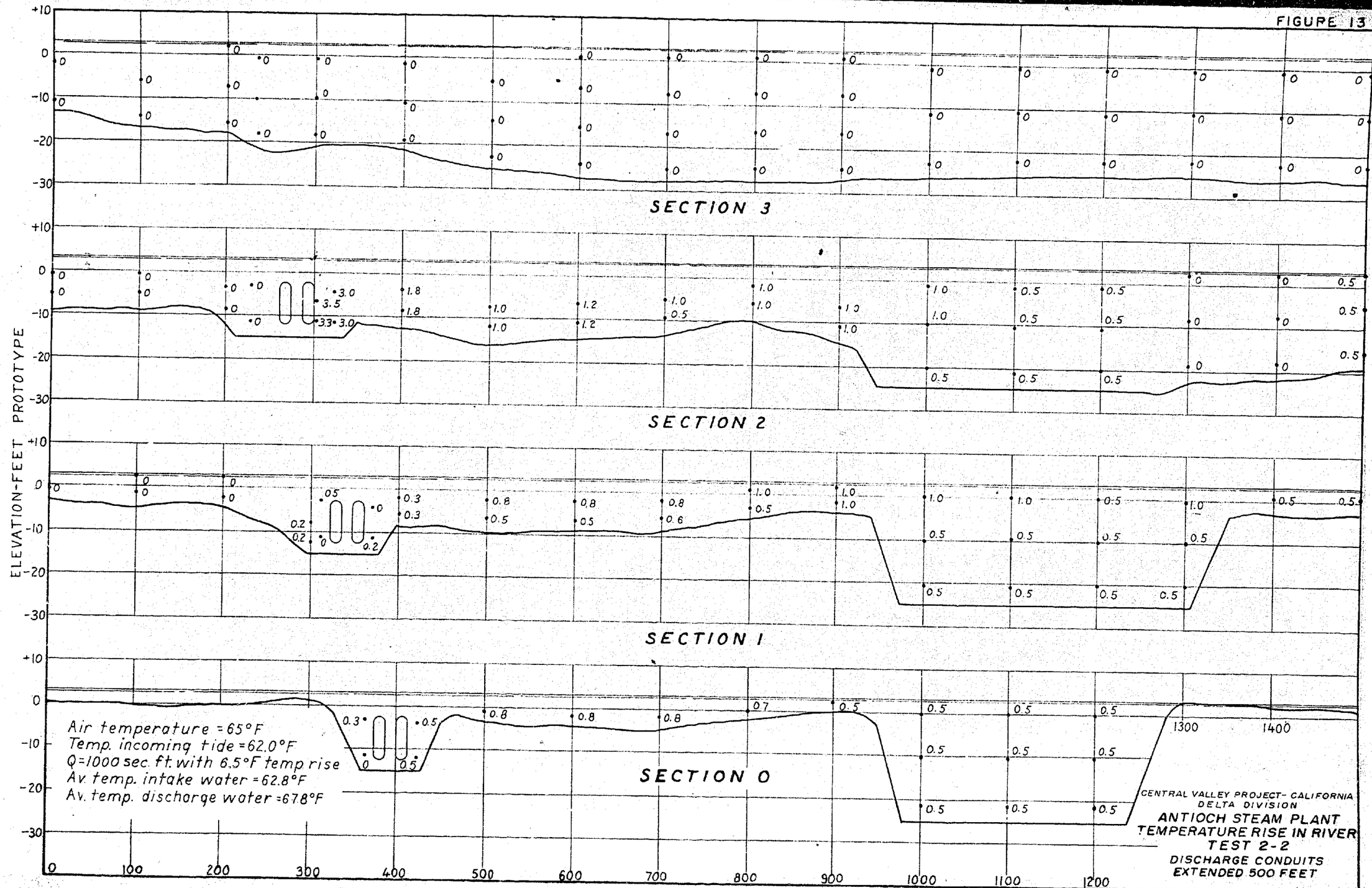
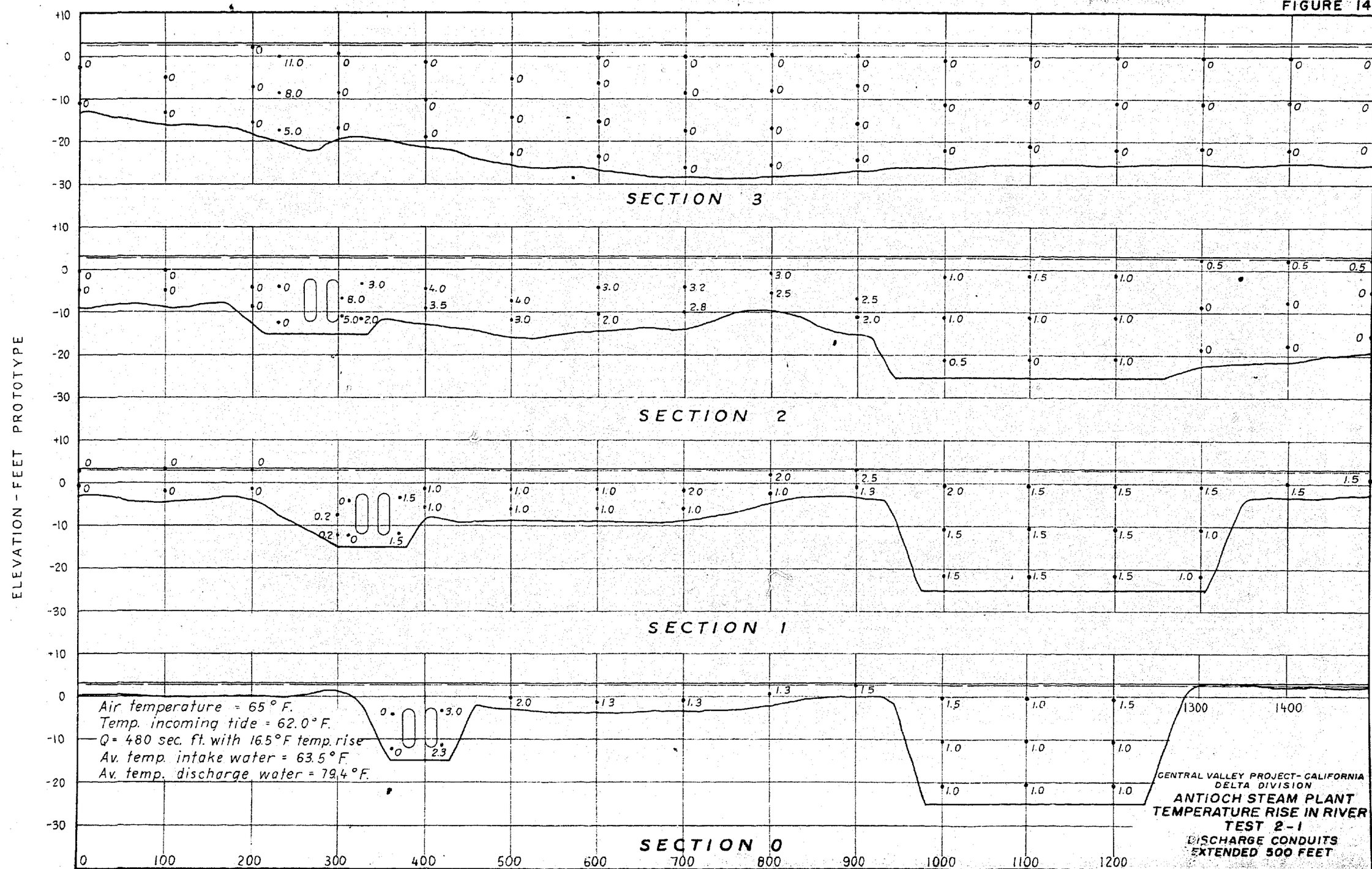

SECTION 3
SECTION 2
SECTION 1
SECTION 0
ELEVATION-FEET PROTOTYPE
+10
0
-10
-20
-30
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Air temperature = 65°F
Temp. incoming tide = 62.0°F
Q = 1000 sec. ft. with 6.5°F temp rise
Av. temp. intake water = 62.8°F
Av. temp. discharge water = 67.8°F
CENTRAL VALLEY PROJECT- CALIFORNIA
DELTA DIVISION
ANTIOCH STEAM PLANT
TEMPERATURE RISE IN RIVER
TEST 2-2
DISCHARGE CONDUITS
EXTENDED 500 FEET

FIGURE 14



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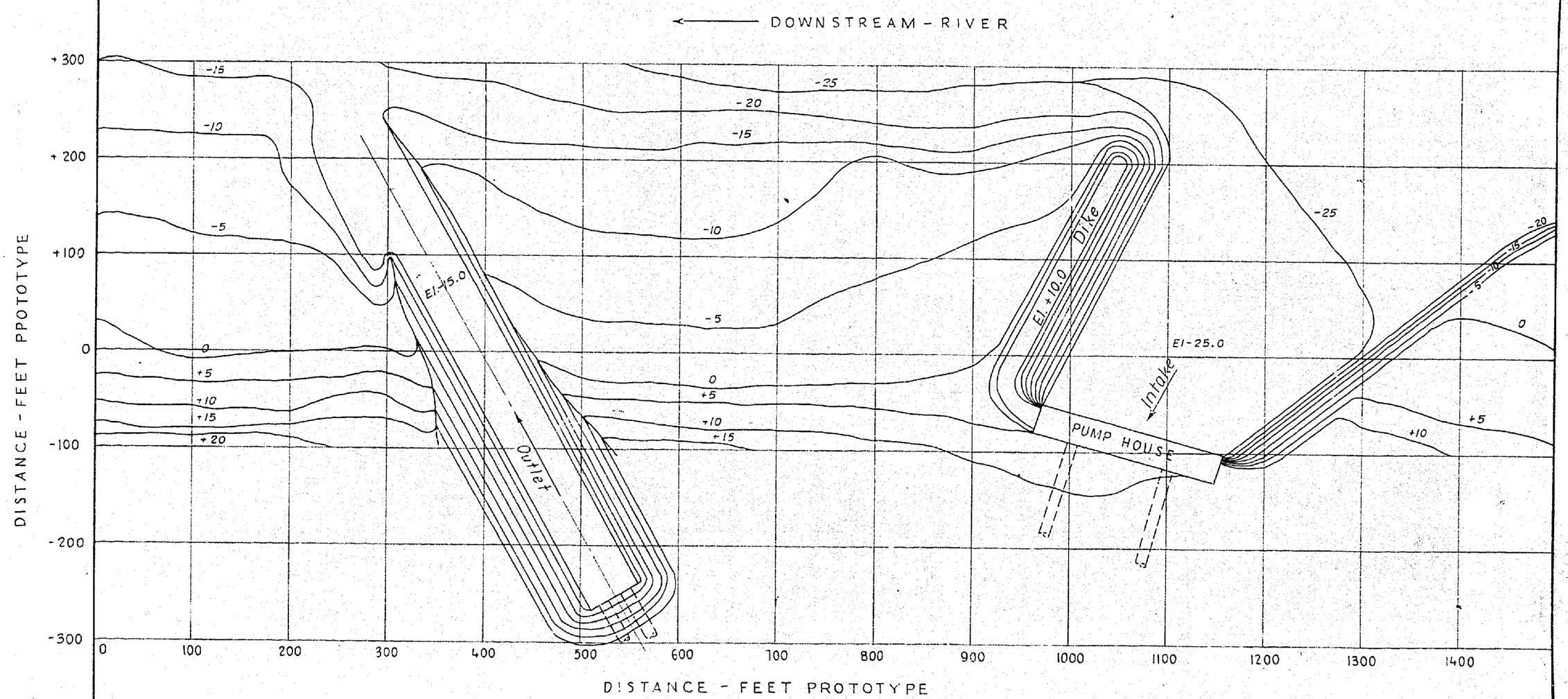
DELTA DIVISION

ANTIOCH STEAM PLANT
TEMPERATURE RISE IN RIVER
TEST 2-1
DISCHARGE CONDUITS EXTENDED 500 FEET

H10-126

FIGURE 15



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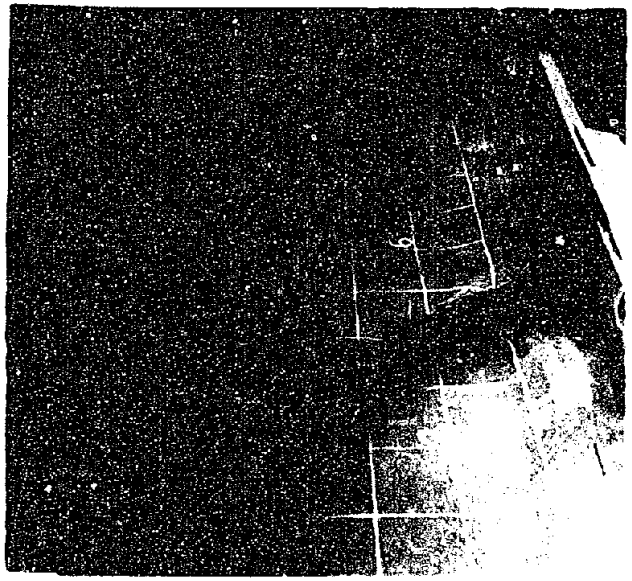
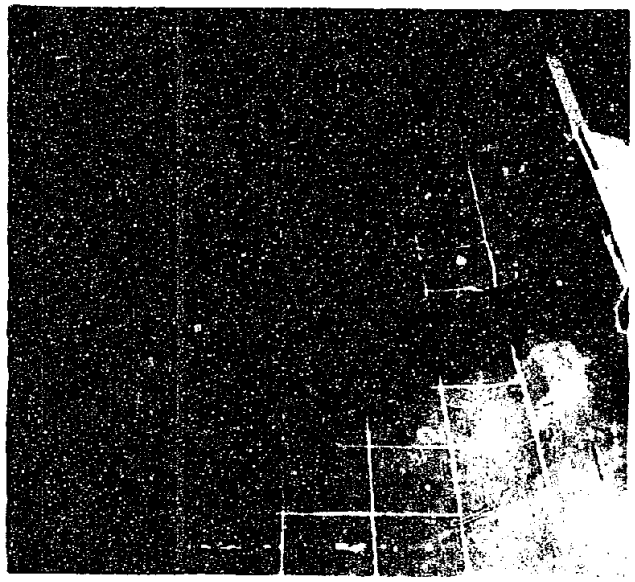
DELTA DIVISION

ANTIOCH STEAM PLANT
LAYOUT FOR TEST 3

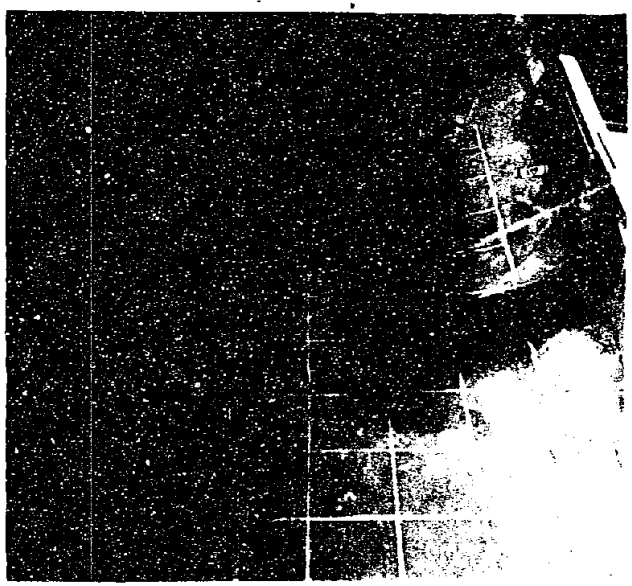
DIKE ON DOWNSTREAM SIDE OF INTAKE



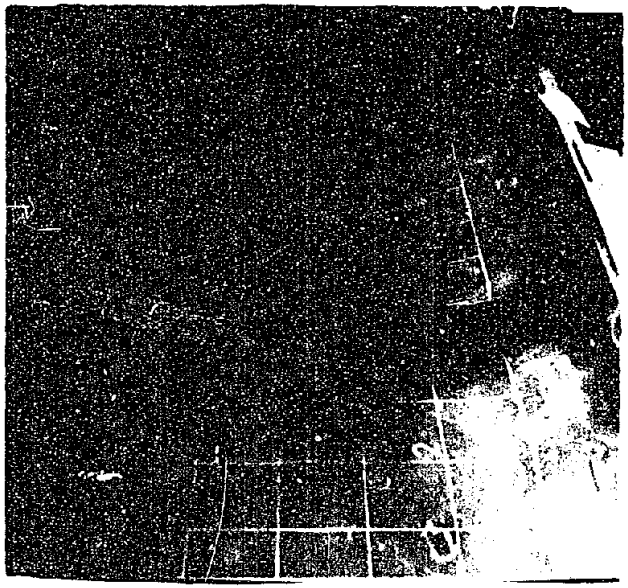
A - 0 Minutes - Beginning of Flow Upstream



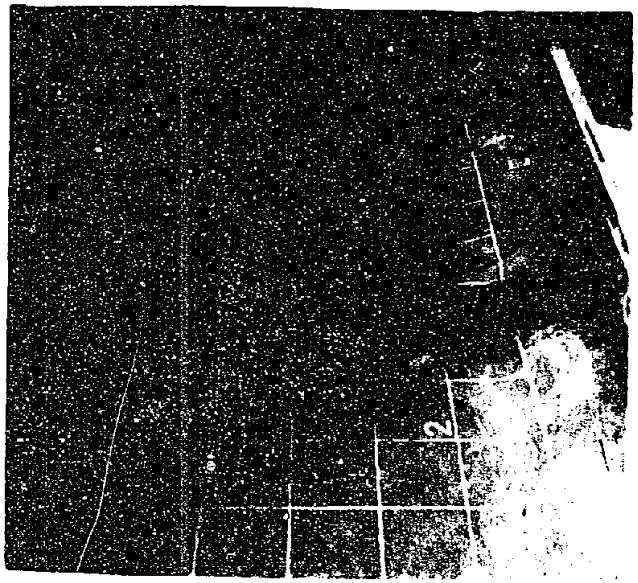
B- 20 Minutes



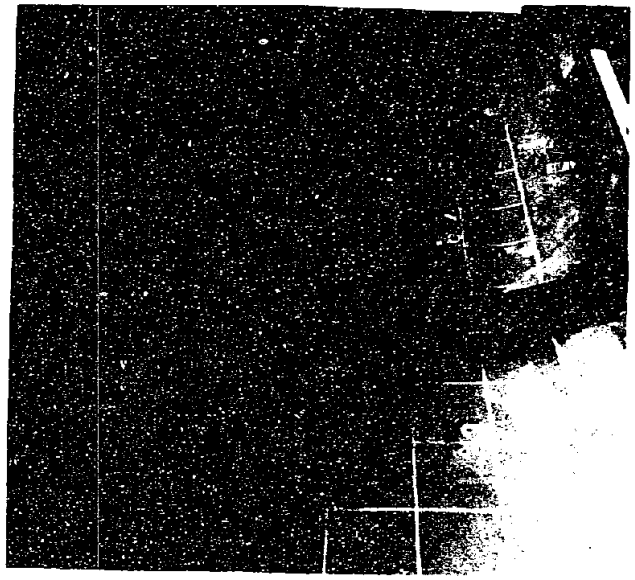
C - 120 Minutes



D - 200 Minutes - Maximum Velocity Upstream



E - 300 Minutes



F - 380 Minutes - Point which Current Reverses to Downstream

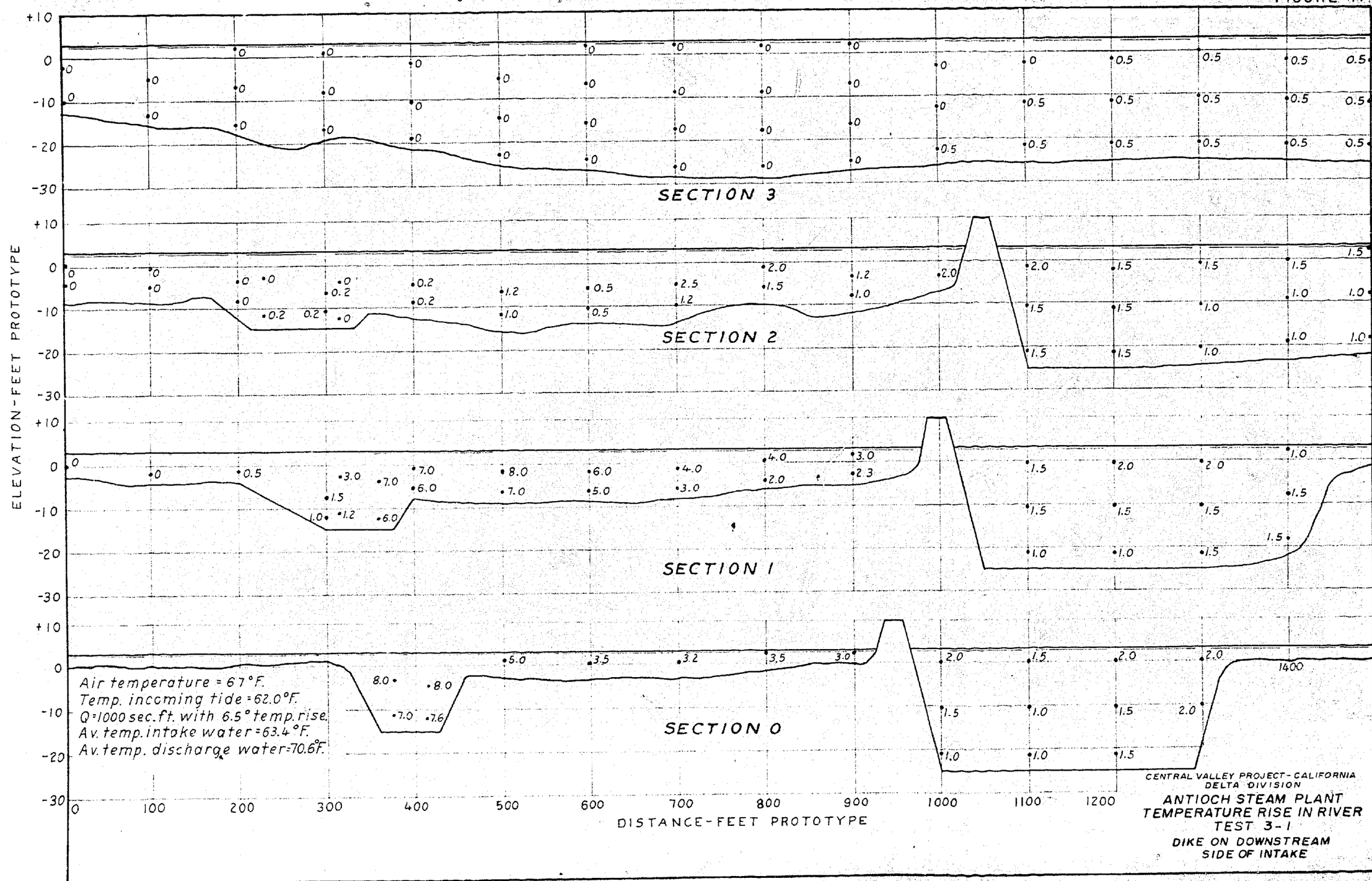
FIGURE 16 PATH OF WARM WATER CURRENTS PRODUCED BY DISCHARGE CONDENSER WATER DURING FLOW TIDE

PUMP BAY PROTECTED BY DIKE - TEST 3

rotating motion experienced at this location. The temperature rise produced in the river by the heated condenser water with the outlet conduits extended 500 feet is shown on figures 13 and 14 for discharges of 1,000 second-feet with 6.5-degree heating and 480 second-feet with 16.5-degree heating, respectively. The recorded temperature rise may appear erratic at some points, but this is not necessarily true. The flow, in most cases, assumed a diagonal course across the grid; thus the cross sections as shown were seldom parallel with the current. Considered as a whole, the temperature records are satisfactory. The intake-water temperature increased 0.8 degrees above tide-water temperature for the 1,000 second-foot discharge and 1.5 degrees for the 480 second-foot discharge. The amount of recirculation in this case was less than for the original design.

6. Dike on downstream side of pump bay (test 3). In a second attempt to reduce recirculation, the outlet-pipe extension was removed and a dike was placed along the downstream side of the pump bay, figures 15 and 16, in anticipation that the heated water would be directed away from the intake. Photographs of the heated-water pattern are shown for the flood-tide cycle on figure 16. Photograph 16B shows that the dike did direct the warm water farther out into the river at the intake; however, the predominating flow of the tide again forced it toward the shore immediately after passing the extremity of the dike. A small portion of this heated water was attracted to the pump bay by the slowly rotating motion of the water therein which gradually produced an accumulation of heat comparable to that in the previous designs. Photograph 16C shows an accumulation of colored water in the pump bay after 120 minutes (prototype time) and photograph F demonstrates the manner in which the colored water remained in the bay during slack tide. Cross sections showing measured temperature rise in the river are shown for

FIGURE 17



CENTRAL VALLEY PROJECT - CALIFORNIA
DELTA DIVISION

ANTIOCH STEAM PLANT
TEMPERATURE RISE IN RIVER
TEST 3-1

DIKE ON DOWNSTREAM
SIDE OF INTAKE

FIGURE 18

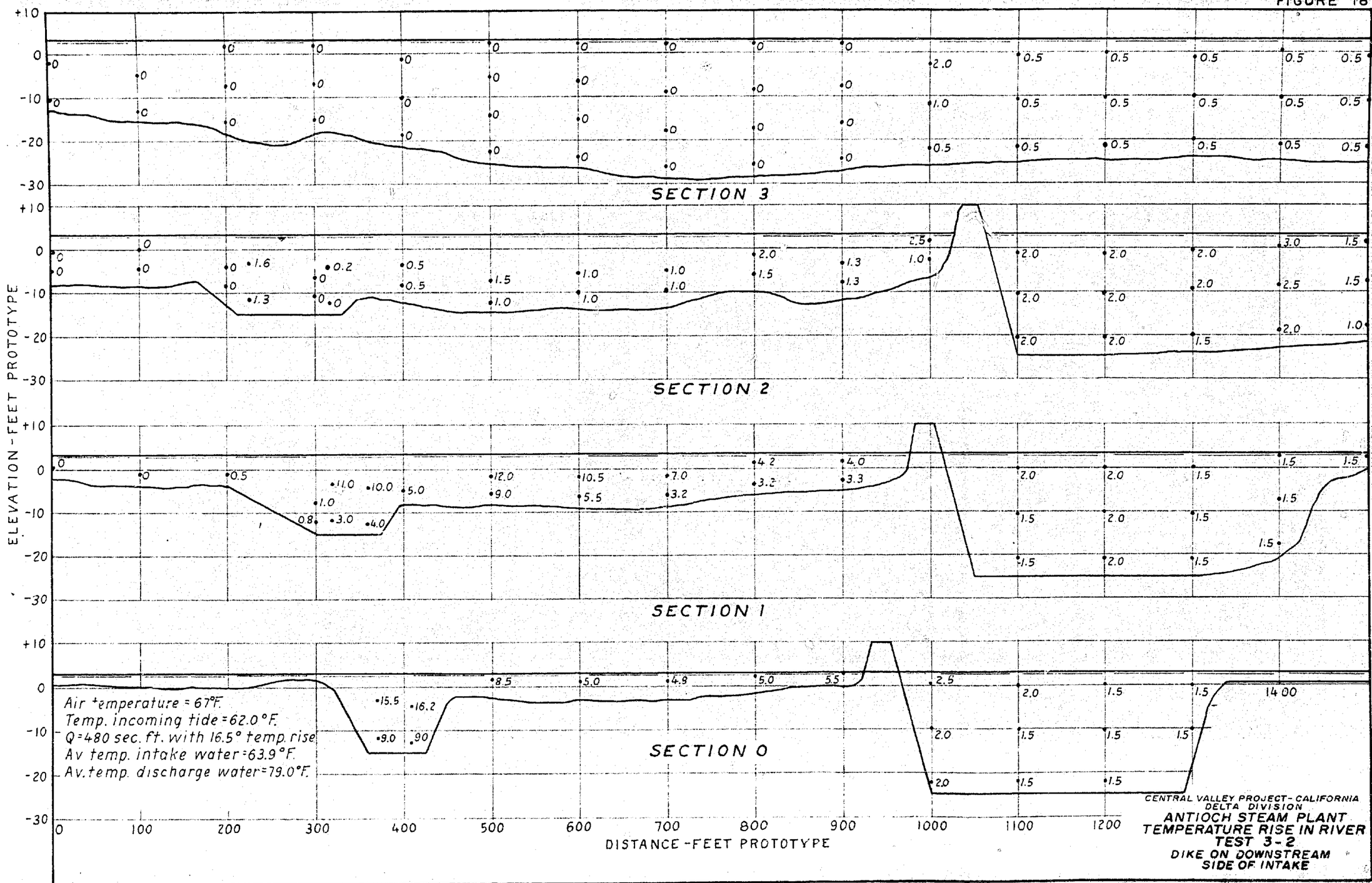
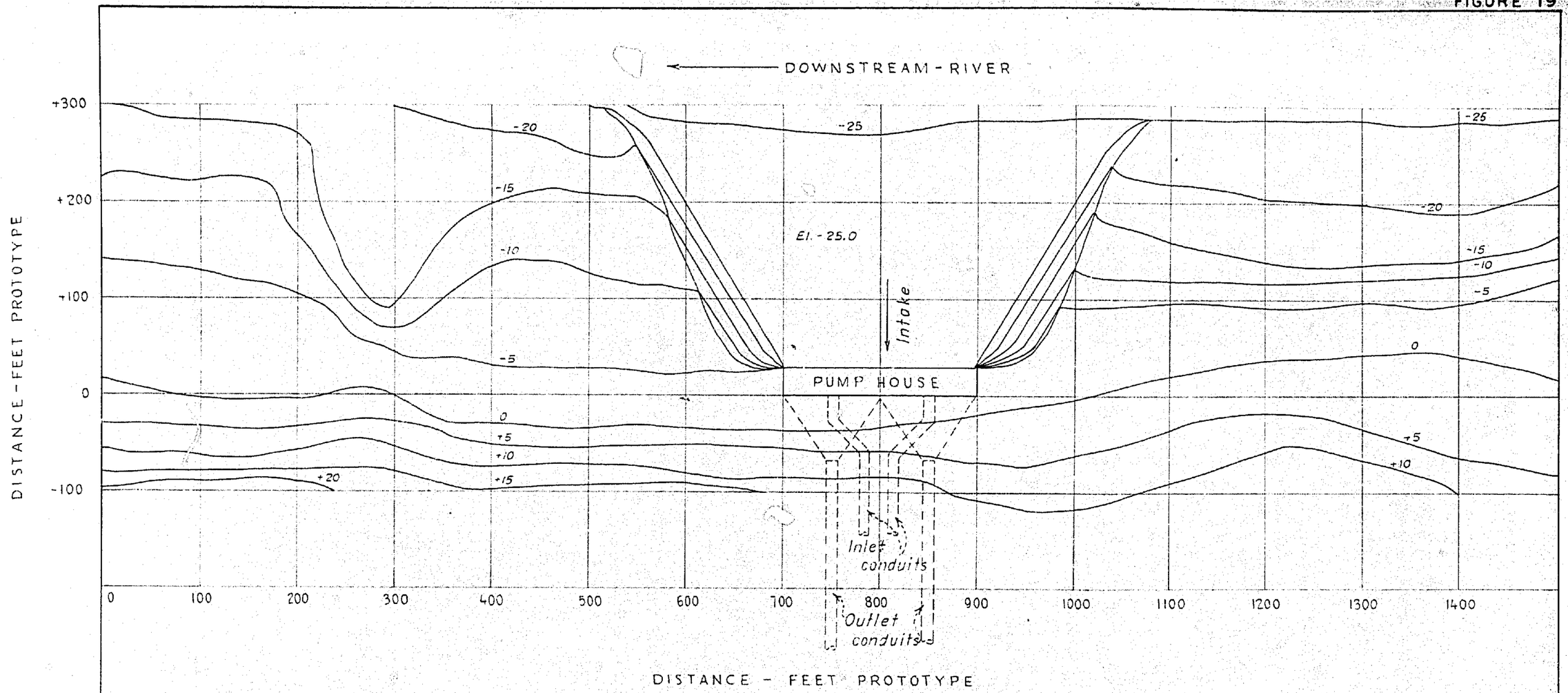
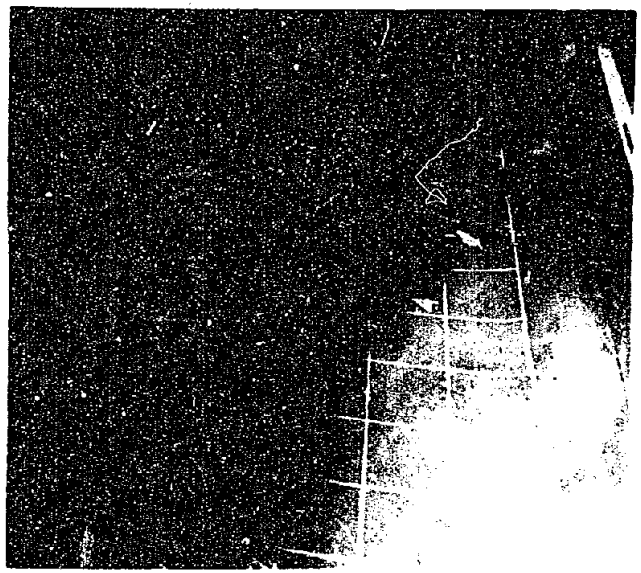

SECTION 3
SECTION 2
SECTION 1
SECTION 0
ELEVATION - FEET PROTOTYPE
DISTANCE - FEET PROTOTYPE
Air temperature = 67°F.
Temp. incoming tide = 62.0°F.
Q = 480 sec. ft. with 16.5° temp. rise
Av temp. intake water = 63.9°F.
Av. temp. discharge water = 79.0°F.
CENTRAL VALLEY PROJECT - CALIFORNIA
DELTA DIVISION
ANTIOCH STEAM PLANT
TEMPERATURE RISE IN RIVER
TEST 3-2
DIKE ON DOWNSTREAM
SIDE OF INTAKE

FIGURE 19

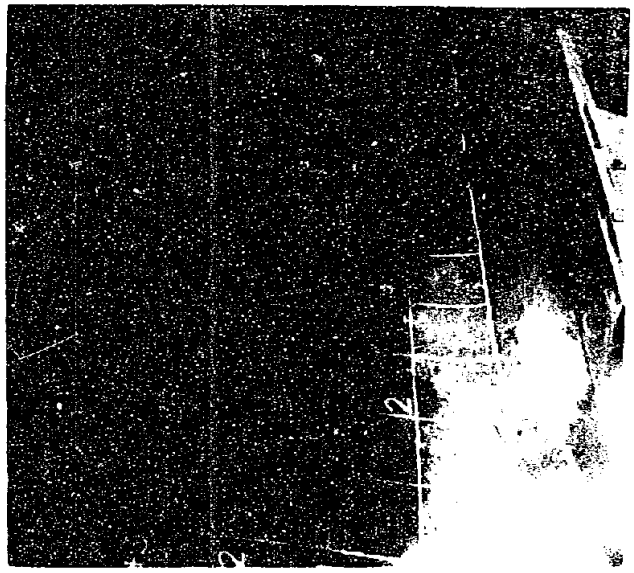


CENTRAL VALLEY PROJECT-CALIFORNIA
DELTA DIVISION

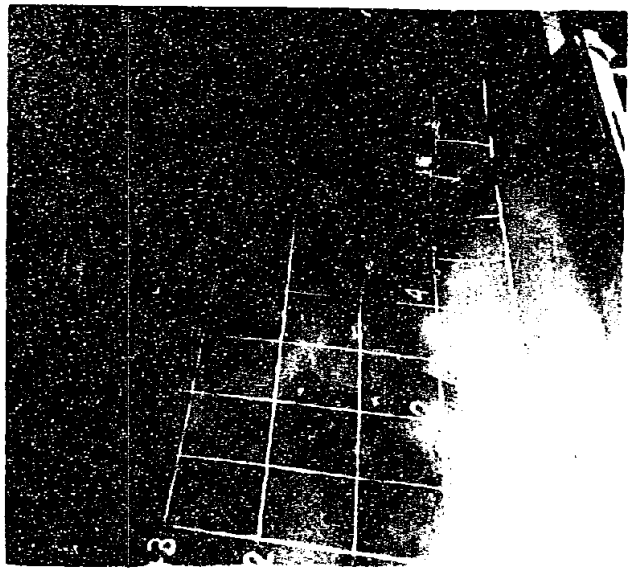
ANTIOCH STEAM PLANT
LAYOUT FOR TEST 5
DISCHARGE DIRECTLY ABOVE INTAKE



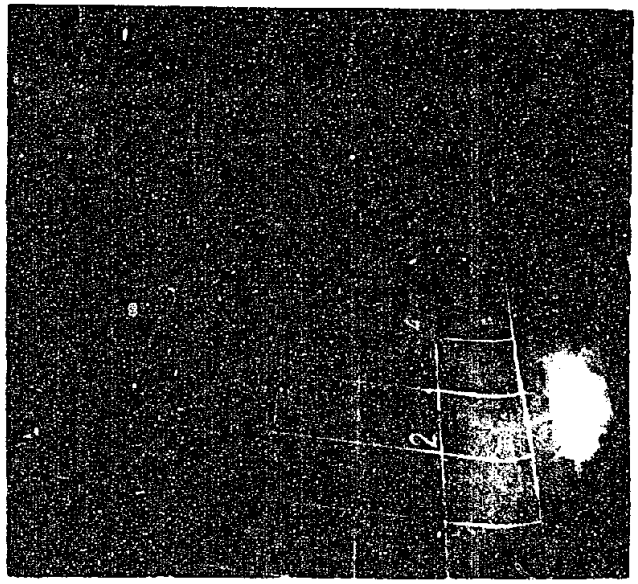
A - Ebb Tide - Flow is Downstream



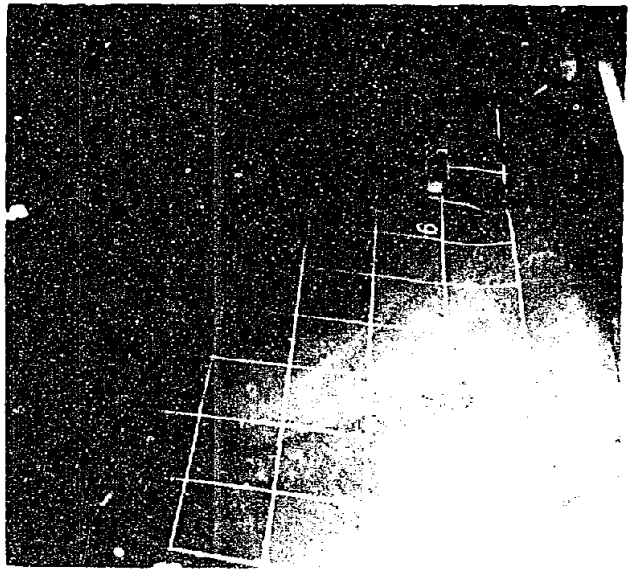
B - Slack Tide - Beginning of Flow Upstream



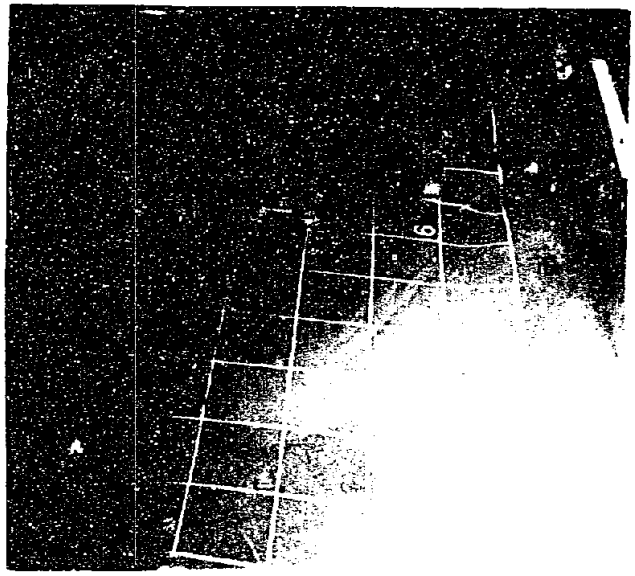
C - 20 Minutes



D - 60 Minutes



E - 200 Minutes - Maximum Velocity Upstream

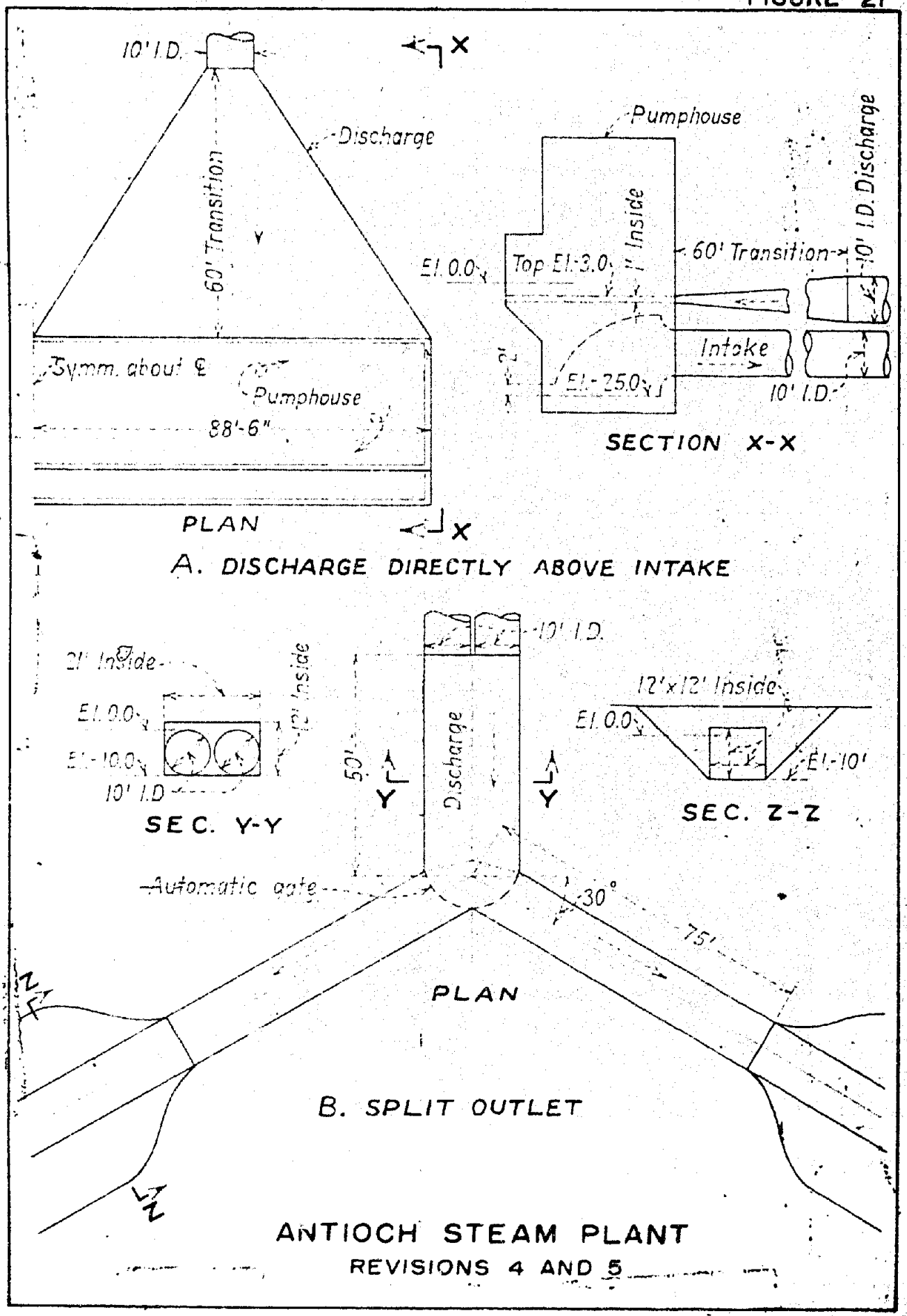


F - Slack Tide - Point at which Current Reverses to Downstream

FIGURE 20 PATH OF WARM WATER CURRENTS PRODUCED BY DISCHARGE CONDENSER WATER

SPLIT OUTLET CHANNELS - TEST 4

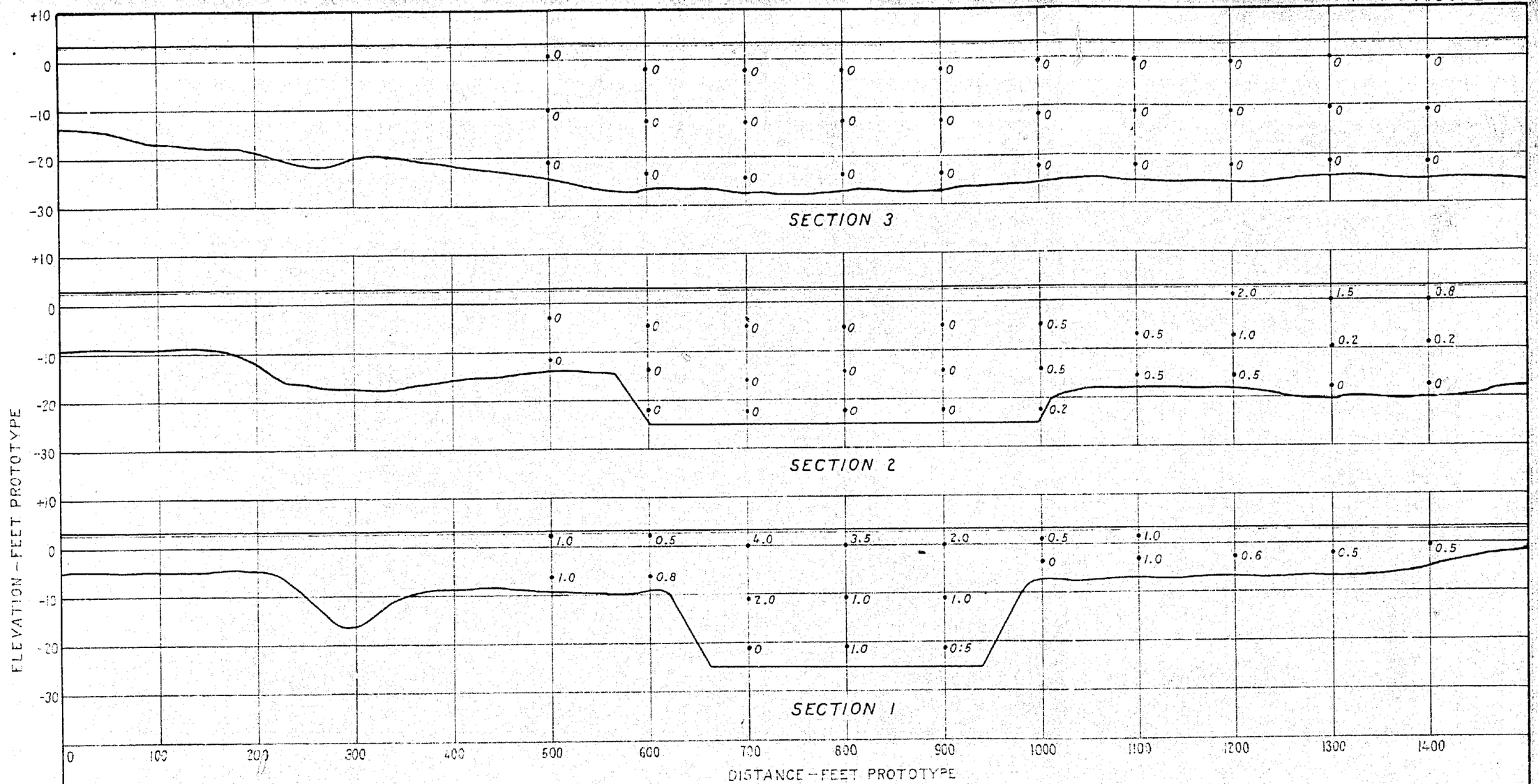
FIGURE 21



ANTIOCH STEAM PLANT

REVISIONS 4 AND 5

FIGURE 22



Air temperature = 68.0°F
Temp. incoming tide = 53.0°F
Q = 1000 sec. ft. with 6.5° temp. rise
Av. temp. intake water 54.2°F
Av. temp. discharge water 61.3°F

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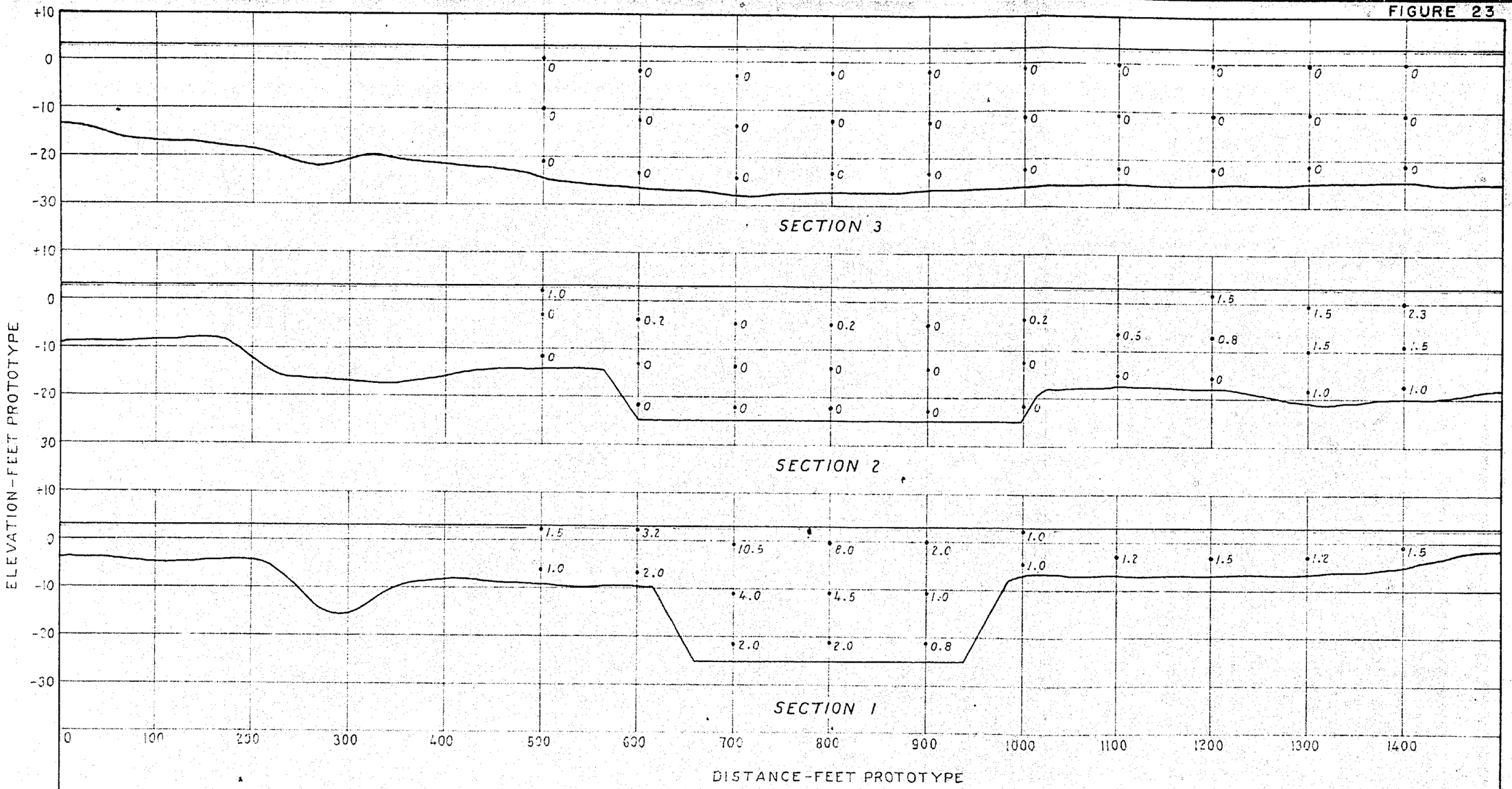
DELTA DIVISION

ANTIOCH STEAM PLANT
TEMPERATURE RISE IN RIVER
TEST 5-2
DISCHARGE DIRECTLY ABOVE INTAKE

FIGURE 23



Air temperature = 67.5°F
Temp. incoming tide = 53.0°F
Q = 480 sec. ft. with 16.5° temp. rise
Av. temp. intake water 54.6°F
Av. temp. discharge water 70.2°F

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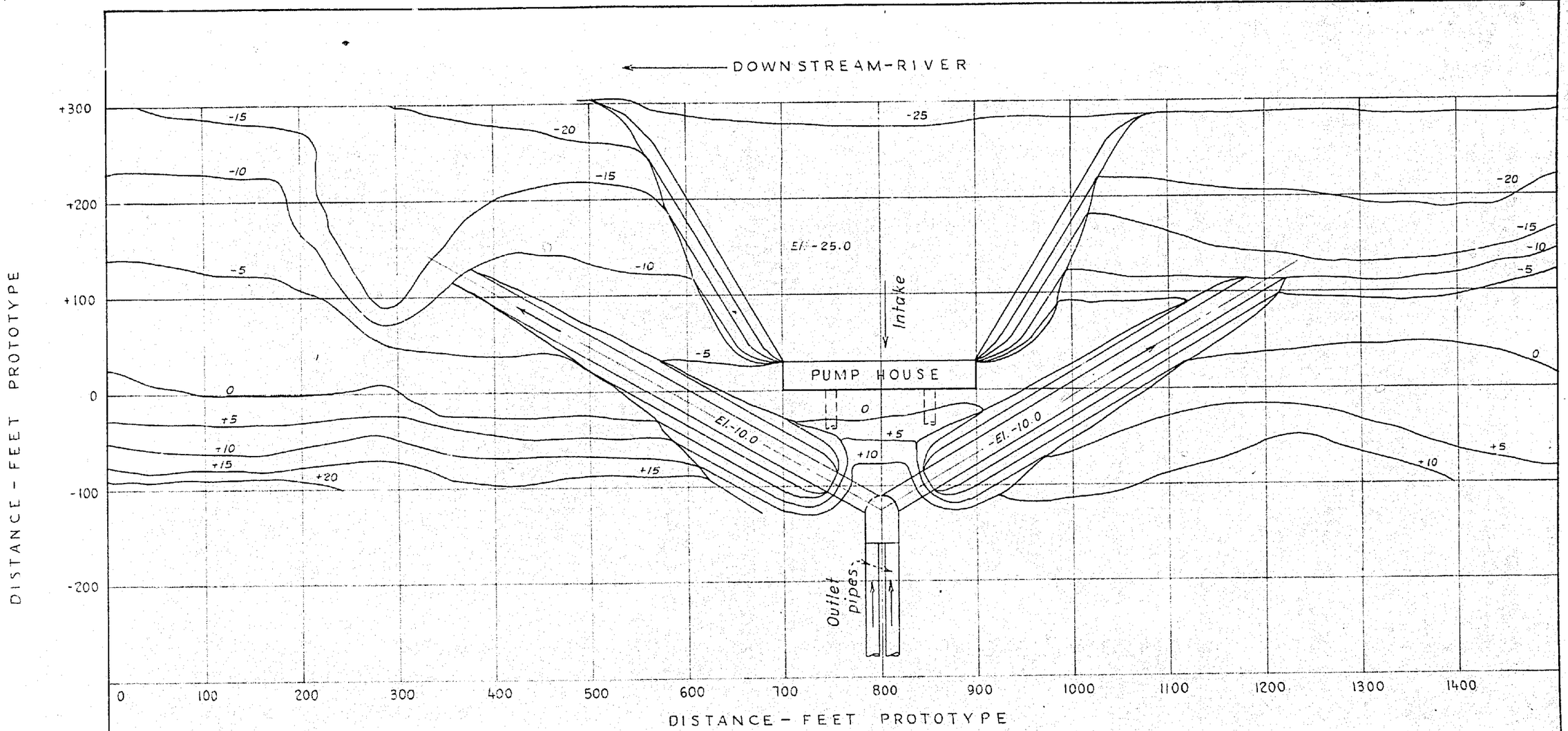
DELTA DIVISION

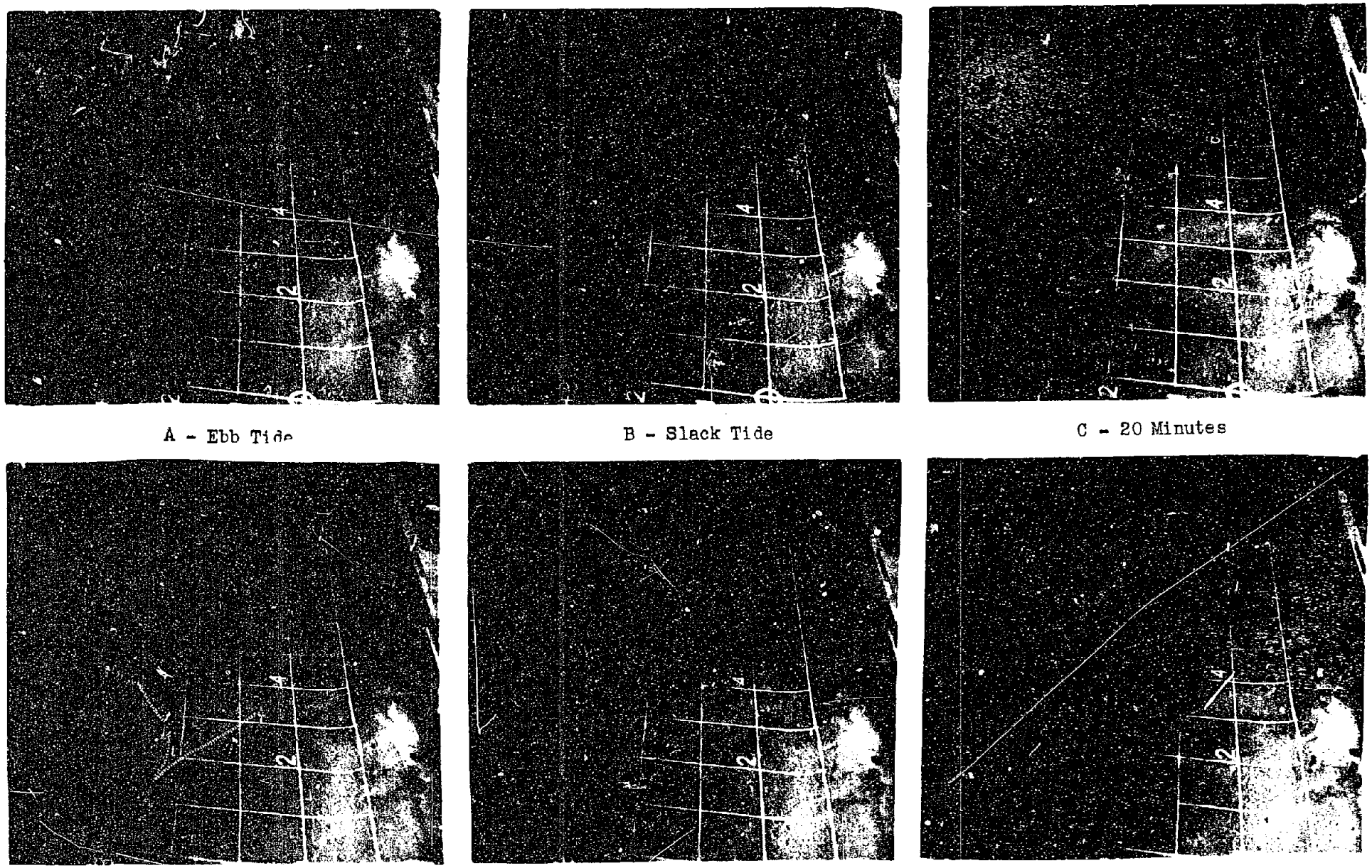
ANTIOCH STEAM PLANT
TEMPERATURE RISE IN RIVER
TEST 5-1
DISCHARGE DIRECTLY ABOVE INTAKE

FIGURE 24



CENTRAL VALLEY PROJECT - CALIFORNIA
DELTA DIVISION

ANTIOCH STEAM PLANT
LAYOUT FOR TEST 4
SPLIT OUTLET CHANNELS



A - Ebb Tide

B - Slack Tide

C - 20 Minutes

D- 60 Minutes

E - 200 Minutes - Maximum Velocity Upstream

F - Slack Tide

FIGURE 25 PATH OF WARM WATER CURRENTS PRODUCED BY DISCHARGE CONDENSER WATER DURING FLOW TIDE

OUTLETS DISCHARGING DIRECTLY ABOVE INTAKE - TEST 5

a condenser discharge of 1,000 second-feet and 480 second-feet on figures 17 and 18, respectively. The former shows an intake-water temperature rise of 1.4 degrees caused by recirculation, while the latter recorded temperature rise was 1.9 degrees.

7. Discharge directly above intake (test 5). In a fourth scheme to reduce the temperature rise of the intake water, the pump house was relocated and the heated condenser water was discharged in a thin sheet directly over the pump intakes, figures 19 and 20. The manner in which the model pump house was revised to obtain this condition is shown on figure 21A. The heated water currents obtained with this layout are shown on figure 20. Temperature-rise conditions in the river are shown on figure 22 for a condenser discharge of 1,000 second-feet heated 6.5 degrees, and a similar record is shown on figure 23 for a discharge of 480 second-feet heated 16.5 degrees above intake-water temperature. The temperature rise of the intake water was 1.2 degrees in the first case and 1.6 degrees in the second, which indicates that the extent of recirculation for this layout is little different than that experienced in previous tests.

8. Split-outlet channels (test 4). It was desired to develop a design in which recirculation would be absent or minimized as much as practically possible. The result is shown on figures 24 and 25 in which a split-outlet channel with automatic diverter gate was utilized to control the direction of flow of the heated condenser water as it entered the river. The heated water was diverted downstream at ebb tide and up river during flood tide, as shown by the photographs on figure 25. A dimensioned sketch of the diverter and split-outlet channels as used in the model, is shown on figure 21B. The diverter gate could be controlled by a velocity device which would actuate a relay when flow reversed in the

FIGURE 26

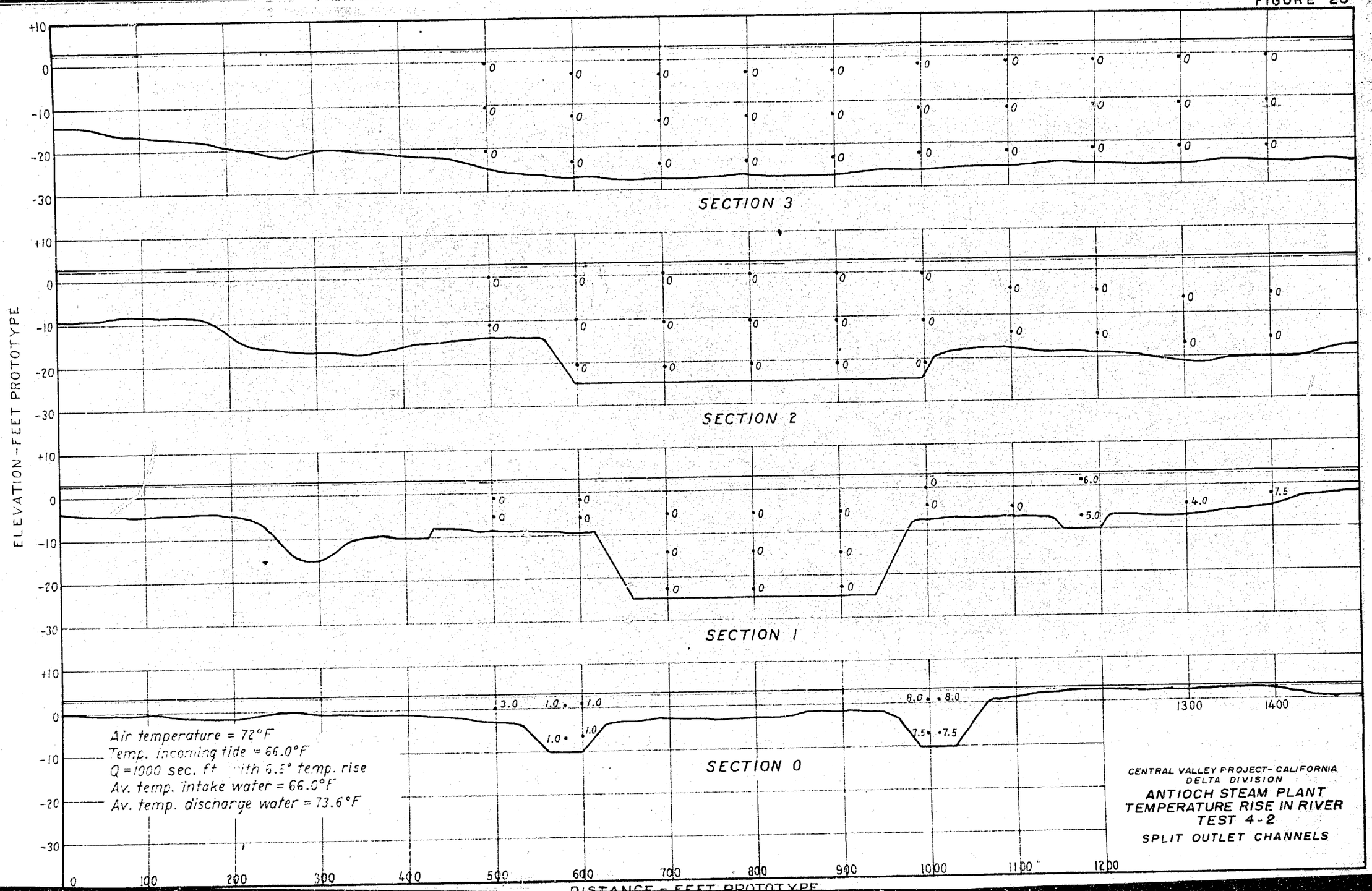
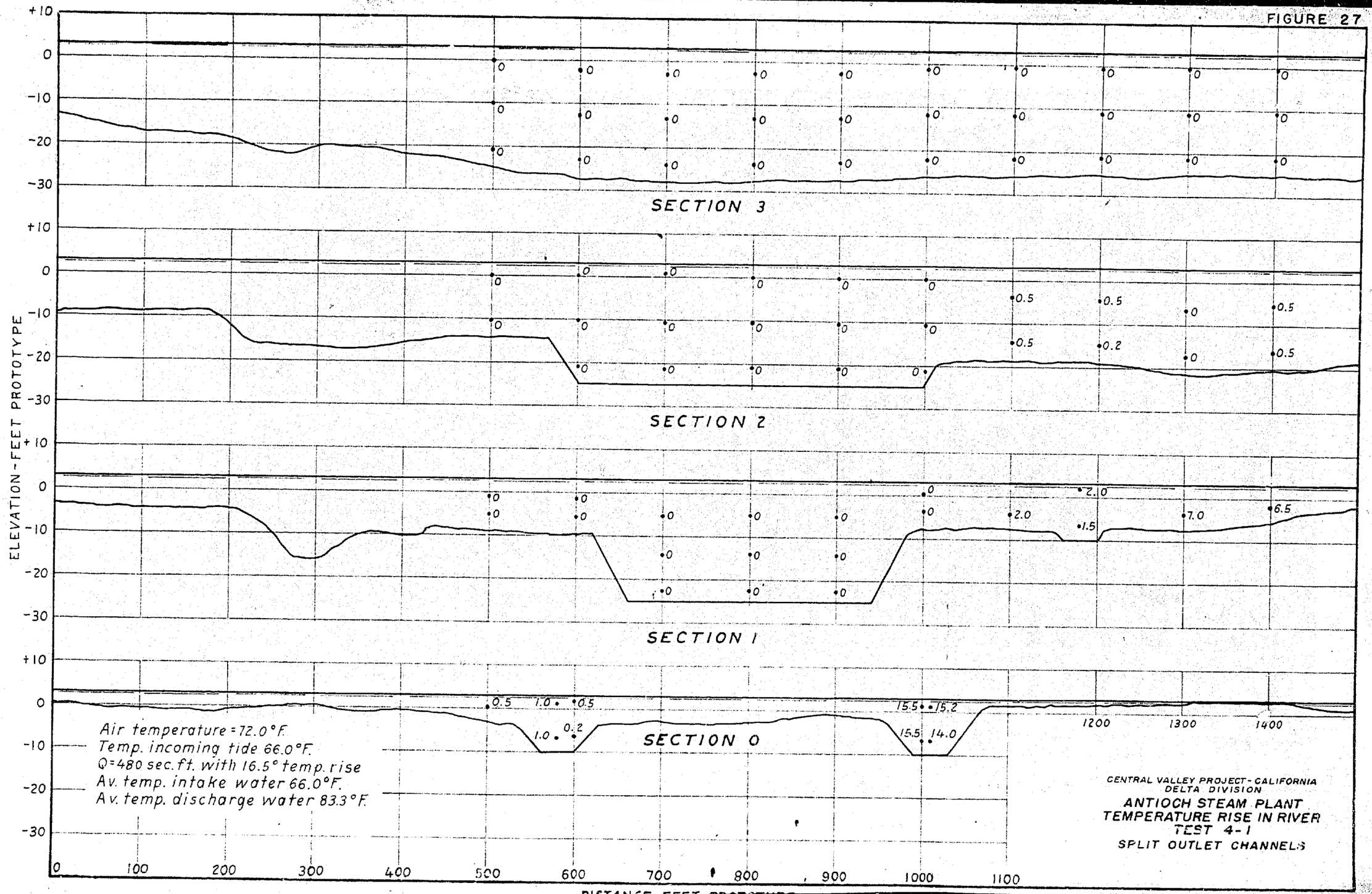

ELEVATION-FEET PROTOTYPE
+10
0
-10
-20
-30
SECTION 3
SECTION 2
SECTION 1
SECTION 0
Air temperature = 72°F
Temp. incoming tide = 66.0°F
Q = 1000 sec. ft with 6.5° temp. rise
Av. temp. intake water = 66.0°F
Av. temp. discharge water = 73.6°F
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
DISTANCE - FEET PROTOTYPE
CENTRAL VALLEY PROJECT- CALIFORNIA
DELTA DIVISION
ANTIOCH STEAM PLANT
TEMPERATURE RISE IN RIVER
TEST 4-2
SPLIT OUTLET CHANNELS

FIGURE 27



CENTRAL VALLEY PROJECT - CALIFORNIA
DELTA DIVISION

ANTIOCH STEAM PLANT
TEMPERATURE RISE IN RIVER
TEST 4-1
SPLIT OUTLET CHANNELS

river or the same result could be obtained by the use of a clock. Should the gate ever fail to operate, no hydraulic damage could result.

Results showing temperature rise in the river for a condenser discharge of 1,000 second-feet with 6.5-degree heating and 480 second-feet with 16.5-degree heating above intake-water temperature are shown on figures 26 and 27, respectively. In both cases no temperature rise of the intake water was recorded, giving the result desired. In this design, heating of the intake water could occur only at slack tide, which, according to figure 6, can exist but a few minutes.

9. Summary of hydraulic-flow studies. The following table summarizes the results of the hydraulic-flow study:

TABLE 1

Temperature Rise of Intake Water above River-Water Temperature

Design	1,000 second-feet		480 second-feet	
	Av. heating by condensers, degrees F.	Temperature rise at intake, degrees F.	Av. heating by condensers, degrees F.	Temperature rise at intake, degrees F.
Original design (test 1)	4.8	1.4	14.3	2.1
Discharge conduits extended 500 feet (test 2)	5.0	0.8	15.9	1.5
Dike on downstream side of pump bay (test 3)	7.2	1.4	15.1	1.9
Discharge directly above intake (test 5)	7.1	1.2	15.6	1.6
Split-outlet channels (test 4)	7.4	0.0	17.3	0.0

HEAT-STUDY RESULTS

10. Analysis of heat losses. The heat in the condenser discharge water can be dissipated in three ways: (1) heat loss to the surrounding atmosphere by convection and evaporation, (2) heat loss to the river bed by conduction, and (3) heat transfer to the cooler river water by conduction and mixing. In the first two cases the heat loss to the atmosphere and the river bed is primarily a function of the contact areas. In the last case volumes are the governing factor.

As stated previously, the rate of dissipation and stratification of heat in model and the prototype bears the ratio of approximately 1:1. Assuming that the initial temperatures in model and prototype are the same, the heat supply to the model is proportional to the quantity of heated condenser water entering the river per unit of time in the ratio of 1/100,000. The heated-water pattern, as it moves from the outlet to intake in the model, occupies a surface area equal to 1/10,000 of that of the prototype. As the heat losses, due to convection and evaporation at the surface and conduction to the river bed, are proportional to the areas exposed, the model losses per unit of time will be 1/10,000 of those in the prototype. The relative losses to atmosphere and river bed are therefore proportionately $\frac{100,000}{10,000}$ or ten times larger in the model. Thus the temperature drop experienced in the model, due to the above losses, was ten times too great.

As the degree of heating of the intake water was of primary interest, the surface area between the outlet and pump intake, shown by the extent of the color in figure 8E, will be considered. This involves an area equal to 800 x 250 = 200,000 squarefeet, prototype. From figure 10, the condenser discharge water was 82 degrees with a corresponding air temperature

of 68 degrees, producing a differential at the outlet of 12.2 degrees. The differential between air and water at the pump intake was -1.7 degrees.

From studies on this subject made by R. E. Glover and F. C. Allen - their memorandum has been included in this report - surface convection from air to the water produces a gain of heat approximating 2.0 B.t.u. per hour per square foot of surface per degree (Fahrenheit) of differential, which amounts to 800,000 B.t.u. per hour for the prototype. Evaporation, on the other hand, is responsible for a loss of heat from water to air of 21.8 B.t.u. per square foot of surface, which is equal to 4,367,000 B.t.u. per hour. The net loss of heat by the water, from these two causes, is therefore 3,567,000 B.t.u. per hour. The total amount of heat entering the river from the condenser outlets, using river-water temperature as base, equals

$$16.4 \times 480 \times 62.4 \times 3600 = 1{,}768{,}400{,}000 \text{ B.t.u. per hour.}$$

The heat loss to the atmosphere is therefore

$$\frac{3{,}567{,}000}{1{,}768{,}400{,}000} = 0.20 \text{ percent of the total.}$$

According to Messrs. Glover and Allen the heat conduction from the heated water to the river bed should be approximately 8.0 B.t.u. per square foot of contact surface per degree of differential per hour for the first hour after reversal of flow in the river, and one-half this amount thereafter. According to their computations, the loss of heat from water to stream bed is about 3,520,000 B.t.u. for the first hour of flood tide, which is 0.20 percent of the total heat entering the river. The combined heat loss to the atmosphere and river bed is therefore approximately 0.40 percent of the total, leaving 99.60 percent of the heat to be transferred to the adjacent cooler river water by mixing. It is now apparent that the

convection, evaporation, and river-bed conduction losses, which were not to scale, are of little importance and could be neglected in these computations. Interpretations of model temperatures would be complicated were it not for the fact that all of the above losses are small in comparison to the heat transferred to the river water by mixing action. Proof of the unimportance of the above makes it possible to deal primarily with the third loss which is basically a hydraulic-flow problem.

The transfer of heat from the warmer to the cooler water is produced by mixing action which, if exactly similar in model and prototype, is governed by the laws of hydraulic similitude. In salinity studies which involve the flow of fresh and salt water, it has been customary to regard the scale ratio of densities as 1:1. Experiments by the U. S. Waterways Experiment Station have shown that the source of error from this procedure is negligible as the density flow of salt water with fresh water, observed from models, duplicates the prototype action closely. This is known as a conservative concentration which can be altered locally only by the process of diffusion and advection. It so happens that heat content in an aqueous solution falls under the same category and the action is similar.[1] In both cases, however, it is essential

[1] Sverdrup, Johnson, and Fleming, "The Oceans, Their Physics, Chemistry and General Biology." Prentice Hall, Publishers, p. 158.

that turbulent flow exist in the model to obtain similar flow conditions with those of the prototype. The lack of a definite method of proof of turbulence in the model discouraged a mathematical expression to this end; however, it can be stated that from observation the flow in the model, used in these tests, was not laminar.

Referring to figure 6, the average maximum prototype velocity in the river for the condition shown on figure 8D is 2.0 feet per second.

Consequently, the velocity of the [illegible] ed water near the shore is about 1.5 feet per second. The averag[illegible] [illegible]on of the colored area, measured normal to the shore line, [illegible] [illegible]are feet. The total discharge flowing through the color[illegible] [illegible]al to

$$1.5 \times 2250 = 3{,}375 \text{ se[illegible]d-feet.}$$

Of this flow, 480 second-feet or 14.2 percent enters the river at 80.2 degrees while 85.8 percent of this total discharge is river water at a temperature of 63.8 degrees. With thorough mixing, the resulting temperature of these two masses of water should be

$$t_o = \frac{480 \times 80.2 + 2895 \times 63.8}{3375} = 66.13 \text{ degrees}$$

or 2.33 degrees above the temperature of the undisturbed river water.

A more accurate figure is obtained by repeating the computation and deducting the heat loss to the atmosphere and river bed. In this case the temperature increase above river-water temperature, at the pump intake, should be

$$\Delta t_o = \frac{1{,}768{,}400{,}000 - 3{,}567{,}000 - 3{,}520{,}000}{3375 \times 62.4 \times 3600} = 2.32 \text{ degrees.}$$

Referring to figure 10, the temperature rise at the pump intake for the above conditions was found to be 2.1 degrees from the model. The agreement is within the experimental error expected in a study of this kind. The tests previously described under "Flow-Study Results" are not merely comparative but represent true prototype results within limits. It is felt that the prototype intake temperature rise as listed in Table 1 will not differ more than 25 percent from those obtained on the model for any given set of conditions. The figures in Table 1 apply for upstream velocities from one to two feet per second. This is evidenced by the photographs

in figure 8 which show little change in the flow pattern over this range. It should be repeated that the tests included herein were made for the most adverse conditions which can prevail at the prototype site. Whether the extent of heating due to recirculation, as indicated by the model tests, is sufficient to be objectionable depends on a study of the plant equipment, which is beyond the scope of this report.

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J. N. Bradley

Denver, Colorado, May 3, 1943.

MEMORANDUM TO MR. J. N. BRADLEY
(R. E. Glover and F. C. Allen)

Subject: Study of cooling water temperature during reversal of stream flow past the Antioch Steam Plant - Central Valley Project.

1. The stream from which condenser cooling water is taken for the Antioch Steam Plant is subject to a periodic reversal of flow due to tidal effects. This reversal of flow places the cooling water inlet to the power plant below the cooling water outlet relative to the direction of water flow and, due to imperfect mixing, causes the temperature of the water at the inlet to be appreciably influenced by the warm water discharged from the power plant. Tests made in the Hydraulic Laboratory on a model of the stream in the vicinity of the power plant have yielded data on the magnitude of this effect. It is the purpose of this study to evaluate the relative effects of mixing and of heat losses upon the water temperatures.

2. The following data have been determined from the dimensions of the prototype and from tests on the model of the stream:

(a) Distance between water inlet and outlet openings = 800 feet.
(b) Water flow through power plant = 480 second-feet.
(c) Average width of return channel = 250 feet.
(d) Return flow in river bed after mixing = 3400 second-feet.
(e) Average velocity in return channel = 1.5 feet per second.
(f) Average depth of return channel = 9.07 feet.
(g) Temperature of water in stream = 63.8° F.
(h) Temperature of water entering power plant = 65.9° F.
(i) Temperature of water leaving power plant = 80.2° F.
(j) Ambient air temperature = 68° F.

3. On the basis of the above date, the temperature of the water mixture (500 second-feet of water at 80.2° F. and 2900 second-feet of water at 63.8° F.) in the return channel should be 66.2 F. Since the measured temperature at the power plant inlet was 65.9° F. in the model test, the difference of 0.3° F. should be at least partially accounted for by the net effect of heat losses from the water in the return channel during transit from the outlet to the inlet openings.

4. The following assumptions were made in evaluating the heat losses from the return channel:

(a) The film conductance at the water-stream bed boundary is infinite.

(b) The film conductance at the water-air surface is 2.0 B.t.u./(hr. x ft.^{2} x $^\circ$F.).

(c) The relative humidity in the laboratory is about 50 percent.

(d) The temperature of the water in the return channel is uniform and constant at the average value of 66° F.

(e) The conductivity of the stream bed is 1.00 B.t.u./(hr. x ft. x $^\circ$F.).

(f) The diffusivity of the stream bed is 0.02 ft.^{2}/hr.

5. The heat gained by the water due to convection at the surface is about 800,000 B.t.u. per hour, and the heat lost by the water due to evaporation is about 4,367,000 B.t.u. per hour. The net loss at the surface is therefore 3,567,000 B.t.u. per hour. This accounts for a water temperature drop at the inlet to the power plant of about 0.0047° F.

6. The total heat loss at the water-stream bed boundary would be about 3,520,000 B.t.u. during the first hour of operation under reversed stream flow conditions. This accounts for a water temperature drop at the inlet to the power plant of about 0.0046° F., which is an average value for the first hour. This would decrease during subsequent hours of operation.

7. The total temperature drop which can be accounted for by heat losses at the air surface and water-stream bed boundary is therefore about 0.009° F. for the prototype. By analogy, the temperature drop would be about ten times as great in the model test or about 0.09° F. This amounts to about one-third of the measured deviation.

8. Under the assumed conditions of operation, the unit heat losses for the three factors considered in estimating the temperature drop are:

Convection = 2.0 B.t.u./(hr. x ft.^{2} x $^\circ$F.)

Evaporation = 21.8 B.t.u./(hr. x ft.^{2})

Conduction = 4.0 B.t.u./(hr. x ft.^{2} x $^\circ$F.) at the end of the first hour.

= 8.0 B.t.u./(hr. x ft.^{2} x $^\circ$F.) average during first hour.

9. The temperature of the cooling water entering the power plant during periods of reversed flow of the stream would be affected by factors not considered here. For instance, imperfect mixing and non-uniform temperatures in the return channel would have some influence.

However, it is apparent that the heat losses to the stream bed and the ambient air have only a superficial influence, and that mixing with river water is the major factor in determining the temperature of the cooling water under the assumed conditions of operation.

- - -

(Sgd.) R. E. Glover.

(Sgd.) F. C. Allen.