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# HYDRAULIC AND ANALYTICAL STUDIES OF THE CAUSES AND THE CONTROL OF SURGING IN THE COACHELLA IRRIGATION DISTRIBUTION SYSTEM ALL-AMERICAN CANAL SYSTEM BOULDER CANYON PROJECT

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CONTENTS


| | Page |
|---|---|
| Purpose | 1 |
| Conclusions | 1 |
| Recommendations | 3 |
| Acknowledgment | 3 |
| Introduction | 4 |
| General Features | 4 |
| Operating Difficulties | 6 |
| Investigations of the Surging | 6 |
| Factors Which Cause Surging | 7 |
| Auto-oscillation | 7 |
| Amplification Factors and Natural Frequencies | 8 |
| The Laboratory Model | 13 |
| Laboratory Tests | 14 |
| Straight Baffles | 14 |
| Pipe Line Vents | 15 |
| Gates Through the Baffles | 16 |
| Siphons in the Baffle | 17 |
| Reduced Flow Area in the Upstream Side of the Stand | 18 |
| Stands with a Central Inlet Riser Pipe | 18 |
| Effect of Pool Depth and Height of Fall on Air Entrainment | 21 |
| Head Loss from the Pipe Stand to the Pipe Line | 22 |
| Airtight Covers | 23 |
| Analytical Investigation of the Stand Covers | 24 |
| Electric Analog Studies | 27 |
| High-frequency analog | 28 |
| Low-frequency analog | 32 |
| Relation of Resonance to the Imposed Oscillation Periods | 34 |
| The Action Within the Pipe System When Flow is Started | 35 |
| Verification of the Analytical and Electric Analog Results by Hydraulic Model Tests | 36 |
| Changing the Period of a Pipe Reach Without Using Covers | 40 |

LIST OF FIGURES


| | Figure |
|---|---|
| Coachella Valley County Water District | 1 |
| Pipe Stand—Coachella Valley Distribution System | 2 |
| Schematic Lateral Profile | 3 |
| 3 cfs Meter Stand | 4 |
| Pipe and Meter Stands Flooding Over Due to Surging in the System | 5 |
| Sketch of a Single Reach of Pipe Between Pipe Stands | 6 |
| Amplification Factors | 7 |
| Schematic Diagram of the Laboratory Model | 8 |
| Head box with Motor-operated, Reciprocating Float for Inducing Surges in Laboratory Model | 9 |
| Pipe Stand Baffles, Baffle Extensions and Baffle Gates | 10 |
| Baffle Elevations for the Initial Tests and for Producing the Maximum and Minimum Surging | 11 |
| Air Entrained in the Downstream Section of the Stand and Carried into the Outlet Pipe of the Laboratory Model | 12 |
| Siphons Through the Baffles | 13 |
| Baffle Siphons Installed in the Pipe Stands | 14 |
| Partitions in Upstream Side of the Stands to Reduce the Flow Area and Increase Friction | 15 |
| Pipe Stand with an Inlet Riser Pipe | 16 |
| Operation of Pipe Stands with Inlet Riser Pipes | 17 |
| Reduced Air Entrainment in Pipe Stand Pool with Inlet Riser Pipe | 18 |
| Air Entrainment Test Facilities | 19 |
| Increase in Air Entrainment with Increase in Flow | 20 |
| Increase in Air Entrainment with Increase in Height of Water Fall | 21 |
| Deflectors and Gratings Used in Attempts to Reduce Air Entrainment | 22 |
| Ineffectiveness of Deflectors and Gratings in Reducing the Air Entrainment | 23 |
| Piezometric Pressures in the Pipe Line and Head Loss from the Downstream Pool to the Pipe | 24 |
| Pipe Stand Cover to Suppress Surging | 25 |
| Sketch of Two Pipe Reaches Having a Common Covered Stand | 26 |
| Comparison Between Hydraulic System and Electric Analog Circuit | 27 |
| Relation of Resonance for Various Pipe Line Systems to the Imposed Oscillation Period | 28 |

LIST OF FIGURES--Continued


Figure

The Action Within the Pipe System When Oscillating Flow Was Started

No Stands Covered . . . . . 29
Stand 1 Covered . . . . . 30
Stands 1 and 2 Covered . . . . . 31
Stands 1 and 2 Covered . . . . . 32
Stands 1, 2, and 3 Covered . . . . . 33
Stands 1, 2, and 3 Covered . . . . . 34
Stands 1, 2, and 3 Covered . . . . . 35

The Action Within the Pipe System When the Flow Was Suddenly Increased . . . . . 36

Relation of Resonance to Imposed Period as Determined by Analytical, Electric Analog, and Hydraulic Model Tests . . 37

## LIST OF SYMBOLS

$a = \frac{2\pi}{T_o}$

A area of pipe cross section - $ft^2$

$B = \frac{K}{g}\left[\frac{A_2F_1L_1}{A_1} + F_2L_2\left(\frac{S_o + F_1H_o}{S_o + F_2H_o}\right)\right]$

C capacity of a condenser - farads

$c_1 = \frac{2gh_o}{V_oL}$

$c_2 = \frac{Ag}{F_1L}$

$c_3 = \frac{2gh_o}{V_oF_1L}$

$c_4 = \frac{2\pi}{T_1F_1}$

$D = \frac{d}{dt}$ differential operator - $\frac{1}{sec}$

E electrical pressure - volts

$F_1$, $F_2$ horizontal cross-sectional areas of the downstream parts of pipe stands - $ft^2$

g acceleration of gravity - $ft/sec^2$

h friction loss in a pipe reach of length L at the velocity V - ft

$h_a$ accelerating head - ft

$h_o$ value of h at the average (mean) velocity, $V_o$ - ft

$H$ instantaneous absolute pressure of the air in a covered pipe stand - ft of water

$H_o$ average absolute pressure of the air in a covered pipe stand - ft of water

$I$ electrical current - amperes

$i$ departure of the current from the average current, $I$ - amperes

$J$ inductance - Henrys

$$K = \frac{A_1 g^2 (S_o + F_2 H_o)}{F_1 F_2 L_1 L_2 S_o}$$

$$K_1 = \frac{c_3\left(c_2 - \frac{4\pi^2}{T_1^2}\right) + c_4 \frac{2\pi}{T_1} c_1}{\frac{4\pi^2}{T_1^2} c_1^2 + \left(c_2 - \frac{4\pi^2}{T_1^2}\right)^2}$$

$$K_2 = \frac{-c_3 \frac{2\pi}{T_1} c_1 + c_4\left(c_2 - \frac{4\pi^2}{T_1^2}\right)}{\frac{4\pi^2}{T_1^2} c_1^2 + \left(c_2 - \frac{4\pi^2}{T_1^2}\right)^2}$$

$L$, $L_1$, $L_2$, $L_n$ length of pipe reaches - ft

$M$ constant

$$M_1 = \frac{1}{A} + K_2 \frac{2\pi F_1}{T_1 A}$$

$$M_2 = K_1 \frac{2\pi F_1}{T_1 A}$$

$n$ analog time – seconds

$n_2$, $n_3$ departure from the running levels on the upstream side of the pipe stands – ft

$q$ departure of the flow from the average flow, $Q_o$ – cfs

$Q$ the instantaneous flow entering a reach – cfs

$Q_o$ the average flow entering a reach – cfs

$R$ electrical resistance – ohms

$R_d = \frac{c_1}{2\sqrt{c_2}}$ ratio of actual damping to that damping which will just make the system stable

$S$ instantaneous volume of air in a covered pipe stand – $ft^3$

$S_o$ average volume of air in a covered pipe stand – $ft^3$

$t$ prototype time – seconds

$T$ surge period – seconds

$T_n$ natural period of a system such as the one shown in Figure 6 – seconds

$T_1$ fundamental (gravest mode) period

$v$ departure from the average velocity, $V_o$, in a pipe reach – ft/sec

$V$ instantaneous cross-sectional velocity in a pipe line – ft/sec

$V_o$ average cross-sectional velocity in a pipe line – ft/sec

$y_1$ $y_2$ departure from the running levels on the downstream side of pipe stands – ft

$y_m$ maximum value of $y$ – ft

$\alpha$ amplification factor $= \sqrt{\left(1 + K_2 \frac{2\pi F_1}{T_1}\right)^2 + \left(K_1 \frac{2\pi F_1}{T_1}\right)^2}$

$\sum$ a summation

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Subject: Hydraulic and analytical studies of the causes and the control of surging in the Coachella Irrigation Distribution System--All-American Canal System--Boulder Canyon Project

## PURPOSE

To determine the causes of the surging in the open-stand-type pipe line irrigation distribution system at Coachella and to find means of preventing the surging or of controlling it within acceptable limits.

## CONCLUSIONS

1. The surging is caused by two separate but complementary factors. The first is the introduction into the system of self-induced and other flow oscillations of small magnitude. The second factor is the ability of a system such as the one at Coachella (Figure 1), and others like it, to amplify small oscillations into surges of unacceptable proportions.

2. The self-induced or auto-oscillations are caused primarily by the storage and subsequent release of air carried into the pipe lines by entrainment. The system cannot be economically modified to eliminate this storage and release of air.

3. Oscillations other than the self-induced ones may be produced by a variety of causes including the disturbances which arise when deliveries are changed, and even by the action of wind blowing across the open stands. Proper operating procedure, such as avoiding rapid changes in delivery rates, can do much to minimize these flow disturbances.

4. The ability of the Coachella System to amplify a surge is due to resonance occurring at or near the natural frequencies of the water columns in the pipe reaches.

5. The natural frequency of the surging in a typical open-system pipe reach--consisting of the downstream section of the preceding pipe stand, the upstream section of the subsequent stand and the pipe line connecting these stands--depends upon the length of the pipe and the water-surface area in the downstream section of the preceding pipe stand.

The surging can be controlled by modifying the lateral to obtain longer natural periods of oscillation in each succeeding reach. This can be done by increasing the water-surface areas in the stands or by lengthening the pipe reaches by omitting stands. However, the cost of progressively increasing the surface areas in a long lateral is prohibitive, and the necessity of serving many individual farms eliminates the alternative of lengthening reaches by omitting stands.

6. The degree of surge amplification in a given reach is influenced by the hydraulic friction. If the friction forces are small, the amplification will be large, and conversely, if the friction is large, the amplification will be small or nonexistent. In the troublesome laterals at Coachella the friction could not be increased to the point of controlling surging at low flows without making it impossible to transport high flows.

7. Airtight covers placed on the pipe stands produce good surge control. These covers must be fitted with flap valves to relieve pressures above atmospheric, and with a vacuum vent to limit subatmospheric pressures (Figure 25). The effect of a cover on a given pipe stand is to connect the two entering reaches into one longer reach with a longer natural oscillating period in the primary mode. The covers may be applied to any number of stands in succession to form a longer reach of closed conduit.

8. The airtight covers provide surge control by:

a. Modifying the periods of the pipe reaches to avoid resonance

b. Reducing the number of successive reaches in which amplification can occur

c. The fact that a reach of a given length and resonance period with covered stands will oscillate less freely than a reach of the same length and resonance period without covers.

9. A section of lateral using covers has a number of natural periods equal to the numbers of pipe reaches in that section. Only the primary (longest) period is of importance since the resonance becomes weak at the shorter periods.

10. Gates placed through the pipe stand baffles (Figure 10) reduce the surging, but the operational difficulties which they present prohibit using them in large numbers.

11. Vents to release air trapped in the pipe lines below the stands (Figure 12B), siphons through the pipe stand baffles (Figures 13 and 14), and centrally located vertical inlet riser pipes (Figure 16) are each capable of reducing the tendency for initiating oscillations in the stand, but they are not capable of controlling surges fed into the reach.

12. The hydraulic models and electric analogies used in this investigation provided a satisfactory means for studying the operation of the open-stand-type pipe distribution system.

## RECOMMENDATIONS

1. Use the airtight covers for controlling surges in the open-stand-type distribution system. The covers must be fitted with flap valves to relieve pressures above atmospheric, and vacuum vents to limit subatmospheric pressures (Figure 25).

2. Use gates through the baffles for surge control when it is practicable to regulate the gates so that no water passes over the baffles (Figure 10).

3. In future systems, design the stands so that minimum volumes of air will be entrained. This may be done by limiting the fall from the baffle crest to the pool to 1 foot or less and by providing 3 or more feet of pool depth over the outlet pipe.

4. Investigate analytically any future distribution systems in which surging might occur to determine the optimum placement of the airtight covers or baffle gates.

## ACKNOWLEDGMENT

This investigation of surging in open-stand, low-pressure distribution systems was made jointly by the Pipe Lines and Siphons Section of the Canals Branch, the Hydraulic Laboratory of the Engineering Laboratories Branch, and the Coachella field personnel under the direction of C. S. Hale. The mathematical approach to the surge problem was prepared by Mr. R. E. Glover, Research Engineer. The Concrete Conduit Company voluntarily modified, at no cost to the Government, one of the field laterals to evaluate the effect of using an inlet riser pipe in each pipe stand.

## INTRODUCTION

### General Features

The Coachella Valley lies in southern California and extends about 33 miles northwest of the Salton Sea (Figure 1). The ground slopes from a maximum elevation of 524 feet at the north downward to the elevation of the Salton Sea, 240 feet below sea level. The east side of the valley is somewhat narrower and steeper than the west side with ground slopes of 5 to 20 feet per mile. The climate is warm and the sun shines practically the year round producing summer temperatures which occasionally exceed 120° F. The temperature seldom falls below freezing, and crops are grown throughout the year. The one natural deterrent to an abundant agricultural economy is the lack of sufficient rainfall; the average fall is about 3 inches per year.

To supplement the inadequate rainfall, irrigation has been used, and for a number of years excellent crops have been grown in the irrigated portions of the valley. The water was originally supplied by artesian wells, but as more wells were used the water table declined to the extent that pumping became necessary. With 12,000 acres finally being irrigated by wells, the water table declined to where some of the pumps approached the economical pumping limit.

The construction of the Coachella branch of the All-American Canal has made possible the delivery of large quantities of Colorado River water to the Coachella Valley. On December 22, 1947, an agreement was reached and signed between the Coachella Valley County Water District, Improvement District No. 1, and the United States Government, wherein the Bureau of Reclamation would construct a distribution system of pipe in the valley to transport the water from the main canal to about 100,000 acres of land. Upon completion of the components, the system would be turned over to the Water District on a supplemental repayment contract basis. The general plan for the system, with the quantities of flow, the points of delivery, and the number designation of the laterals is shown in Figure 1. For construction purposes the distribution system was divided into the following units (Figure 1):

Unit 1--Lateral 97.1, Stations 0+00 to 377+85

Unit 2--Laterals 99.8 (exclusive of Lateral 99.8-0.51 beyond Station 131+00) through 106.9

Unit 3--Laterals 107.3 through 115.3

Unit 4--Laterals 115.6 through 119.6

Unit 5--Lateral 97.1 and Sublaterals
beyond Station 377+85

Unit 6--Laterals 119.64 through 123.4

Unit 7--Lateral 123.45

Unit 8--LaQuinta laterals

Unit 9--Laterals 88.6, 91.4, 93.0, 94.2, 97.0, 98.0, 99.4 and Sublateral 99.8-0.51 beyond Station 131+00.

Prior to preparing the cost estimate required for the supplemental repayment contract, studies were made to determine whether an open-canal system, a low-pressure pipe system, or a high-pressure pipe system would be most economical, both in initial cost and in operation and maintenance expense. The studies indicated that the low-pressure pipe system would be slightly more costly to build than the open-canal system but would permit higher delivery gradients with smaller seepage and evaporation losses and hence lower operating costs. In addition, the pipe system would entail less right-of-way encroachment through cultivated areas and hence less right-of-way expense. Further studies made by the Denver office of the Bureau and by private engineers retained by the Coachella Valley County Water District Board indicated that a low-pressure pipe system would be materially less expensive to construct than a high-pressure system. On the basis of these findings, the decision was made to construct the low-pressure pipe distribution system.

The laterals were located along section and mid-section lines, and quarter-mile sublaterals were provided to serve the adjoining lands. The general criteria required a turnout for a farm delivery to each 40 acres of land; or one or possible two turnouts at each quarter-mile of lateral. To maintain a low internal head on the concrete pipe lines, open-topped box or pipe stands were constructed at each turnout point with the top of the stand 2 feet higher than the maximum operating water surface. A baffle or partition in the stand served as a check at low flows to provide the head required for the turnout deliveries (Figure 2). The portion of the total flow which exceeded the turnout delivery in a given stand passed over this baffle, then fell into the downstream half of the stand, and entered the outgoing pipe line to flow on to the next stand. This design divided each lateral into a series of elongated U-tubes, with the upper leg formed by the downstream side of one stand and the lower leg formed by the upstream side of the subsequent stand. At low flows water poured over the baffles from one U-tube to the next U-tube (Figure 3). Turnouts from the laterals are controlled by gate valves or by valves of the disk type built integrally with a propeller-type meter (Figure 4).

## Operating Difficulties

The first reports of operating difficulties in the distribution system were made to this office on March 22, 1950, by Construction Engineer C. S. Hale. It was found that the longer laterals in the flat valley floor could not be operated satisfactorily because of severe surging which occurred regularly with a period of about 60 seconds. (The term "surging" as hereafter used, means a continual and rhythmical increase and decrease in the flow past a given point in a lateral.) Excessive surging, that is surging great enough to cause farm delivery difficulties, occurred at low flows in the long laterals located in relatively flat areas where the baffle in any stand is sufficiently high to back water up in the preceding stand and cause the pipe to run full at the upper end (Figure 3; B, C, and D). Only minor surging occurred in the first few pipe line reaches of the lateral, but the surge became progressively greater toward the downstream reaches. So long as the surging component of the average flow was less than the average flow, water continued to pass over the baffles and the small change in head on the turnouts had no appreciable effect on the turnout deliveries. However, when the surging component was equal to the average flow, the water in the pipe came to rest for an instant and the flow over the baffles in the stands would cease. This resulted in a large enough head variation on downstream turnouts to appreciably affect the farm deliveries. When the surging component was greater than the average flow the water reversed its direction of travel during part of the cycle and flowed back up the pipe line. Thus the water within the upstream part of the stand not only ceased to flow over the baffle, but receded from the baffle crest. During the opposite part of the cycle the water entered the stands so rapidly that in some cases the baffles were inundated before flow could be established in the outgoing pipe line. This produced extreme head variations on the turnouts, ranging from heads too small to produce flow to heads which produced flows larger than those for which the turnouts were designed. The farm deliveries then consisted of periods of zero flow, followed by large flows which submerged the flow meter and its totalizing mechanism, overtopped the meter stands, and spilled from the ditches (Figure 5). These deliveries were undesirable, wasteful, and in some cases resulted in insufficient flows to meet the farmers' needs.

## INVESTIGATIONS OF THE SURGING

An analytical investigation of the factors which influence surging was begun in this office in May 1950. Concurrently, field tests were attempted on various laterals to more accurately determine the magnitude of the surges in the pipe stands, the period of the surge cycles, and the relationships between the surge cycle in one structure and that in adjacent structures. Considerable difficulty was encountered

in conducting these field tests because the laterals had no provisions for wasting flow. As a result, it was seldom possible to obtain the flow conditions required and the tests had to be limited to periods when deliveries of approximately the desired quantities were being made. An additional problem was encountered in the distances between the structures which made communication and accurate timing difficult. The scope of the anticipated test program for developing and evaluating surge control measures demanded flexibility and control beyond these prototype limitations. To obtain this flexibility and control, a model was built in the Hydraulic Laboratory in Denver to represent a portion of a typical field lateral. A discussion of this laboratory equipment and the results obtained from it are presented later in this report. The final evaluations of the control measures developed on the model were made in the field on the prototype laterals.

## Factors Which Cause Surging

The surging appears to be caused by two factors. The first is the presence of air-driven auto-oscillations of small amplitude, and oscillations from other sources. The second is an amplifying tendency which builds these small oscillations into surges of unacceptable size.

### Auto-oscillation

The storage and release of entrapped air has been found to be a source of initiating oscillations in certain pipe reaches. The mechanics of this auto-oscillation may be described as follows: The water falling over a baffle in a pipe stand plunges into a water pool on the downstream side of the baffle and entrains a mass of air bubbles. These bubbles penetrate the pool to considerable depths and a portion of them are carried into the pipe with the flowing water. After entering the pipe they float to the top and collect in a long bubble which lies against the top of the pipe. Since the pipe has a gradient in the direction of flow and the bubble tends to float, there is a force tending to move the bubble upstream. As the bubble grows in volume the buoyancy finally overcomes the drag of the water, and the bubble moves upstream until it vents into the pipe stand. The volume of air released is then replaced by water having the velocity of the water in the pipe reach. In this way an increment of kinetic energy is fed into the system to initiate a succession of water level and velocity changes in the reach. These changes have an influence on the behavior of the long bubble and tend to fix the time when the blowback will occur. Observations indicate that the blowback tends to occur in that part of the cycle which will permit energy to be fed into the oscillation. The end result is that the filling and emptying of the long bubble falls into step with the oscillations and supplies the energy necessary to maintain them.

Small oscillations can be produced by other sources as well. The disturbances which arise when delivery changes are made too rapidly is an example. Even the force of the wind blowing past the open pipe stands can, in some cases, initiate oscillations. It is probable that additional sources exist.

The amplitude of these oscillations or surges is ordinarily not large and would be of only minor significance if another factor were not involved. The trouble experienced in the field occurs where a pipe line has been built down a section line for several miles with a pipe stand at every quarter of a mile. This equal spacing of the stands and gently sloping terrain provides a succession of pipe reaches whose natural periods are nearly the same. Under these conditions a small auto-oscillation originating in an upstream reach can be amplified into a surge of detrimental proportions in successive reaches.

Amplification Factors and Natural Frequencies

Formulas for the amplification factors and for the natural frequencies are given in the following paragraphs. The symbols used are defined in the list of symbols at the front of this report.

The performance of a system consisting of a single pipe reach connecting two pipe stands (Figure 6) can be described in terms of an equation of continuity and an equation of motion. The equation of continuity expresses the requirement that if water is fed into the upstream end of the system, it must either be discharged at the downstream end or stored by a rise of the levels at $y_1$ and $n_2$. The equation of motion expresses the requirement that the acceleration of flow must obey Newton's law with respect to the accelerating head applied between the upstream and downstream ends of the pipe. These two equations are

Continuity

$$+ Q - F_1 \frac{dy_1}{dt} - AV = 0 \qquad (1)$$

Motion

$$\frac{L}{g} \frac{dV}{dt} = h_a \qquad (2)$$

The accelerating head is equal to the differential between the prevailing level and the level which would exist if the velocity $V_o$ were present in the pipe. The friction loss actually varies with the square of the velocity V but its introduction in this form would lead to mathematical difficulties. It will be desirable, therefore, to use a linear approximation to represent the friction loss. To obtain this set

$$V = V_o + v \tag{3}$$

where $V_o$ represents the average velocity over a period of time and v represents a departure from the average. Then if the friction loss is

$$h = MV^2 \tag{4}$$

where M is a constant, the loss expressed in the new variable is

$$h = M(V_o + v)^2$$

or

$$h = M(V_o^2 + 2V_o v + v^2)$$

Now if the ratio $\frac{v}{V_o}$ is small compared to unity, the term $v^2$ will be small compared to the term $2V_o v$ and may be neglected; then approximately

$$h = MV_o^2 + 2MV_o v, \quad \text{where} \quad \left(\frac{v}{V_o} < 1\right)$$

If $h_o$ represents the head loss when $V = V_o$, this expression can be written as:

$$h = h_o + \frac{2h_o}{V_o} v, \text{ where } \left(\frac{v}{V_o} < 1\right) \tag{5}$$

With this approximation the continuity equation and the equation of motion become, respectively,

$$F_1 \frac{dy_1}{dt} + Av = q \sin \frac{2\pi}{T_1} t \tag{6}$$

and

$$\frac{L}{g} \frac{dv}{dt} = y_1 - \frac{2h_o}{V_o} v \tag{7}$$

By differentiation and substitution

$$\frac{d^2y_1}{dt^2} + \frac{2gh_o}{V_o L} \frac{dy_1}{dt} + \frac{Ag}{F_1 L} y_1 = + \frac{2gh_o}{V_o} \frac{q}{F_1 L} \sin \frac{2\pi}{T_1} t + \frac{2\pi}{T_1} \frac{q}{F_1} \cos \frac{2\pi}{T_1} t \tag{8}$$

The particular integral of this equation is of interest because it permits an evaluation of the amplification factor to be made and because it represents the conditions which will be present in the reach after the starting oscillations have died out.

In order to state the particular integral concisely, it is expedient to rewrite Equation 8 in the form shown below. The c quantities are constants which may be evaluated by comparison of the two forms of the equation.

$$\frac{d^2y_1}{dt^2} + c_1 \frac{dy_1}{dt} + c_2 y_1 = c_3 q \sin \frac{2\pi}{T_1} t + c_4 q \cos \frac{2\pi}{T_1} t \tag{9}$$

The particular integral is then:

$$y_1 = K_1 q \sin \frac{2\pi}{T_1} t + K_2 q \cos \frac{2\pi}{T_1} t \tag{10}$$

Where:

$$K_1 = \frac{c_3 \left(c_2 - \frac{4\pi}{T_1^2}\right)^2 + c_4 \frac{2\pi}{T_1} c_1}{\frac{4\pi^2}{T_1^2} c_1^2 + \left(c_2 - \frac{4\pi^2}{T_1^2}\right)^2} \tag{11}$$

and

$$K_2 = \frac{-c_3 \frac{2\pi}{T_1} c_1 + c_4 \left(c_2 - \frac{4\pi^2}{T_1^2}\right)}{\frac{4\pi^2}{T_1^2} c_1^2 + \left(c_2 - \frac{4\pi^2}{T_1^2}\right)^2} \tag{12}$$

the maximum amplitude of oscillation of $y_1$ is

$$y_m = q \sqrt{K_1^2 + K_2^2} \tag{13}$$

The velocity variation from the average is obtainable from the continuity condition as

$$v = \frac{q}{A} \sin \frac{2\pi}{T_1} t - \frac{F_1}{A} \frac{dy_1}{dt} \tag{14}$$

from which, by substitution

$$v = \left(\frac{1}{A} + K_2 \frac{2\pi}{T_1} \frac{F_1}{A}\right) q \sin \frac{2\pi}{T_1} t - \left(K_1 \frac{2\pi}{T_1} \frac{F_1}{A}\right) q \cos \frac{2\pi}{T_1} t \tag{15}$$

This may be expressed, for purposes of simplicity, by

$$v = M_1 q \sin \frac{2\pi}{T_1} t - M_2 q \cos \frac{2\pi}{T_1} t \tag{16}$$

Where $M_1$ and $M_2$ are constants to be evaluated by comparison, then the amplification factor is $\alpha = \frac{Av}{q}$ or

$$\alpha = \sqrt{\left(1 + K_2 \frac{2\pi F_1}{T_1}\right)^2 + \left(K_1 \frac{2\pi F_1}{T_1}\right)^2} \tag{17}$$

The undamped natural period of the system can be obtained by setting the right-hand member and the constant $c_1$ equal to zero in Equation 9 and solving the differential equation which remains. This is:

$$\frac{d^2 y_1}{dt^2} + c_2 y_1 = 0 \tag{18}$$

These changes impose the conditions that there be no friction present and that no unsteady flow enters the reach. The required solution is:

$$y_1 = B_n \sin \sqrt{c_2}(t + \beta) \tag{19}$$

Where $B_n$ and $\beta$ are constants. If the undamped natural period is $T_n$, then a complete cycle will be performed in the time $T_n$ and

$$\sqrt{c_2}\, T_n = 2\pi$$

or

$$T_n = 2\pi\sqrt{\frac{F_1 L}{Ag}} \tag{20}$$

If the imposed period $T_1$ is made to approach the natural period $T_n$ and the friction as expressed by the constant $c_1$ is allowed to approach zero, the $K_1$ and $K_2$ constants will become very large and as a consequence the amplification factor $\alpha$ will also become very large. Since $h_o$ is proportional to $V_o^2$, the constant $c_1$ becomes smaller as flows are reduced. This explains why surges of large amplitudes can be built up at low flows when the incoming flow has a sinusoidal component which has a period close to the natural period of the reach. The significance of a factor greater than unity is that the amplitude of the sinusoidal component of flow leaving the lower end of the reach is greater than the amplitude of the sinusoidal variation entering it. In any case, the period of the forced oscillation is $T_1$. The amplification factor may be considered as a function of the ratio $\frac{T_n}{T_1}$ and the ratio $\frac{c}{2}\sqrt{c_2}$. The latter ratio expresses the relation between the actual damping and the critical damping. The significance of the term "critical" damping is that if the friction is equal to or greater than this amount the system will not oscillate if displaced from its position of rest and released. In terms of the present notation, the damping is critical if

$$c_1 = 2\sqrt{c_2}$$

If the damping is less than critical, the system will return to its position of rest by executing a series of damped oscillations about the position of rest. Values of $\alpha$ greater than unity can never be obtained if $\frac{c}{2}\sqrt{c_2} > 1$. The relations of the amplification factors $\alpha$ to the period ratio $\frac{T_n}{T_1}$ for several values of $\frac{c}{2}\sqrt{c_2}$ are shown in Figure 7.

It may be concluded that if a flow, oscillating about an average value with a period $T_1$, is fed into a reach whose natural undamped period is near to $T_1$ and if the friction is sufficiently small, amplification may be expected to occur in the sense that the amplitude of the flow oscillation leaving the lower end of a reach will be greater than the amplitude of the oscillation fed into it at its upstream end. Amplification factors up to six per reach have been found under field conditions.

## The Laboratory Model

The laboratory test set-up was constructed to represent a typical section of the open-stand-type distribution lateral used at Coachella and at a number of other projects. For convenience this set-up is referred to as a "model" in this report, although in a strict sense it was not a scale model of any particular structure. It consisted of a water supply system, a head box, three vertical 20-inch-diameter pipe stands, each divided into two equal vertical sections by a baffle, three 8-inch-diameter by 125-foot-long pipe lines connecting the stand in series, and an 8-inch line to return the water to the main supply channel (Figure 8). Space limitations in the laboratory and reasons of convenience in operation and viewing required that the model be compact. It was arranged with the head box and the stands side by side and with the pipe lines extended about 60 feet downstream, then turned 180° and extended back to enter the subsequent stand. The first 16 feet of the initial pipe line was laid on a slope of 1 inch in 16 feet to represent a typical prototype slope. The first 6 feet of this section was made of transparent plastic to permit observing the flow inside the line. The rest of this line and the two other lines were sloped to accomplish a total drop of 3 feet each.

Water was supplied to the model by an 8-inch portable pump and an 8-inch supply line which contained a standard, calibrated, laboratory orifice venturi meter for measuring the rate of flow. The water entered the upstream portion of the head box through an 8-inch-diameter pipe and then passed through a rock baffle, which removed the major flow turbulences (Figure 9). Immediately downstream from this baffle a motor-operated, vertically reciprocating float was provided to be used, when desired, to produce uniform, tidelike, depth variations in the head box. The surges or oscillations so created are subsequently called forced oscillations and are not to be confused with self-induced or auto-oscillations. After passing the rock baffle and the float mechanism, the water moved toward the downstream end of the box which was provided with a rectangular baffle 20 inches wide. The water passed over this baffle in the same manner as over the baffles in pipe stands, and entered the equivalent of the downstream half of a stand. From the half-stand the water entered the pipe line to flow to Stand 1. There it filled the upstream half of the stand, passed over the baffle, filled the downstream half of the stand sufficiently to produce flow in the pipe and then flowed to Stand 2. The process was repeated through Stands 2 and 3 and then the water was returned to the main supply channel for recirculation.

The baffles which divided the stands into vertical sections were made of 1/8-inch sheet steel and were bolted into place in the stands. Higher baffle elevations were obtained by placing one or more

baffle extensions upon these base baffles (Figure 10, A, B, and D).. Eight-inch-diameter sheet-metal slide gates were placed in the base of the baffles at the elevation of the outlet pipe to permit studying the effect of gates for controlling the surging (Figure 10, B and C). Windows were provided near the bottom in the downstream section of the stands so that the water inside the stand and at the entrance of the outlet pipe could be observed.

The amplitude of the surges in the stands was measured by suitable point gages mounted on portable bases which were placed on the top of the stands. To obtain a representative average surge measurement, it was necessary to take repeated readings at the high and low points of the individual surges. The amplitude as well as the period of successive surges varied greatly and thus all results, unless otherwise qualified, are given as average figures.

## Laboratory Tests

### Straight Baffles

In the initial tests the tops of the straight baffles were arbitrarily placed at about 41 inches above the floors of their respective stands and the slide gates were closed (Figure 11A). Surging similar to that encountered in the field was noted in the model as soon as water was passed through it. This surge occurred even though the water was entering the head box at a constant rate and no oscillations were being forced into the system by the reciprocating float. Thus, the surging was entirely self-induced in the same manner as the surges in the field. The surging was greatest at a flow of 0.37 cfs and diminished when the rate of flow was either increased or decreased. Large quantities of air were carried into the pool in the downstream section of the stands by the falling nappes and much of this air was carried into the pipe line with a swirling motion (Figure 12). The air bubbles rose to the top of the pipe where they joined in a large bubble which periodically attained sufficient buoyancy to move upstream in the sloping pipe to the pipe stand. There it vented itself to a point where its buoyancy was greatly decreased, whereupon it was carried downstream. The continual replenishment of the air supply, in the form of the small bubbles, again increased the size and buoyancy of the bubble to the point where it again moved upstream and vented itself. This cycle was continually repeated, and it was in phase with the surging, as explained in the Auto-oscillation section of this report.

The depth of the water pool in the downstream section of each stand was controlled by the hydraulic losses through the pipe line leading to the next stand, the velocity in the pipe line, the height of the baffle in the successive stand, and the difference in elevation between

the stands. Each stand was 36 inches lower than the one upstream, and thus the pools created by the 41-inch-high baffles were fairly shallow. These pool depths were increased by adding extensions to the baffles, and these depths were found to have a pronounced effect upon the surging. The maximum surge occurred when the baffles were at elevations 13 feet 4-3/4 inches, 10 feet 9-1/2 inches, and 8 feet 7 inches, in Stands 1, 2, and 3, respectively (Figure 11B). (Elevations are measured from a reference point on the laboratory floor.) The amplitude, or difference in elevation between the high and the low points of the surges in Stand 3, was as great as 1.40 feet and averaged 0.84 foot. The flow over the baffle was intermittent. The average time interval between the high point of one surge and the high point of the next surge was 28 seconds.

When the baffles in Stands 1 and 2 were raised to elevations 14 feet 11-1/4 inches and 11 feet 3-1/2 inches, respectively (Figure 11C), the self-induced surging became too small to measure. The baffle in Stand 1, when at elevation 14 feet 11-1/4 inches, was only 6-1/2 inches lower than the fixed head box baffle at elevation 15 feet 5-3/4 inches. The head required to cause flow through the line and over the baffle in Stand 1 existed as water depth in the half-stand and thus the water surface in the half-stand was at about the same elevation as the head box baffle. Water flowed over this baffle and entered the pool quietly without entraining appreciable quantities of air. Without a supply of air being carried into the outlet pipe, the air bubble in the pipe could not exist, and without the periodic venting of this bubble there was no force creating oscillations. This suggested a solution to the surge problem, particularly in future designs, wherein deep-water pools might be provided with a minimum fall from the baffle crests to the pool surfaces to prevent air being carried into the pipe line. This possibility was investigated in a larger test apparatus, and it is discussed in a subsequent section of this report.

Amplification tendencies were still present in the system with the high baffles, because severe surging occurred in Stand 3 when the motor-driven float was operated.

Pipe Line Vents

The periodic build-up of the long air bubble within the outlet pipe and its venting into the stand suggested that if the pipe line were vented by other means the air would lose its effectiveness in creating the surge. A 1-inch-diameter vertical pipe was placed in the plastic portion of the first pipe line and a ball of modeling clay was used to close it off when it was not being used (Figure 12B). The vent could be opened by simply removing the ball of clay. When the vent was opened, air escaped forcefully and slugs of water were thrown several feet into the air. In the laboratory it became necessary to confine the escaping water and to direct it into a waste pipe. The surge into Stand 1 and

hence into Stands 2 and 3 was considerably reduced by opening this vent, thereby indicating that the vent reduced the surge formation in the reach. There was, however, amplification of the small surge present in Stand 1 which resulted in an average surge amplitude of about 0.09 foot in Stand 3.

The partial success of the vent in the plastic pipe indicated that additional vents in the pipe lines between Stands 1 and 2 and between Stands 2 and 3 would stop most of the residual surging. Vents were put into these outlet pipes by inserting, through the stand, "L-" shaped tubes made of two sections of 1-inch pipe and a 90° ell fitting. The horizontal section of the vent pipe extended downstream along the top of the pipe into the air bubble. The fact that these vents operated was established by the continual discharge of air and the occasional violent expulsion of water from them. These vents had only a slight effect upon the surging, however, and reduced the average amplitude in Stand 3 from 0.09 with one vent in the plastic pipe section to 0.08 foot. When the vent in the plastic pipe line was closed but the other two vents were left open, the average surge in Stand 3 was about the same as without vents, or 0.80 foot. The effect of the vents was, therefore, to reduce the part the air plays in creating the surges, but the air vents had no effect in suppressing the amplification of the residual surge in the system. If a surge is present due to any cause, the pipe line vents will not prevent the amplification of this surge down through the system. It was concluded that the difficulty of effectively placing these vents in the prototype system, the impracticability of providing means for collecting and disposing of the water ejected by the vents, the cost, and the fact that the vents are ineffective in suppressing surges make the pipe line vents impractical for prototype surge control.

## Gates Through the Baffles

It is well known that the rate of discharge over a weir varies greatly with a relatively small change in head. In the pipe stands small head variations such as those imposed by the storage and release of air in the upstream stands will cause large flow fluctuations over the baffles and hence into the downstream stands. The rate of flow through an orifive, however, is relatively unaffected by the same change in head, provided the orifice is operating under an appreciable head. An attempt was made to stop the surging by utilizing the more stable flow of orifices. This was done by placing orifices, in the form of slide gates, through the baffles (Figure 10). In the model 8-inch-diameter holes were cut at the elevation of the outlet pipes and sheet-metal gates were placed on the upstream baffle faces so that the orifices (gates) could be opened or closed. When the gates were opened so that all the water flowed through them and none overtopped the baffles, no surging occurred in the system. However, if part of the water overtopped the baffles, surging

immediately started. In the prototype structure it is necessary to maintain the water level in the upstream half of the stand at or near the baffle crest to obtain the head required to make farm deliveries. This close control is difficult to obtain when many gates are used because a change in opening of any one gate greatly influences the water surfaces both up and downstream from that gate. Thus, to satisfactorily operate a prototype lateral, a trained crew would be required to move repeatedly up and down the lateral and adjust the gates to establish the right conditions. Any operating change (for instance an additional farm delivery) would require a new and painstaking readjustment of all gates in the lateral. This type of operation seemed impractical and the gates therefore should not be used extensively for surge control. However, they might be used in limited numbers to gain partial control.

Model tests were also made with the baffles removed from the stands and with slide gates installed at the entrances to the outlet pipes. These gates were adjusted so that the water backed up high enough into the pipe stands to produce the required head for turnout deliveries. In the model the gates were extremely sensitive to adjustment and great care had to be taken to avoid the one extreme of too little or no head, and the other extreme of overtopping the stands. In the prototype structure, when similar or even greater difficulty might be experienced with the gate adjustments, it would be necessary to install overflow pipes from the top of the stands to the pipe lines downstream. This would again permit the entrainment of air and surging would occur much the same as with the standard baffled stands.

Siphons in the Baffle

A method of insuring farm deliveries by maintaining the water surface high in the stands and still not overtopping the baffles was to use siphons through the baffles with the inlets near the baffle tops. Two of the 6-inch baffle extensions were modified by cutting two 2-1/2-inch-high by 4-inch-wide holes in each and attaching hoods on the upstream faces and siphon downlegs on the downstream faces (Figure 13A). The exit openings of the siphon downlegs were placed at different elevations to create opposing swirls in the downstream section of the stands and thereby permit the escape of entrained air (Figure 13B). These siphon baffles were installed in Stands 1 and 2 and a flow of 0.37 cfs was passed through the siphons in Stand 1 without difficulty (Figure 14A). Considerable air was drawn into the siphon through vortices which formed in the water at the siphon entrances. This air was carried through the siphons and created turbulence in the downstream part of the stand with the result that much of the air entered the outlet pipe. Slight surge occurred in Stand 2 and air was again drawn through the siphons with the water and into the outlet pipe. Some of this air vented back via the 8-inch pipe into the stand while the remainder was carried on to Stand 3.

Surge occurred in this unmodified stand with an average amplitude of about 0.14 foot with continuous flow over the baffle. When oscillations were forced into the system amplification occurred in each reach.

The negative pressures in the siphon, in addition to aiding the formation of vortices, created a pronounced draw-down in the water surface at the siphon inlet. This draw-down was so great that, even with the water near the baffle top, air was drawn into the siphon. To relieve this draw-down and hence reduce the admission of air, the hoods were removed from the upstream face of the baffles (Figures 13B and 14B). The revised siphons were then capable of just passing 0.37 cfs when the water surface was level with the baffle crest. Large quantities of air still entered the siphons through vortices and were carried into the downstream section of the stands. The surge in Stand 3 increased from 0.14 to 0.22 foot. The baffle in Stand 2 with the siphons and the baffle in Stand 3 without the siphons were periodically overtopped by surges. It was concluded that the siphons were not capable of controlling field surging, and the model tests on them were terminated.

Reduced Flow Area in the Upstream Side of the Stand

It has been shown that the friction which opposes the flow exerts a damping force upon the surging. To obtain a moderate increase in friction in the model, in a way suitable for possible field use, the flow areas on the upstream side of the stands were decreased to the area of the inlet pipe by installing partitions normal to the baffles and extending them to the stand walls (Figure 15). The overflow width of the baffle was reduced to about one-third the former width. At a flow of 0.37 cfs and with the baffles at the heights to produce the maximum surging, the surge amplitude in Stand 3 averaged 0.43 foot, or about half the surge with the original upstream stand flow area and baffle width. This decrease in surge amplitude, while appreciable, was not enough to give acceptable flow in the long field laterals. It was impossible to further increase the friction without incurring marked reductions in the capacity of the system.

Stands with a Central Inlet Riser Pipe

The Concrete Conduit Company, which has been manufacturing and selling irrigation system components for many years, became interested in the Coachella surge problem and offered to modify, at no cost to the Government, a part of one of the troublesome laterals to the design which they believed would stop the surging. The modifications to each stand consisted of removing the straight baffle and extending the inlet pipe into the stand, turning it vertically upward in the stand center, and terminating it at the original baffle elevation (Figure 16). The flow spilled over the pipe end and fell into a pool which occupied nearly the full cross-sectional area of the pipe stand. The offer was accepted by

the Government and the Concrete Conduit Company proceeded to modify the lateral. During the time interval required for the field changes the laboratory model was modified to the same design. The baffles were removed from the three pipe stands and the 8-inch inlet pipes were extended into the stands and then turned upward by a 90° elbow so that they rose vertically in the center of the stand. The height of these riser pipes was made the same as the original baffles and further height increases were made by adding pipe extensions. The water entered the stands through these riser pipes and spilled from their tops into the bottom of the stand from which it entered the outlet pipes (Figure 17A). The water cushion, or pool, in the stand occupied all the cross-sectional area of the stand except that part taken up by the inlet riser pipe and elbow instead of only the downstream half of the stand, as was the case with the straight baffle. The larger pool, together with the thinner and longer nappe from the riser pipe, resulted in much less air entrainment in the pool and a much better chance for the air to separate from the water. It was not feasible to modify the half-stand at the head box, and therefore the first pipe reach operated throughout these tests as though it had a pipe stand with a straight baffle at its upper end.

The model was first operated with the top edge of the riser pipes set at the elevations which had produced the maximum surging when the straight baffles were used (Figure 11B). Observation through the windows near the bottom of the stands showed the riser pipe arrangement to be effective as a means of reducing air entrainment (Figure 18A). The water discharged from the periphery of the riser pipe and as the water fell, the nappe became both thinner and more evenly distributed than with the straight baffles. The air was not carried deeply into the pool of water and thus was able to escape to the surface before the water entered the outlet pipe. The flow concentrations produced where the entering pipe deflected the falling water resulted in the deepest air penetration in the pool. Surging occurred in the system with an average amplitude at Stand 3 of 0.24 foot. This was less than the value of 0.84 with the straight baffles, but more than the best value of 0.08 foot with air vents in the pipe downstream of each stand.

Extensions were added to the riser pipes to raise them to the elevations which produced no measurable surge when the straight baffles were used. No measurable surge was observed at all flows with the riser extensions. When the plunger motor was operated to force surges into the system, amplification was observed.

The outlet ends of the riser pipes were returned to the elevations which produced the maximum surging and were provided with a 90° vee-notch on the side opposite the discharge pipe (Figure 17B). The notch was deep enough to make the two upper corners occur at the opposite ends of a diameter. Surging occurred with this arrangement with the same amplitude as with the level riser pipe ends. Air entrainment was

somewhat more pronounced than with the level pipe end due to the flow concentration caused by the notch. This concentration of water carried some of the air deep into the pool (Figure 18B). When the notched pipes were raised to the maximum elevations no measurable surge occurred. Surge amplification occurred when the plunger was used to force oscillations.

In general, the inlet riser pipes, both level and with the V-notch, are effective in reducing air entrainment. This is due to the larger water cushion area and to the thinner, more equally distributed nappe entering the cushion. The improved performance obtained with this design appears to be due to the elimination of the air-driven auto-oscillations of the flow. However, the fact that surge still occurred and that there was amplification of surges which enter the system under favorable conditions made the inlet riser pipes unsuitable for surge control.

The action of the prototype system, as modified by the Concrete Conduit Company, is described in the following extract taken from the field report dated October 31, 1951, from C. S. Hale to the Chief Designing Engineer, Denver, Colorado:

> "In initially testing the stands about 1.5 cfs was turned into the lateral and the gates upstream of the overflow stands adjusted until very little or no surge could be detected at the control structure at Station 105+78 which meant that the incoming side of the overflow stand at Station 119+03 was free of surge. With this flow the stands operated satisfactorily; i.e., there was very little surge to be detected at Station 158+97, the first stand downstream of the three overflow stands, but this condition also existed when these three stands were operating as pipe stands. However, when the flow was increased to 3 c.f.s., surge was detected which was magnified progressively by the 3 stands.
>
> "About 8.1 c.f.s. was then placed in the lateral. After adjustments of the gates upstream of the overflow structures so that no detectable surge existed at Station 105+78 the following readings on the surge at the inlet side of the overflow structure were measured:

| Station | Surge | Period |
|---|---|---|
| 119+03 | 1/2" - 1-1/4" | 25 Sec. |
| 135+53 | 1" - 2" | 20 Sec. |
| 145+47 | 1' - 2' | 1 Min. 3 Sec. |

"The crest of the overflow at Station 145+47 submerged at regular intervals. The variation in surge was not regular with a complete cycle of surges taking about 11 minutes and 35 seconds. There was also some variation in the period at all these structures. The baffle in the control structure immediately downstream at Station 158+97 also submerged periodically. Whether the latter submergence backed up the lateral to Station 145+47 or whether the surge at 145+47 was repeated at Station 158+97 was not possible to definitely determine. However, the surge at Station 158+97 could not be controlled by operating the gate which would at least indicate that the surge was developing progressively downstream as was also indicated by the surge readings on the first two overflow stands.

"From the observations, it was apparent that surging developed in the overflow stands although possibly at a lower rate than in pipe stands."

Effect of Pool Depth and Height of Fall on Air Entrainment

The surge reduction obtained when the riser pipes were used and when the straight baffles were raised was largely attributed to the reduced quantities of air which entered the stand outlet pipes. When the baffle crests were raised the depths of the water cushions were increased, thereby permitting most of the air entrained by the nappes to escape to the pool surface instead of being carried into the outlet pipe. This suggested that by providing adequate pool depths in the field structures, the primary force creating the surges--that is, the storage and release of air in the pipe line--could be reduced or eliminated. To investigate this a test section of near prototype dimensions was constructed in the 4-foot-wide glass-walled laboratory test flume (Figure 19). Flows from 1 to 9 cfs were used and the depth of the pool downstream from the baffle was controlled by a slide gate at the end of the 16-inch-diameter outlet pipe. In all tests the height of the baffle crest was maintained at 8.25 feet from the flume floor (elevation 8.25). The rate of flow, the elevation of the water upstream from the baffle (headwater), the baffle crest elevation, and the effective elevation of the pool within the stand (tail water) were recorded on a placard which appears in the photographs showing the flow (Figures 20 and 21). A grid with 0.5-foot intervals and with appropriate numbers at each foot mark was placed over the glass wall of the stand. The effective elevation of the tail water was taken as the elevation of the water column surface in the manometer tube connected to piezometer 2, Figure 19. The visible tail-water surface is higher than the effective elevation due to the air entrained in the water and the consequently reduced density.

The rate of flow had a pronounced effect on the quantity of air carried into the pool and only small amounts were entrained by 1 cfs whereas large amounts were entrained by 6 and 9 cfs (Figure 20, A and B). The distance the water fell from the baffle crest to the pool surface also affected the rate of air entrainment with almost no air being carried into the pool at a fall of 0.15 foot, whereas much air was entrained at falls of 3 and 5 feet (Figure 21, A and B). The depth to which the air was carried depended mainly upon the downward velocity of the stream transporting the air. This depth was found to be surprisingly great with a fall of only 1.25 feet at a discharge of 1 cfs being sufficient to carry air downward through more than 5 feet of water to the outlet pipe.

A visual examination of the flow in the stand showed that the water passing over the baffle crest at flows of 2 cfs or more had sufficient horizontal velocity to cross to the downstream wall where it was turned to flow vertically downward through the pool in an unbroken, high-velocity stream. This type of flow was ideal for transporting the entrained air, and as a result the air was carried deep into the pool. If a practical method could be found to direct this stream so the air could separate from the water, or if the stream could be broken up so the air was not carried deeply into the pool, the amount of air which entered the outlet pipe would be materially reduced. Tests were made in which the effect of various deflectors, gratings, and combinations of deflectors and gratings were investigated (Figure 22), but none of the designs was successful in appreciably reducing the volumes of air carried into the well and the outlet pipe (Figure 23, A, B, C, and D). It was therefore concluded that within practical design limits, where there were falls of more than 1.25 feet from the baffle to the pool, the existing stands cannot be modified to prevent air being carried into the outlet pipes. In future designs wherever falls of less than 1 foot can be maintained in conjunction with pool depths of several feet or more, there should be no air entrainment problems.

## Head Loss from the Pipe Stand to the Pipe Line

Piezometers were installed at several places in the 16-inch-diameter outlet pipe to determine the head loss from the stand to the pipe line (Figure 19). Tests were made for the condition where no baffles were used in the stand and for the condition with a ski-jump deflector on the downstream well wall above the outlet pipe (Figure 22J). The piezometer readings taken in these tests are tabulated in Figures 24A and B, respectively. The head loss, in feet of water, between the pool and a point 19.5 diameters downstream in the 16-inch-diameter outlet pipe was about 1.5 times the pipe line velocity head (Figure 24C). No difference was noted in the loss for the conditions with or without a baffle and the loss was independent of the depth of the water pool.

## Airtight Covers

When an airtight cover (Figure 25B) was placed over Stand 1, the surging in the system quickly decreased to a much smaller amplitude. This indication of positive control immediately led to investigations of the practicability of the covers for field use. A periodic positive pressure, tending to lift the cover from the stand, occurred whenever flow was started through the system or when a cover was first placed on a stand. A flap valve was installed on the cover to vent the positive pressures, and to seal and hold any subatmospheric pressures which occurred in the stand. The effectiveness of the cover was not changed by this valve.

The hydraulic grade line of the prototype lateral requires that the water-surface elevations in the stands be nearly as high as the baffle crests to insure adequate discharges in the farm deliveries. The subatmospheric pressure which develops inside the covered stands reduces the head and therefore the magnitude of this pressure had to be held within definite limits to avoid an objectionable reduction in head on the turnout. A relief vent consisting of a 1/2-inch-diameter pipe was extended from the atmosphere through the cover and into the water on the upstream side of the baffle (Figure 25B). The depth to which the pipe was submerged in the water was varied so that various negative pressures would be required to draw the water out of the tube and thus admit air to relieve any tendency for the subatmospheric pressure to increase. As the negative pressure returned to the point where it equalled the submergence of the pipe, air would no longer pass through the pipe to enter the stand. Further decreases in the negative pressure would allow the pipe to partially fill. The amount of subatmospheric pressure in the stand had a direct effect upon the surging, with too little negative pressure being unable to adequately suppress the surges. The negative pressure required for good control was small, however, and in the laboratory the cover was effective with 0.30-foot submergence of the relief vent pipe.

With Stand 1 covered the average surge in Stand 3 was reduced from the original value of 0.84 to 0.06 foot. When covers were used on both Stands 1 and 2 the surge was reduced to 0.01 foot. Forced oscillations were imposed on the system by the mechanical surge apparatus with an amplitude of the head box of 0.04 foot and a period of 26 seconds. With no covers on the stands the surge in Stand 3 was 1.83 feet. With Stand 1 covered the surge was reduced to 0.17 foot while with Stands 1 and 2 covered the surge was 0.06 foot. It was apparent that the covers reduced both the propagation and the amplification of surging.

Field tests were made on the covers by using them on several stands in one of the prototype laterals. In the preliminary tests they were found to reduce the surging only slightly. This was due to leaking seals between the covers and stands. When airtight seals were obtained by allowing the heavy concrete covers, with the help of the sun's heat, to press into an asphaltic cement on the rims of the stands, the covers were effective. More covers were found necessary for adequate surge control in the field than had been anticipated by the laboratory tests. This does not involve undue expense, however, because the cost of building and installing the covers is small and the stands were to be eventually covered to prevent the entry of foreign objects into the system.

The initial design of the relief vent pipe presented an operational difficulty in that when a very large surge occurred, due for instance to the too rapid closure of a turnout, the baffle would be inundated and the stand filled nearly to the bottom of the cover. After the surge subsided the water was held up under the cover by the negative pressure. The relief vent pipe was deeply submerged and hence was unable to supply air to let the water drop to a normal level. The result was that the effective head in the stand was reduced to the point that turnout deliveries were drastically reduced. To overcome this difficulty an external relief vent pipe situated on top of the lid was suggested by the field personnel (Figure 25A). This design consisted of a short pipe section divided into two compartments, one above the other, with the upper compartment being an emergency reservoir and the lower compartment being airtight and partly filled with liquid. A small pipe, open to the atmosphere, passes through the upper compartment and into the liquid in the lower compartment. A second small pipe extends from above the liquid level downward through the stand cover. The operation of this relief vent pipe design is basically similar to the initial design in that when the desired maximum subatmospheric is reached in the stand, air flows through the first pipe, bubbles out into the liquid pool, and then flows into the stand through the second pipe. The magnitude of the negative pressure required to draw air is controlled by the depth of submergence of the first pipe in the fluid. With the relief vent pipe operating with its own fluid (probably light oil to minimize evaporation) the water depth within the stands cannot influence the subatmospheric pressure regulation. A model was constructed of this relief vent design using only the bottom compartment, and it was found to operate satisfactorily in all respects.

## Analytical Investigation of the Stand Covers

The model and the prototype studies demonstrated that the airtight covers were effective in controlling the surging, but did not revealed the reasons for this effectiveness. Studies were made to obtain this knowledge so that it could be applied in the design of future structures.

The installation of an airtight cover on a stand alters the dynamic characteristics of the two adjacent pipe reaches because the air volume trapped under the cover is subject to pressure changes which modify the action of both reaches (Figure 26). It was desired to investigate the characteristics of such a system to determine what its possibilities for surge suppression are and how to use them to advantage. Because of the complexity of this analysis, friction will be neglected in the interest of simplification. The definition of the symbols is given in the list of symbols at the front of this report.

The isothermal relation for the air under the cover is:

$$SH = S_oH_o \tag{21}$$

for small changes.

$$\frac{dH}{dS} = -\frac{S_oH_o}{S^2} \tag{22}$$

If these changes in S are small compared to $S_o$, then it will be approximately true that:

$$\frac{dH}{dS} = -\frac{H_o}{S_o} \tag{23}$$

If the small variations of level $n_2$ and $n_3$ are neglected, the continuity equations are:

$$Q_o + q \sin \frac{2\pi}{T_o}t - F_1 \frac{dy_1}{dt} - A_1V_1 = 0 \tag{24}$$

$$A_1V_1 - F_2 \frac{dy_2}{dt} - A_2V_2 = 0 \tag{25}$$

The dynamic equations are:

$$\frac{L_1}{g} \frac{dV_1}{dt} = y_1 - \frac{H_oF_2}{S_o} y_2 \tag{26}$$

$$\frac{L_2}{g} \frac{dV_2}{dt} = \left[1 + \frac{H_oF_2}{S_o}\right] y_2 \tag{27}$$

The required solution of these equations is

$$V_1 = \left[A_2 - \frac{a^2 F_2 L_2 S_o}{g(S_o + F_2 H_o)}\right] \frac{Kq \sin at}{A_1(a^4 - Ba^2 + A_2 K)} + \frac{Q_o}{A_1} \tag{28}$$

$$V_2 = \frac{Kq \sin at}{a^4 - Ba^2 + A^2 K} + \frac{Q_o}{A_2} \tag{29}$$

$$y_1 = \left[\frac{A_2 L_1}{A_1 g} - \frac{a^2 F_2 L_1 L_2 S_o}{A_1 g^2 (S_o + F_2 H_o)} + \frac{F_2 H_o L_2}{g(S_o + F_2 H_o)}\right] \frac{aKq \cos at}{a^4 - Ba^2 + A_2 K} \tag{30}$$

$$y_2 = \frac{aL_2 S_o}{g(S_o + F_2 H_o)} \frac{kq \cos at}{(a^4 - Ba^2 + A_2 K)} \tag{31}$$

$$a = \frac{2\pi}{T_o} \quad K = \frac{A_1 g^2 (S_o + F_2 H_o)}{F_1 F_2 L_1 L_2 S_o} \quad B = \frac{K}{g}\left[\frac{A_2 F_1 L_1}{A_1} + F_2 L_2 \left(\frac{S_o + F_1 H_o}{S_o + F_2 H_o}\right)\right] \tag{32}$$

A scrutiny of these equations will show that the response of the system also occurs at the imposed period $T_o$ as in the case without an airtight cover. There are now two resonance frequencies, however, whereas there was only one before. These frequencies occur at values of "a" which are roots of the equation.

$$a^4 - Ba^2 + A_2 K = 0. \tag{33}$$

Actually, there are four roots of this equation, but they lead only to two frequencies. Thus, the system consisting of two pipe reaches with the intermediate pipe stand covered has two natural frequencies and will resonate with impressed frequencies which are near to either of these natural mode frequencies. The use of covers on alternate pipe stands of a lateral will change the dynamic properties of the lateral, but may not be effective in the suppression of surging. In the one case tried in the field, there were four pipe reaches and two covered stands arranged to form two systems of the type investigated. It was found possible to propagate surges through these reaches.

There should be some advantage from covering alternate stands, however, even though the air-driven auto-oscillation may be present and fall into step with one of the natural frequencies of the first system so that the phenomenon of amplification can be observed in the second and subsequent systems. This is due to the fact that there will be only half as many amplifications as would be the case if no covers were used. Covered stand systems may also be helpful if skillfully used for the purpose of altering the frequencies of certain parts of a lateral whose individual reaches would have nearly the same frequencies and correspondingly high amplification factors if no covers were used. This will not provide a complete solution since the surge will be propagated through the covered stand system in some amount so that amplification in succeeding reaches would be possible. There should be a definite gain, however, because the number of amplifications has been reduced by one and the amplification factor for the covered stand system would be less than for the individual reaches due to its being out of synchronism with the imposed frequency.

A system with three pipe reaches with the two intermediate pipe stands covered would provide a system with three corresponding natural mode frequencies. However, the primary period for the two-cover system should be longer than the primary period for the one-cover system which is longer than the single mode period of an individual reach, providing that the reaches were such as to have approximately the same natural frequency before any covers were applied. To illustrate how these relations might be used, consider a system having six pipe reaches. With a certain part flow, an amplification factor of four in each reach would be quite possible. With such a factor the build-up of a surge originating in an air-driven auto-oscillation in the first reach would be $4^5 = 1024$, and serious trouble would probably be present. With three alternate stands covered to form three one-cover systems, the amplification factor might still be four, but now the over-all amplification might be about $4^2 = 16$. If the covers are applied to provide a lateral design with an individual reach feeding into a system of two reaches with the intermediate stand covered, which in turn feeds into a system of three reaches with the two intermediate stands covered, a surge originating anywhere on this system would not be amplified much because the possibilities of resonance have been largely destroyed. This is in accord with field experience; i.e., that better operating conditions are obtained as more covers are applied.

## Electric Analog Studies

It is desirable, in the interests of economy and good engineering practice, to avoid the indiscriminate use of the covers. If additional data on the behavior of transient flow in pipe lines with covered pipe stands were available, a more effective and economical installation could

generally be made. It is also possible that the reasons for minor difficulties experienced with covers could be found if the transient conditions in such systems were better understood.

It was estimated that about 3 months' time for two men would be required to obtain the desired additional information by direct analytical means. This amount of time and effort seemed excessive and the possibility of using an electronic analog device to facilitate the work was therefore considered. It appeared that such a device could be constructed and operated to provide the required information in much less time.

High-frequency analog. A hydraulic system with three pipe reaches and two covered pipe stands is shown in Figure 27A. The analogous electrical circuit is shown in Figure 27B. The symbols used on these figures and elsewhere are defined at the front of this report.

The following equations are written for a hydraulic system with three pipe reaches and two covered pipe stands and for the analogous electrical circuit.

The continuity equations for the hydraulic system are

$$Q_o + q_o \sin \frac{2\pi}{T_o} t - F_1 \frac{dy_1}{dt} - Q_1 = 0.$$

$$Q_1 - F_2 \frac{dy_2}{dt} - Q_2 = 0 \qquad (34)$$

$$Q_2 - F_3 \frac{dy_3}{dt} - Q_3 = 0$$

The dynamic equations for the three pipe reaches are

$$\frac{L_1}{A_1 g} \frac{dQ_1}{dt} - y_1 + \frac{H_2 F_2}{S_2} y_2 = 0$$

$$\frac{L_2}{A_2 g} \frac{dQ_2}{dt} - \left(1 + \frac{H_2 F_2}{S_2}\right) y_3 + \frac{H_3 F_3}{S_3} y_3 = 0 \qquad (35)$$

$$\frac{L_3}{A_3 g} \frac{dQ_3}{dt} - \left(1 + \frac{H_3 F_3}{S_3}\right) y_3 = 0$$

The electrical continuity equations are

$$I_o + i \sin bn - C_1 \frac{dE_1}{dn} - I_1 = 0$$

$$I_1 - C_2 \frac{dE_2}{dn} - I_2 = 0 \qquad (36)$$

$$I_2 - C_3 \frac{dE_3}{dn} - I_3 = 0$$

The electrical dynamic equations are

$$E_1 - J_1 \frac{dI_1}{dn} - E_2 = 0$$

$$E_2 - J_2 \frac{dI_2}{dn} - E_3 = 0 \qquad (37)$$

$$E_3 - J_3 \frac{dI_3}{dn} = 0$$

Before the analog could be set up, it was necessary to write a set of correlation equations and to convert the hydraulic equations to electrical equations by substituting the correlation equations into them. The capacities and inductances required in the electrical circuit were found by this process.

The correlation equations adopted were as follows:

$$y_1 = E_1$$

$$y_2 = \frac{S_2}{H_2F_2} E_2$$

$$y_3 = \frac{S_3}{H_3F_3} E_3 \qquad (38)$$

$$Q = 1{,}000\ I$$
$$t = 1{,}040{,}000\ n$$

The process of transformation may be illustrated as follows:

Transform the equation:

$$Q_o + q_o \sin \frac{2\pi}{T_o} t - F_1 \frac{dy_1}{dt} - Q_1 = 0$$

By substitution from the correlation equations:

$$1{,}000\ I_o + 1{,}000\ i_o \sin \frac{2\pi}{T_o} (10)^6 (1.04) n - F_1 \frac{dE_1}{(1.04)(10)^6 dn} - 1{,}000\ I_1 = 0$$

or, after reduction:

$$I_o + i_o \sin bn - \frac{F_1}{(10)^9 (1.04)} \frac{dE_1}{dn} - I_1 = 0$$

A comparison of the transformed equation with the first of Equations (36) will show that the value of $C_1$ must be

$$C_1 = \frac{F_1}{(10)^9 (1.04)}$$

The second of the hydraulic equations

$$Q_1 - F_2 \frac{dy_2}{dt} - Q_2 = 0$$

Becomes

$$1{,}000\ I_1 - F_2 \frac{S_2}{H_2 F_2} \frac{dE_2}{(1.04)(10)^6 dn} - 1{,}000\ I_2 = 0$$

Or

$$I_1 - \frac{F_2 S_2}{H_2 F_2 (10)^9 (1.04)} \frac{dE_2}{dn} - I_2 = 0$$

And a comparison with the second of Equations (36) shows that

$$C_2 = \frac{S_2}{H_2 (10)^9 (1.04)}$$

The first of the dynamic equations in the hydraulic set is, from Equations (35),

$$\frac{L_1}{A_1 g}\frac{dQ_1}{dt} - y_1 + \frac{H_2F_2}{S_2}y_2 = 0$$

This becomes, on substitution from the correlation equations,

$$\frac{L_1}{A_1 g}\frac{1{,}000\ dI_1}{(1.04)(10)^6 dn} - E_1 + E_2 = 0$$

A comparison of this equation with the corresponding electrical equation, which is the first of the three Equations (37), shows that the inductance required is

$$J_1 = \frac{L_1}{A_1 g(1{,}040)}$$

The only difficulty encountered in this process is that the quantities $\frac{H_2F_2}{S_2}$ and $1 + \frac{H_2F_2}{S_2}$ and also $\frac{H_3F_3}{S_3}$ and $1 + \frac{H_3F_3}{S_3}$ cannot be differentiated. It is therefore necessary to use an average value for both $\frac{H_2F_2}{S_2}$ and $1 + \frac{H_2F_2}{S_2}$ and likewise $\frac{H_3F_3}{S_3}$ and $1 + \frac{H_3F_3}{S_3}$.

The quantities used in the analog are:

$A = 3.1416\ ft^2$ (for a 2-foot-diameter pipe)

$C_1 = 8.2380(10)^{-9}$ farads

$C_2 = C_3 = C_4 = (2.7460)(10)^{-9}$ farads

$F_1 = F_2 = F_3 = 8.5675\ ft^2$ (for a 5-foot-diameter pipe stand)

$g = 32.2\ ft/sec^2$

$H_2 = H_3 = H_4 = 34\ ft$

$L_1 = L_2 = L_3 = L_4 = 1{,}320\ ft$

$S_2 = S_3 = S_4 = 121.4\ ft^3$

$$\frac{H_2F_2}{S_2} = \frac{H_3F_3}{S_3} = 1 + \frac{H_2F_2}{S_2} = 1 + \frac{H_3F_3}{S_3} = 3$$

$$J_1 = J_2 = J_3 = J_4 = 0.0125 \text{ Henrys}$$

The resistance of these coils is about 3.5 ohms.

This analog will work at around 10,000 cycles per second and will be referred to hereafter as the high-frequency analog. The natural periods obtained with this system are shown in the following table:

Table 1

NATURAL PERIODS OF THE PROTOTYPE HYDRAULIC SYSTEM AS OBTAINED FROM OPERATION OF THE HIGH-FREQUENCY ANALOG

| Open stands | Covered stands | Prototype period seconds | | |
|---|---|---|---|---|
| 1 | 0 | 64.0 | | |
| 1 | 1 | 94.5 | 24.8 | |
| 1 | 2 | 120.9 | 32.5 | 21.0 |
| 1 | 3 | 148.6 | 41.6 | 24.1 |

It will be noted that there is more than one natural period for each system except the first. There should be a number of periods equal to the number of pipe reaches in the system. However, only three periods where resonance occurs could be found for the system with four pipe reaches and three covered stands.

Low-frequency analog. Another analog system was designed to work at about 50 cycles per second and was called the low-frequency analog. This analog had the advantage that the frequencies were low enough to permit the sequence of starting oscillation to be recorded on an oscillograph. The Equations (34), (35), (36), and (37) as described previously were used with the correlation equations

$$y_1 = E_1 \qquad E_2 = \frac{H_2F_2}{S_2} y_2 \qquad E_3 = \frac{H_3F_3}{S_3} y_3$$

$$Q = 1{,}000\ I \qquad t = 3{,}320\ n \tag{39}$$

These correlation equations lead to the values:

$$C_1 = 2.58(10)^{-6} \text{ farads}$$

$$C_2 = C_3 = C_4 = (0.86)(10)^{-6} \text{ farads}$$

$$J_1 = J_2 = J_3 = J_4 = 3.93 \text{ Henrys}$$

The resistance of the inductances is 200 ohms. An iron core with an air gap was used to obtain the high inductance required in this system. In such an analog, the resistances must be small compared with the critical resistance

$$R_c = \frac{4J}{C}$$

if the resonance points are to be clearly shown. A check will show that both systems fulfill this requirement.

The observed resonance points of the analog are shown in the following table:

Table 2

RESONANCE POINTS--LOW-FREQUENCY ANALOG

| Open stands | Covered stands | Observed frequencies cycles per second | | |
|---|---|---|---|---|
| 1 | 0 | 50 | | |
| 1 | 1 | 32.5 | 133 | |
| 1 | 2 | 26 | 98 | 156 |
| 1 | 3 | 21 | 76 | 133 |

These results converted to prototype periods are as follows:

Table 3

NATURAL PERIODS OF THE HYDRAULIC SYSTEM OBTAINED FROM THE OBSERVATIONS OF TABLE 2

| Open stands | Covered stands | Natural periods seconds | | |
|---|---|---|---|---|
| 1 | 0 | 66 | | |
| 1 | 1 | 102 | 25 | |
| 1 | 2 | 128 | 34 | 21 |
| 1 | 3 | 158 | 44 | 25 |

In the last case, where there was one open stand and three covered stands, there should be four frequencies, but, as before, only three were found.

The periods computed directly from Equations (34) and (35) are:

Table 4

COMPUTED PERIODS

| Open stands | Covered stands | Computed periods seconds | | |
|---|---|---|---|---|
| 1 | 0 | 66.4 | | |
| 1 | 1 | 90.1 | 26.6 | |
| 1 | 2 | 107.0 | 36.0 | 22.4 |
| 1 | 3 | Not computed | | |

Relation of Resonance to the Imposed Oscillation Periods

The relation of resonance for various pipe line systems to the imposed oscillation periods, obtained by feeding the output of the low-frequency analog into an oscillograph recorder and then plotting these records in graphical form, is shown on Figure 28. A diagram on each of the four graphs shows the system represented. The total flow in the hydraulic system is assumed to be made up of an average flow upon which an oscillatory component is superimposed. Only the oscillatory component is represented on the plots. The input component, $q_o$, is shown on the bottom plot of each group of plots, while the subsequent components, $q_1$, $q_2$, etc., are shown above in ascending order. The periods are shown for a prototype structure with 5-foot-diameter pipe stands connected with 1,320 feet of 2-foot-diameter pipe. Since the scale on all the q records is the same (within about 4 percent) the

amplification factors can be obtained by comparing the band widths of the q records. For example, on the system with no covers, the amplification factor at a period of 74 seconds is about 4 (Figure 28A).

It has been noted that there is some variation in the observed periods in different runs with the low-frequency analog. This is believed due to the use of iron-cored coils and the discrepancies are not regarded as being serious for these tests.

## The Action Within the Pipe System When Flow is Started

Tests were made on the low-frequency analog to determine the action within the pipe system when flow was first started in the line. In this case, both the average flow and the oscillatory component were studied. The results of the analog runs were recorded on an oscillograph in which the paper speed was increased to the point where the starting oscillations and the phase relations could be distinguished. Sample records are shown in Figures 29 through 35 for the case with the oscillating components of flow, and in Figure 36 for the case with the average flow. In all cases the middle trace represents the flow passing over the baffle of the open stand at the upstream end of the system ($q_o$ and $Q_o$). The traces above represent flows in the successive pipe reaches of the system; $q_1$, $q_2$, etc., and $Q_1$, $Q_2$, etc. The trace $y_1$ at the bottom of the records represents the departure from the normal running level in the open pipe stand at the upstream end of the system. The next traces above represent the departure from normal level in the downstream halves of the subsequent covered pipe stands, $y_1$, $y_2$, etc.

In the original records 1 inch of amplitude represents 1 cubic foot per second on the flow (q) traces, and 1 foot of height on the elevation departure (y) traces. This unit distance is shown in proper scale on the smaller-sized reproductions in Figures 29 through 36. The records cover the cases of 0, 1, 2, and 3 stands covered. An important fact shown by Figures 29 through 35 is that when the imposed period is longer than the fundamental (gravest mode) period of the system the flow pattern in all the pipe reaches in the system are alike. This means that the system, under such conditions, behaves as though the covered stands were removed and the pipes were connected together. The gravest mode period, $T_1$, for such a system can therefore be estimated from the formula:

$$T_1 = 2\pi\sqrt{\frac{F_1}{g}\sum\frac{L_n}{A_n}}$$

The term "system" is here used to describe a group of the pipe reaches and pipe stands which behave dynamically as a unit. Such a "system" can comprise a single pipe reach connecting the pipe stand

sections, or any number of pipe reaches together with the downstream half of the pipe stand at the upstream end of the first reach, the upstream half of the stand at the downstream end of the last reach, and the covered pipe stands between. Note that a "system" created by the application of covers has all of the interior stands covered.

The effect in the pipe system of suddenly increasing a nonoscillating type of flow (the average flow) is shown in Figure 36. The effect is that surges are immediately initiated in the reaches downstream, but that these surges quickly die out. This demonstrates that it is necessary to have a driving force present at all times in order to have continuous surging similar to that at Coachella and in the laboratory model. This small driving force is believe to arise in the process of entrapment and subsequent release of air in the pipe lines.

## Verification of the Analytical and Electric Analog Results by Hydraulic Model Tests

It was desirable to have evidence in the form of actual tests results to substantiate the accuracy and dependability of the initial analytical and analog results. To obtain this evidence it was convenient to construct an analog to represent the hydraulic model and to run a series of analog tests. Concurrently, the natural periods of the hydraulic system were computed and hydraulic tests were made. The results of the studies are shown in Figure 36 for the conditions of Stands 1 and 2 covered, Stand 1 covered, and no stands covered.

The computations of the natural periods of oscillation of the Coachella model were made in the following manner. For a system of two consecutive covered pipe stands following an open pipe stand connected by two reaches of pipe, the continuity equations are:

$$A_1V_1 + F_1 \frac{dy_1}{dt} - Q_o - q \sin \frac{2\pi t}{T} = 0$$

$$A_1V_1 - A_2V_2 - F_2 \frac{dy_2}{dt} = 0$$

and

$$A_2V_2 - A_3V_3 - F_3 \frac{dy_3}{dt} = 0$$

The dynamic equations are

$$\frac{L_1}{g} \frac{dV_1}{dt} - y_1 + \frac{H_2F_2}{S_2} y_2 = 0$$

$$\frac{L_2}{g}\frac{dV_2}{dt} - \quad 1 + \frac{H_2F_2}{S_2} \quad y_2 + \frac{H_3F_3}{S_3}\, y_3 = 0$$

and

$$\frac{L_3}{g}\frac{dV_3}{dt} - \quad 1 + \frac{H_3F_3}{S_3}\, y_3 = 0$$

Considering these as six equations in six unknowns, $V_1$, $V_2$, $V_3$, $y_1$, $y_2$, and $y_3$, $y_2$ may be solved by using $\frac{d}{dt} = D$ as an operator. By evaluating sixth order determinants, we have

$$\left[K_1D^6 + gK_2D^4 + g^2K_3D^2 + g^3K_4\right] \quad y_1 =$$

$$-\frac{1}{F_1}\left\{K_1D^5 + g \quad (K_2 - \frac{A_1K_1}{L_1F_1}) \quad D^3 + g^2\left[K_3 - \frac{A_1}{L_1F_1} \quad (K_2 - \frac{A_1K_1}{L_1F_1}) + \frac{A_1^2K_1}{L_1^2F_1}\frac{H_2}{S_2}\right] \quad D\right\} \quad \left[Q_o + q \sin\frac{2\pi t}{T}\right]$$

where

$$K_1 = F_1F_2F_3L_1L_2L_3$$

$$K_2 = K_1\left[\frac{A_1}{L_1} \quad (\frac{1}{F_1} \quad \frac{H_2}{S_2}) + \frac{A_2}{L_2} \quad (\frac{1}{F_2} \quad \frac{H_2}{S_2} \quad \frac{H_3}{S_3}) + \frac{A_3}{L_3}\,(\frac{1}{F_3} + \frac{H_3}{S_3})\right]$$

$$K_3 = K_1\left\{\frac{A_1A_2}{L_1L_2}\left[\frac{1}{F_1} \quad (\frac{1}{F_2} + \frac{H_2}{S_2}) + \frac{H_3}{S_3} \quad (\frac{1}{F_1} + \frac{H_2}{S_2})\right] + \frac{A_2A_3}{L_2L_3} \quad (\frac{1}{F_2} + \frac{H_2}{S_2}) \quad (\frac{1}{F_3} + \frac{H_3}{S_3}) + \frac{A_1A_3}{L_1L_3} \quad (\frac{1}{F_1} + \frac{H_2}{S_2}) \quad (\frac{1}{F_3} + \frac{H_3}{S_3})\right\}$$

and

$$K_4 = K_1\,\frac{A_1A_2A_3}{L_1L_2L_3}\,\frac{1}{F_1} \quad (\frac{1}{F_2} + \frac{H_2}{S_2}) \quad (\frac{1}{F_3} + \frac{H_3}{S_3})$$

The conditions after the starting disturbances have died away are of interest. As a trial solution of the above differential equation, let

$$y_1 = Z \cos a\, t$$

where

$$a = \frac{2\pi}{T}$$

The differential equation then becomes

$$\left( - K_1 a^6 + g K_2 a^4 - g^2 K_3 a^2 + g^3 K_4 \right) Z =$$

$$- \frac{g}{F_1} \left\{ K_1 a^5 - g \left(K_2 - \frac{A_1 K_1}{L_1 F_1}\right) a^3 + g^2 \left[ K_3 - \frac{A_1}{L_1 F_1} \left(K_2 - \frac{A_1 K_1}{L_1 F_1}\right) + \frac{A_1^2 K_1 H_2}{L_1^2 F_1 S_2} \right] a \right\}$$

Z, which is the amplitude of vibration, becomes indefinitely large yielding the points of resonance whenever its coefficient becomes zero provided the right-hand member of the equation does not simultaneously vanish; consequently of interest are the values of "a" which satisfy

$$K_1 a^6 - g K_2 a^4 + g^2 K_3 a^2 - g^3 K_4 = 0 \tag{40}$$

From Equation (39) in a previous discussion we have a comparable equation for one covered stand following an open stand connected by one reach of pipe, that is

$$a^4 - g \left[ \frac{A_1}{L_1} \left(\frac{1}{F_1} + \frac{H_2}{S_2}\right) + \frac{A_2}{L_2} \left(\frac{1}{F_2} + \frac{H_2}{S_2}\right) \right] a^2 + \tag{41}$$

$$g^2 \frac{A_1 A_2}{L_1 L_2} \frac{1}{F_1} \left(\frac{1}{F_2} + \frac{H_2}{S_2}\right) = 0$$

From Equation (20) we have

$$a^2 = \frac{gA_1}{L_1F_1} \tag{42}$$

for an open pipe stand.

Using the following constants for the hydraulic model of the laboratory,

pipe diameter = 8 inches

stand diameter = 20 inches

$A_1 = A_2 = A_3 = 0.349\ ft^2$

$F_1 = F_2 = F_3 = 1.0908\ ft^2$

$L_1 = L_2 = L_3 = 125\ ft$

$g = 32.2\ \frac{ft}{sec^2}$

$H_1 = H_2 = H_3 = 27\ ft$

$S_1 = 7.85\ ft^3$ (tail water 3 ft below top of baffle, lid 2.10 ft above top of baffle)

$S_2 = 7.24\ ft^3$ (tail water 3 ft below top of baffle, lid 1.82 ft above top of baffle)

$S_3 = 4.54\ ft$ (tail water 3.5 ft below top of baffle, lid 0.33 ft above top of baffle)

We find from Equation (40) and the relation $T = \frac{2\pi}{a}$, that for the condition with Stands 1 and 2 covered

$T = 5.2$ sec, $T = 9.0$ sec, $T = 36.5$ sec

Similarly, from Equation (41) and $T = \frac{2\pi}{a}$, for the condition of Stand 1 covered

$T = 7.3$ sec, $T = 30.1$ sec

And from Equation (42) and $T = \frac{2\pi}{a}$, for the condition of no stands covered

$T = 21.9$ sec

These periods appear in Figure 37, C, B, and A, respectively, as short vertical lines.

In the hydraulic tests water was supplied to the model at the constant rate of 0.25 cfs. The straight baffles were used in the stands and the baffles were set at the maximum elevations (Figure 11C) to suppress any tendency for inducing surging at periods other than that imposed by the mechanical surge mechanism in the head box. The covers contained flap valves but no relief-vent pipes.

In both the hydraulic model and analog tests, oscillations of known amplitude and period were imposed on an open pipe stand which in turn fed into the particular stand arrangement being tested. The data were plotted as the imposed period versus the oscillatory component of flow. In the hydraulic tests the flow rate is measured in cubic feet per second while in the analog tests it is measured in milliamperes. The resonant periods found in the hydraulic tests (40.0 and 9.5 seconds for Stands 1 and 2 covered, 34.0 and 7.2 seconds for Stand 1 covered, and 21.9 seconds for no stands covered) were in close agreement with the analytical values. The analog resonant periods (40.4 and 10.2 seconds, 21.9 and 7.5 seconds, and 22 seconds) were also in close agreement. The third resonant period for the condition of Stands 1 and 2 covered was not found in either the hydraulic or analog studies. The maximum resonance occured at the longest periods and the falling off of resonance at the shorter periods (where there was more than one period) was clearly demonstrated. Finally the tests showed that for a given imposed oscillation on the open pipe stand which feeds the systems the surge which entered the first stand of a covered system was of smaller amplitude than that which entered the first stand of an open system. On the basis of the agreement between the analytical, electric analog, and hydraulic tests, it is believed that the analyses and analog devices described herein accurately portray the performance of the field structures.

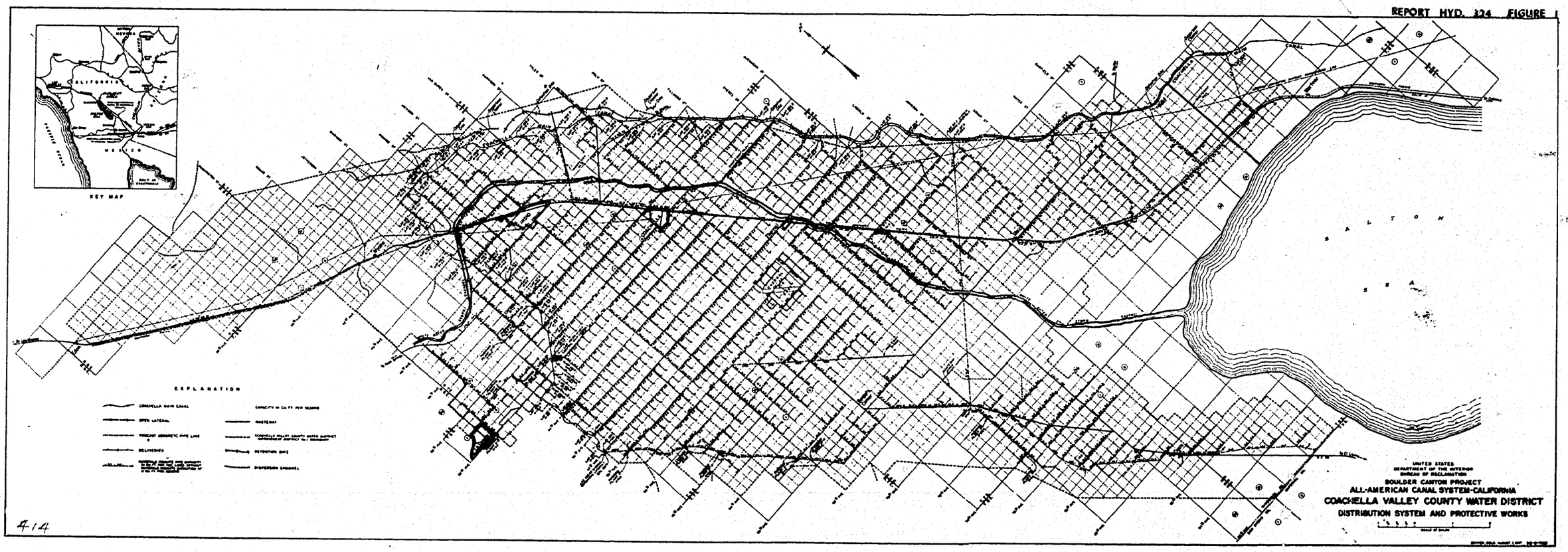
## Changing the Period of a Pipe Reach Without Using Covers

Since the resonance period of a given open pipe reach depends upon the length of the pipe line and the areas of the water surfaces in the connected stands, the period can be changed by changing either or both of these variables. The most effective direction for a period change is to increase it in a downstream direction. It is readily seen that the cost of progressively increasing the surface areas in the stands by any appreciable amount would be prohibitive in a long lateral. The length of the pipe line cannot be economically increased because it is necessary to serve many individual farms and each farm delivery requires a stand turnout. It is therefore impractical to obtain surge control based upon taking the system out of resonance by using progressively larger stands or longer pipe lines or a combination of the two.

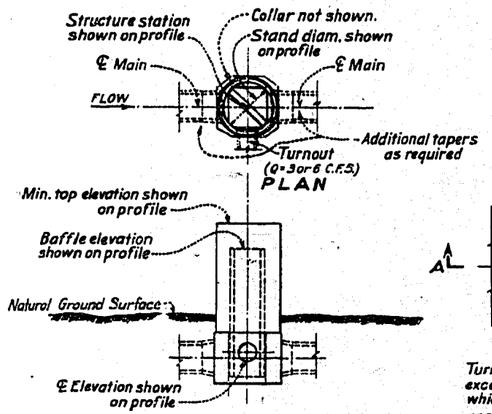


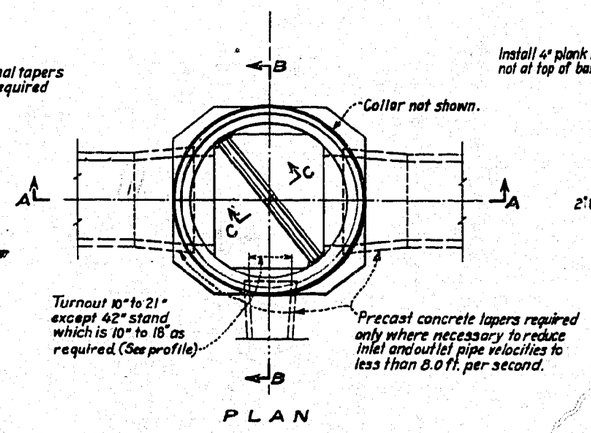
Interior - Reclamation - Denver, Colo.

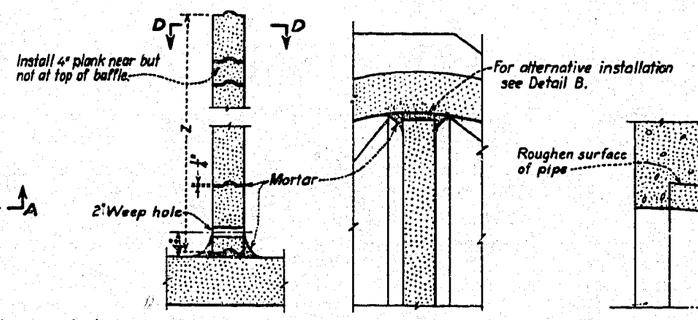
REPORT HYD. 324 FIGURE 1

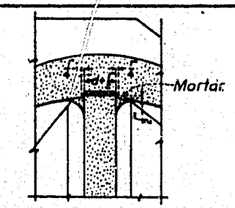


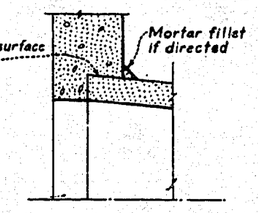

414

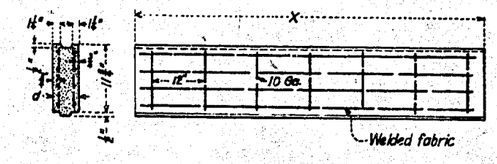


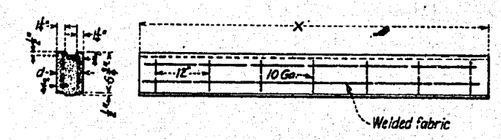



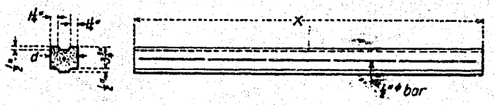



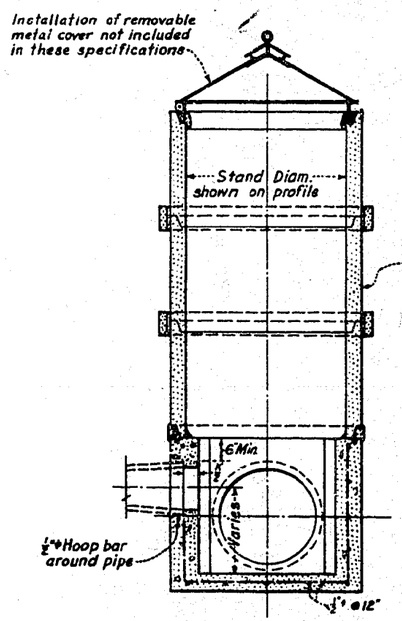



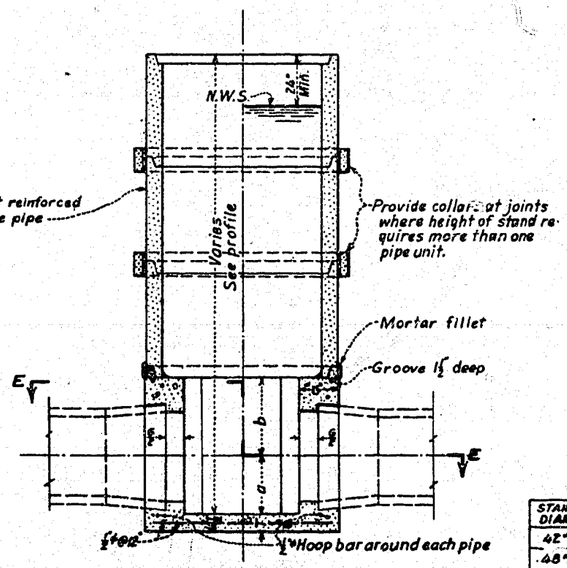



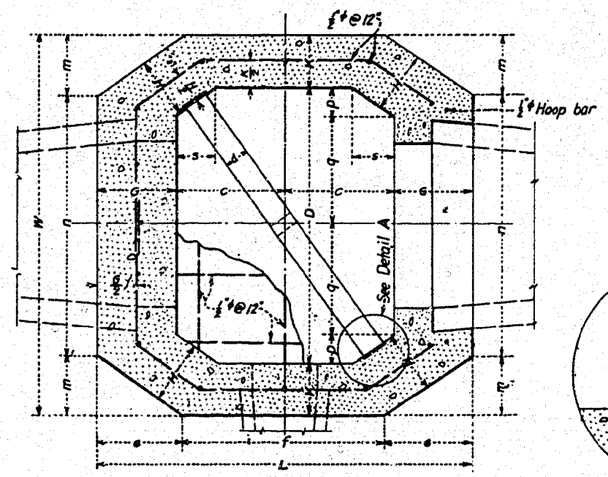



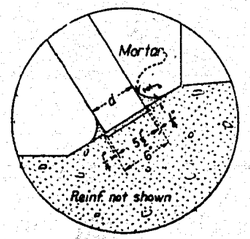

Note: For X=3'-4½" to 4'-4½", use 3/12" x 000ga./10ga. welded fabric.
For X=4'-10½" to 5'-10½", use 2/12" x 000ga./10ga. welded fabric.




## PLANK COMBINATIONS

| Z | NUMBER OF PLANKS | | |
|---|---|---|---|
| | 12" WIDE | 7" WIDE | 4" WIDE |
| y Ft-1 In. | y-2 | 3 | 1 |
| " 2" | y-1 | 2 | 0 |
| " 3" | y-1 | 1 | 2 |
| " 4" | y | 0 | 1 |
| " 5" | y-2 | 3 | 2 |
| " 6" | y-1 | 2 | 1 |
| " 7" | y | 1 | 0 |
| " 8" | y | 0 | 2 |
| " 9" | y-1 | 3 | 0 |
| " 10" | y-1 | 2 | 2 |
| " 11" | y | 1 | 1 |
| " 0" | y | 0 | 0 |

## DIMENSIONS

| STAND DIAM. | a | b | c | d | p | e | f | g | H | K | L | m | n | p | q | s | T | W | X* | Q-cfs MAX. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 42" | 12" | 18" | 18" | 4" | 3'-0" | 13½" | 2'-1" | 8" | 7" | 8" | 4'-4" | 13½" | 2'-1" | 7⅞" | 10½" | 7½" | 6" | 4'-4" | 5'-4½" | 15 |
| 48" | 14" | 22" | 20½" | 4" | 3'-7" | 16" | 2'-3" | 9" | 8" | 8" | 4'-11" | 14" | 2'-7" | 8½" | 13" | 9½" | 6" | 4'-11" | 5'-10½" | 24 |
| 54" | 17" | 2'-1" | 22½" | 4½" | 4'-0" | 18" | 2'-5" | 10" | 8" | 9" | 5'-5" | 15½" | 2'-11" | 8½" | 15½" | 9½" | 7" | 5'-6" | 6'-4½" | 32 |
| 60" | 20" | 2'-4" | 25½" | 4½" | 4'-5½" | 18" | 3'-1" | 13" | 10" | 10½" | 6'-1" | 15½" | 3'-6" | 6¾" | 19" | 7½" | 7" | 6'-1" | 6'-10½" | 39 |
| 66" | 24" | 2'-8" | 24" | 5" | 5'-1½" | 23" | 2'-10" | 16" | 10½" | 9" | 6'-8" | 15½" | 4'-½" | 8½" | 22½" | 12½" | 8" | 6'-7½" | 5'-4½" | 46 |
| 72" | 2'-3" | 3'-0" | 2'-1" | 5½" | 5'-8" | 23" | 3'-6" | 18" | 12" | 9" | 7'-2" | 14½" | 4'-8½" | 8" | 2'-2" | 13" | 8" | 7'-2" | 5'-10" | 53 |

* Increase X dimension by 1" if Detail B is used.

## NOTES

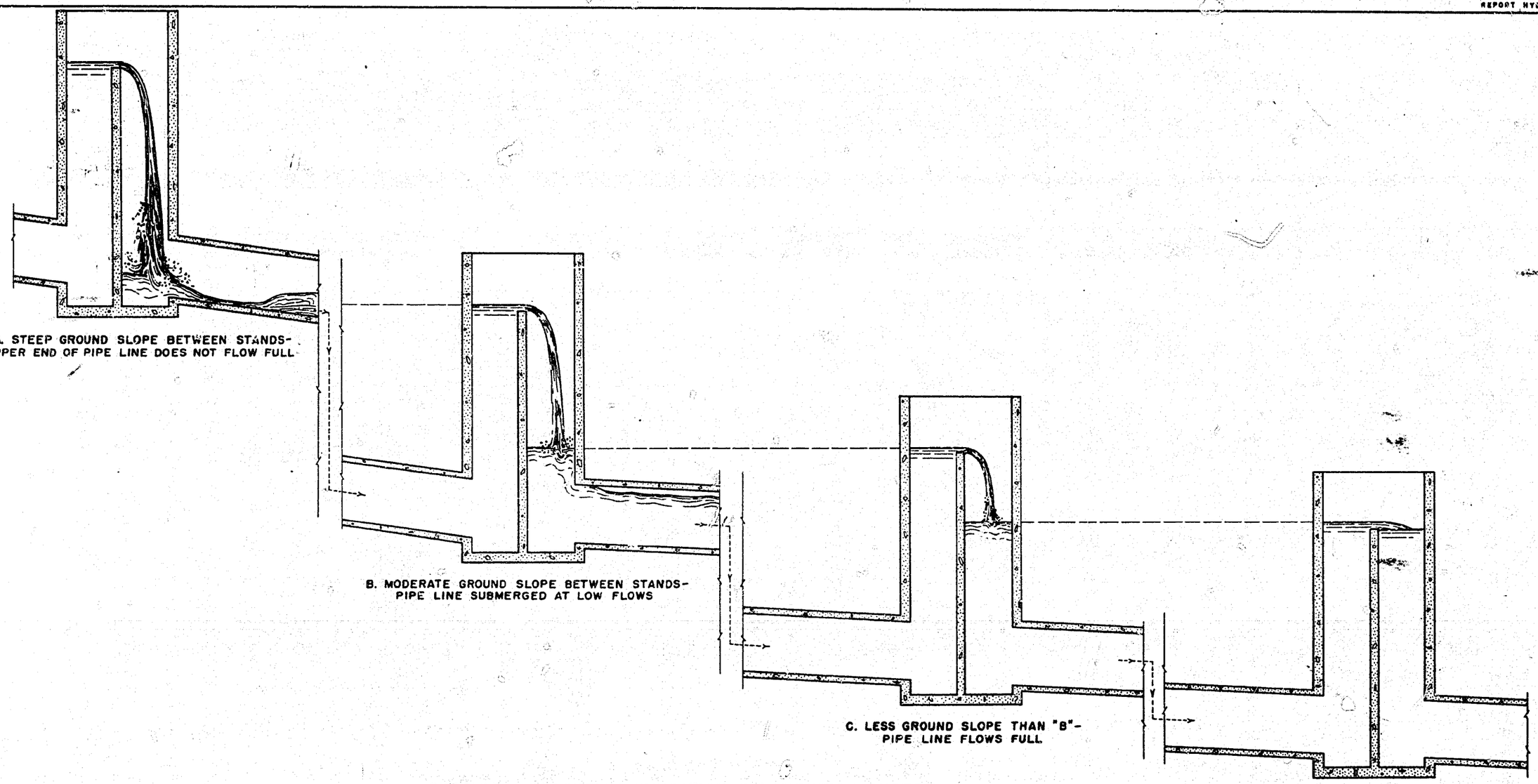
Lap all bars 17" at splices.
Precast tapers may be replaced by stepped pipe tapers as shown on Dwg. 212-D-7611.

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
BOULDER CANYON PROJECT

ALL-AMERICAN CANAL SYSTEM-CALIFORNIA
COACHELLA VALLEY DISTRIBUTION SYSTEM

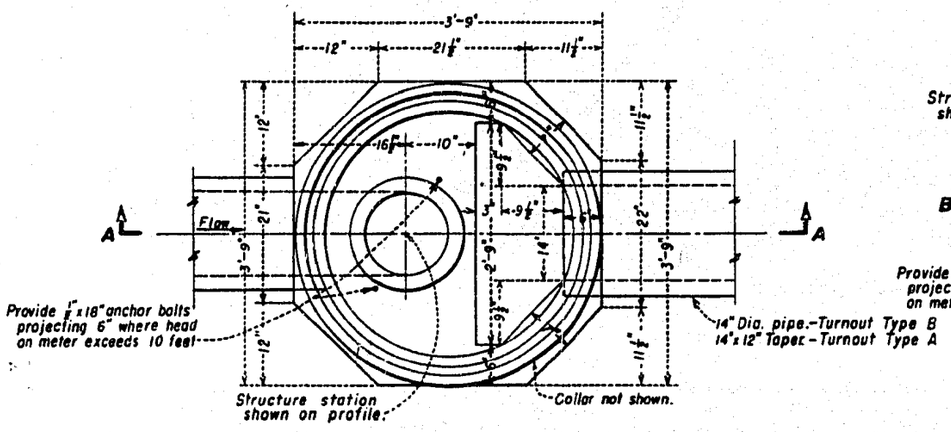
# PIPE STAND

DRAWN R.B.J. SUBMITTED W.R. MacRainey
TRACED J.M. RECOMMENDED W.P. Blaylock
CHECKED A.M. NEC APPROVED [illegible]
DENVER, COLORADO, APR. 28, 1945 — 212-D-7561

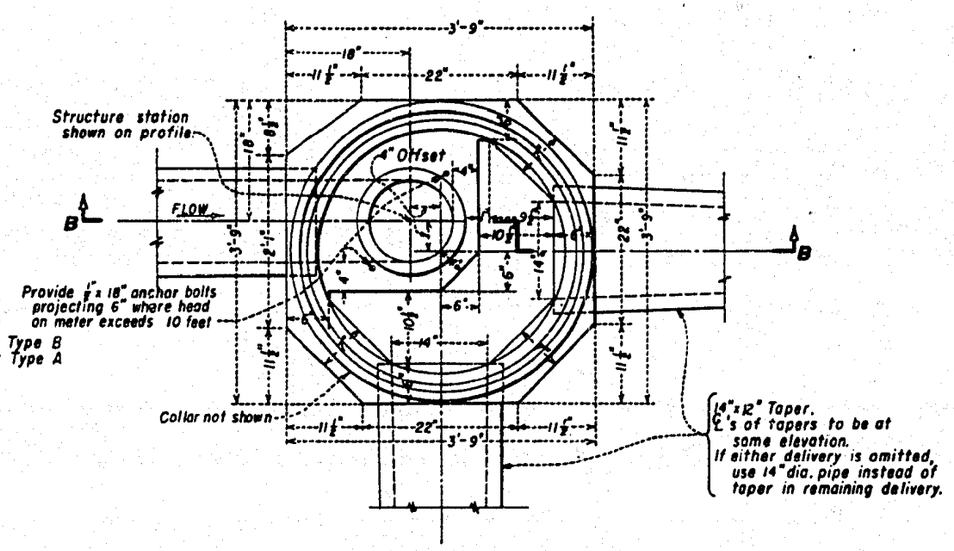



SURGING - COACHELLA IRRIGATION DISTRIBUTION SYSTEM

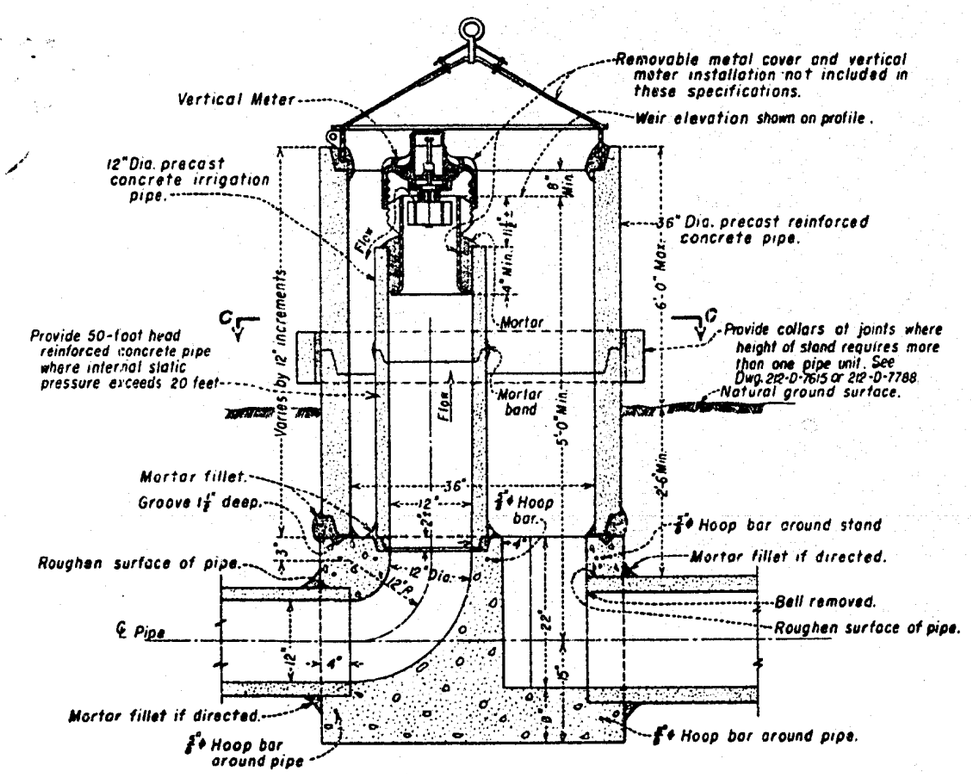
SCHEMATIC LATERAL PROFILE



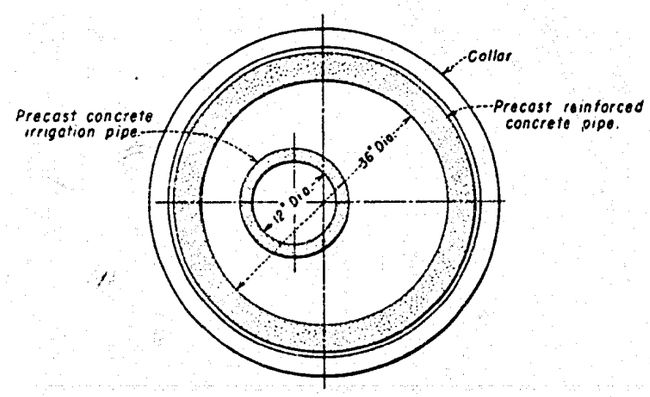

**PLAN**
(Meter and cover not shown.)




**3 C.F.S. METER STAND WITH SIDE DELIVERY**
(Meter and cover not shown.)
Either delivery may be omitted if directed.




**SECTION A-A**
(Section B-B Similar)




**SECTION C-C**

**NOTES**
Lap all bars 22" at splices.
Installation with side delivery may be opposite hand if directed.
Precast tapers may be replaced by stepped pipe tapers as shown on Dwg. 212-D-7611.

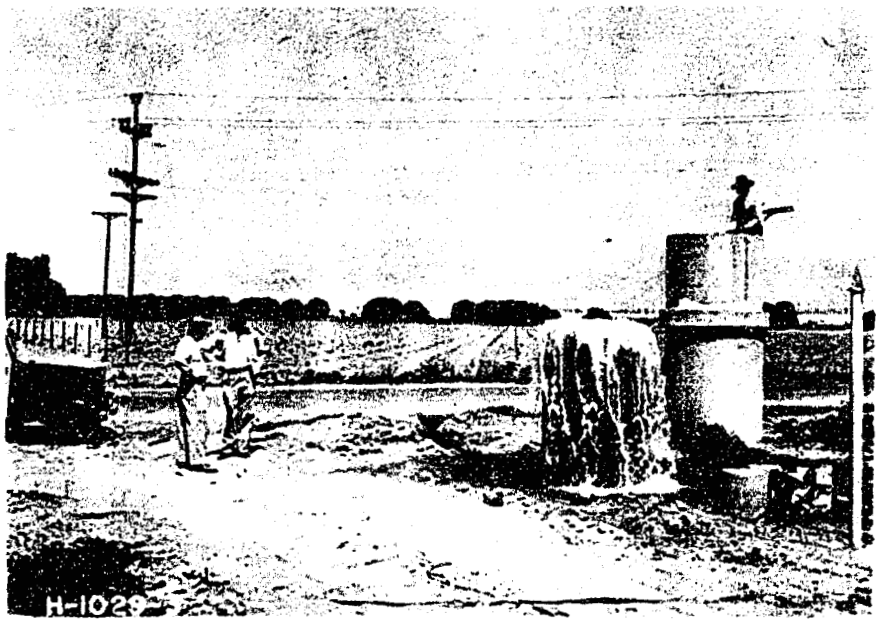
SCALE OF FEET

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
BOULDER CANYON PROJECT
ALL-AMERICAN CANAL SYSTEM-CALIFORNIA

**COACHELLA VALLEY DISTRIBUTION SYSTEM**
**3 C.F.S. METER STAND**

DRAWN R.B.J. SUBMITTED
TRACED R.B.J.-C.J.S. RECOMMENDED
CHECKED APPROVED
DENVER, COLORADO - APRIL 28, 1946
212-D-7360

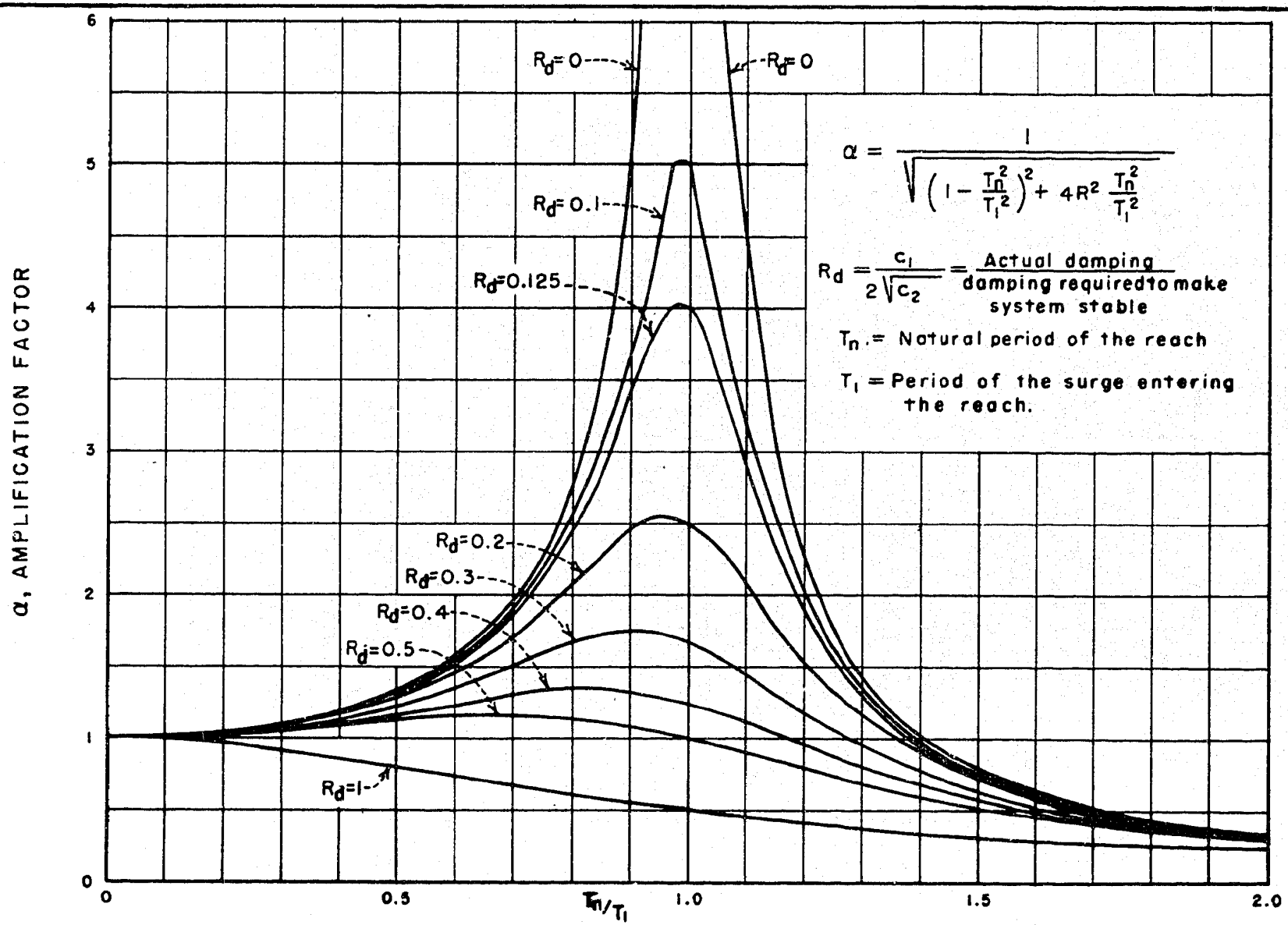
(A) Pipe Stand.




(B) Meter Stand.

SURGING - COACHELLA IRRIGATION DISTRIBUTION SYSTEM

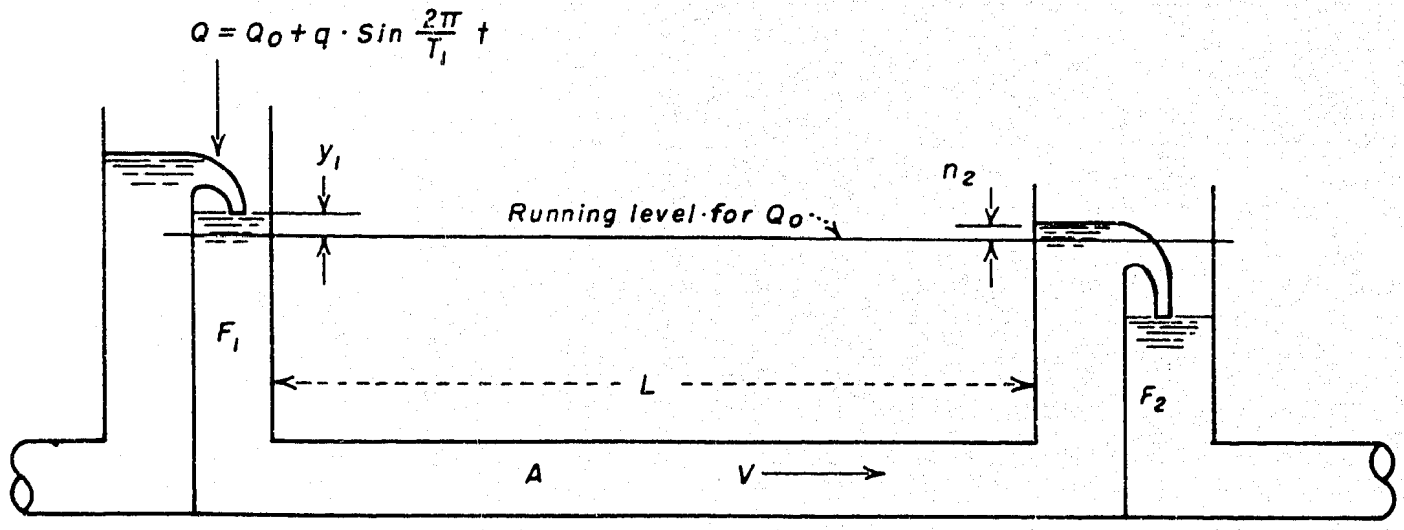
Pipe and Meter Stands Flooding Over Due to Surging in the System




SURGING - COACHELLA IRRIGATION DISTRIBUTION SYSTEM
AMPLIFICATION FACTORS

FIGURE 7
REPORT HYD. 324

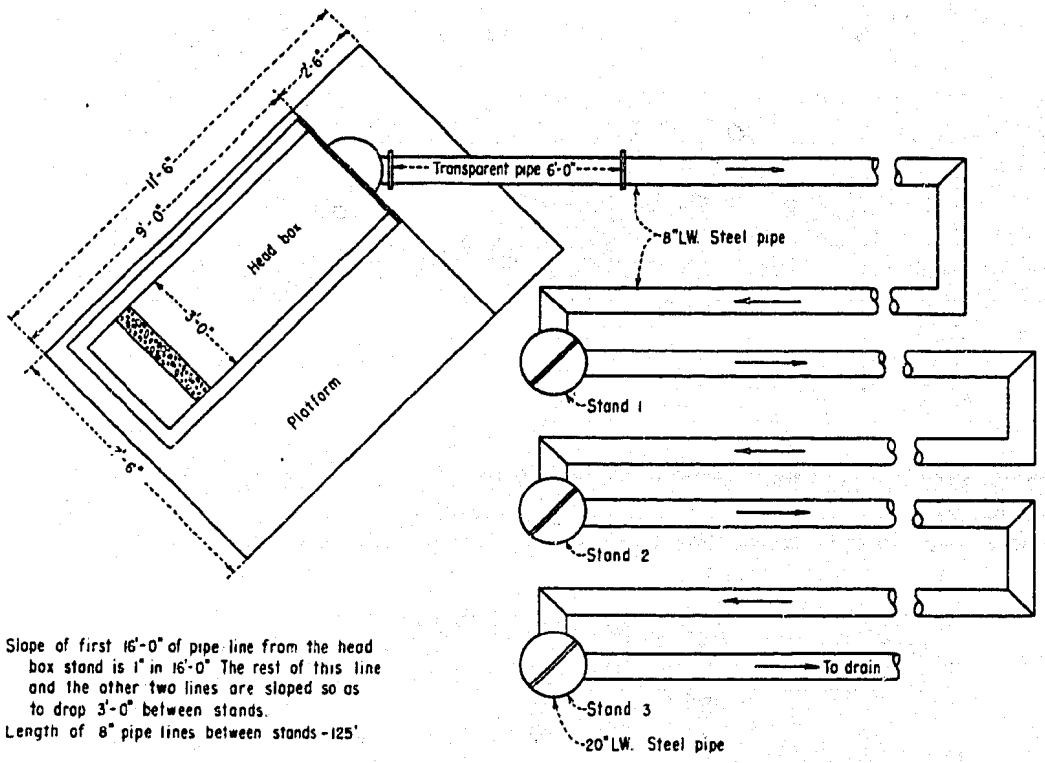
414




SURGING - COACHELLA IRRIGATION DISTRIBUTION SYSTEM
SKETCH OF A SINGLE REACH OF PIPE BETWEEN PIPE STANDS
ANALYTICAL STUDY

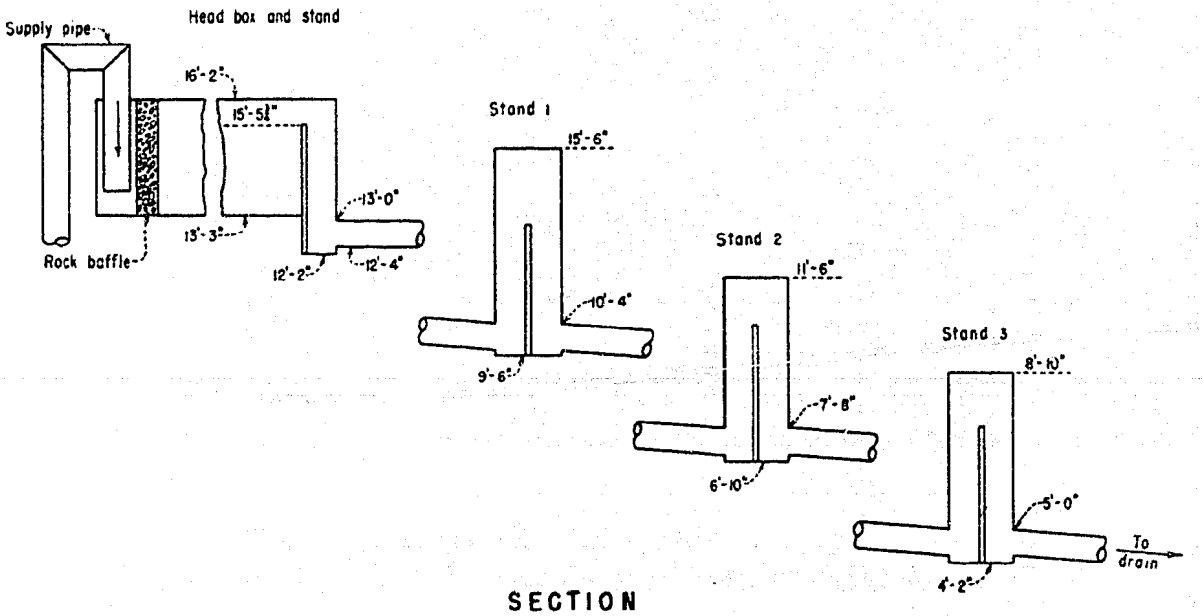
FIGURE 6
REPORT HYD. 324

414




Slope of first 16'-0" of pipe line from the head box stand is 1" in 16'-0" The rest of this line and the other two lines are sloped so as to drop 3'-0" between stands.
Length of 8" pipe lines between stands - 125'

PLAN



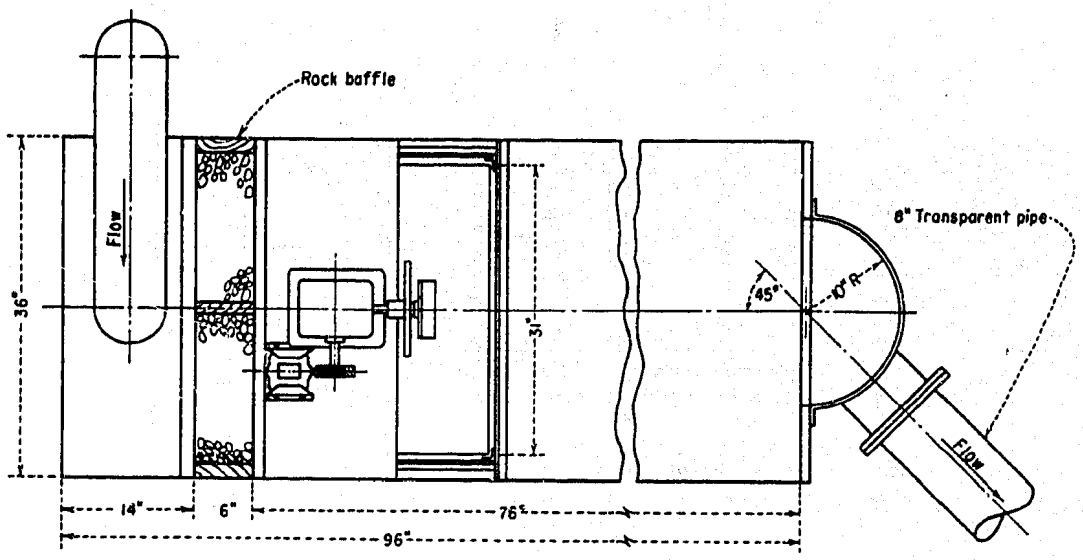

SECTION

The dimensions given are elevations measured from a reference point on the floor.

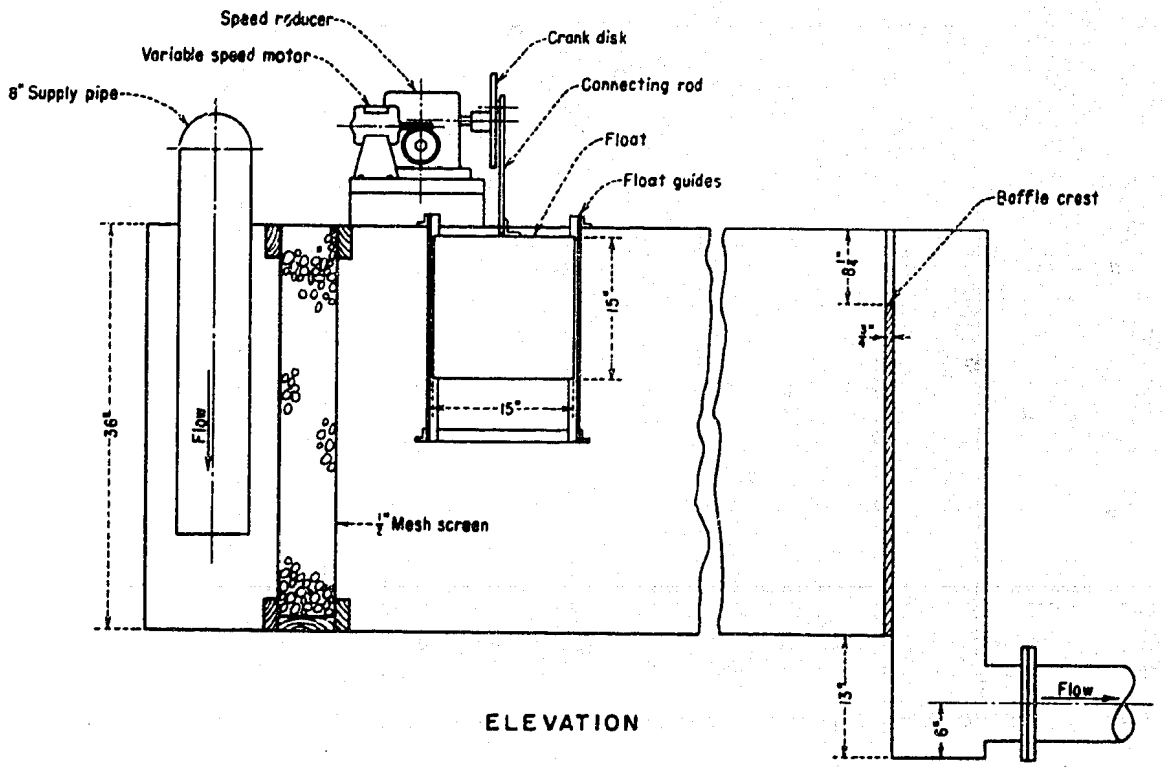
**SURGING - COACHELLA IRRIGATION DISTRIBUTION SYSTEM**

**SCHEMATIC DIAGRAM OF THE LABORATORY MODEL**

FIGURE 9
REPORT HYD. 324

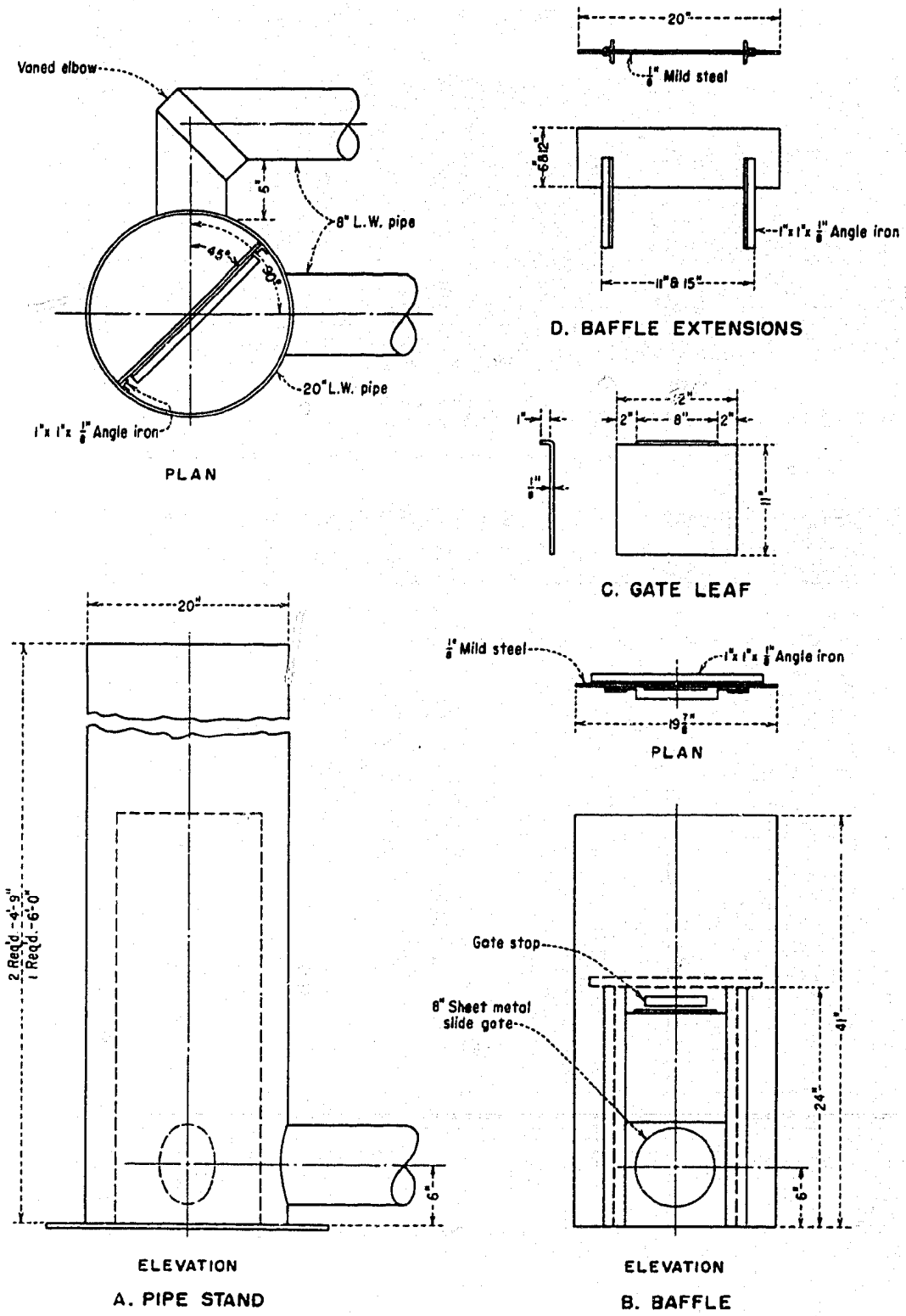



PLAN




ELEVATION

**SURGING – COACHELLA IRRIGATION DISTRIBUTION SYSTEM**
**HEAD BOX WITH MOTOR-OPERATED RECIPROCATING FLOAT FOR INDUCING SURGES IN LABORATORY MODEL**

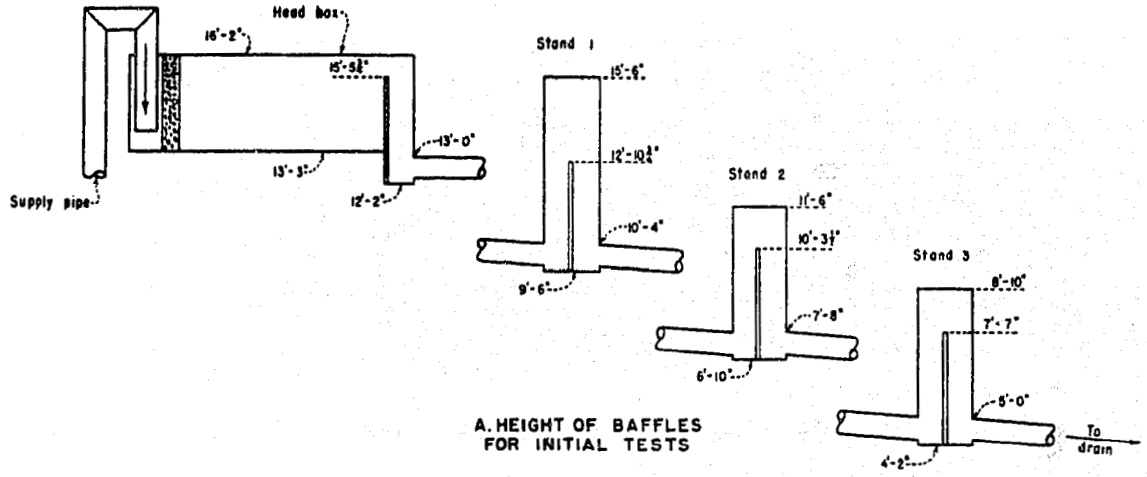



SURGING — COACHELLA IRRIGATION DISTRIBUTION SYSTEM

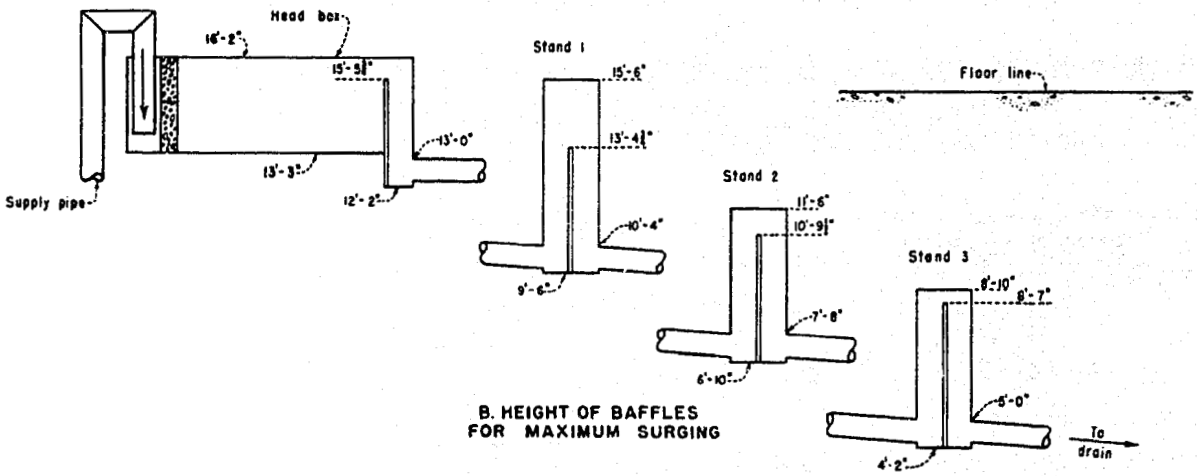
PIPE STAND BAFFLES, BAFFLE EXTENSIONS, AND BAFFLE GATES

LABORATORY MODEL

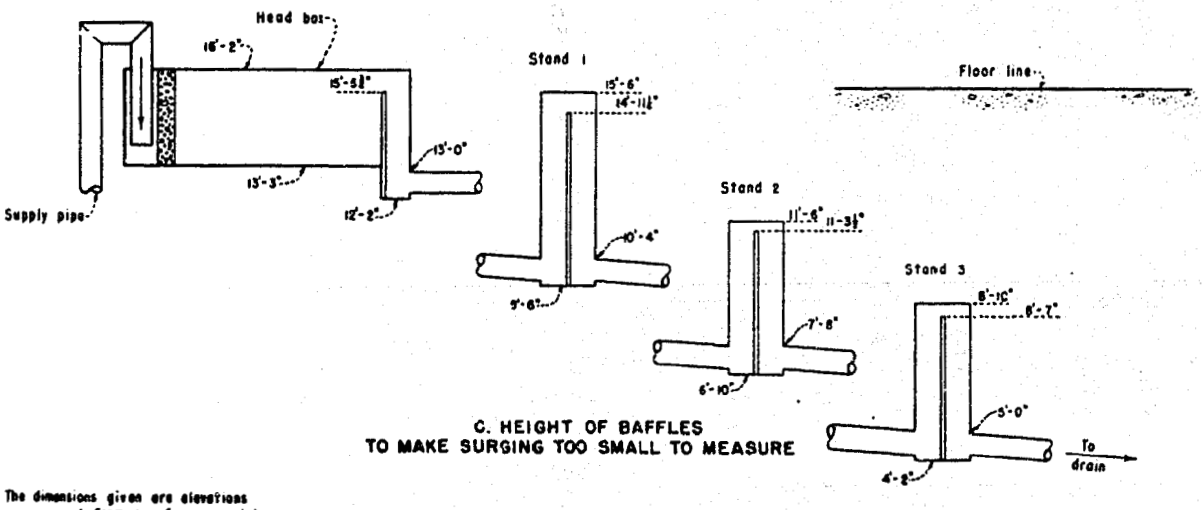
FIGURE 11
REPORT HYD. 394




A. HEIGHT OF BAFFLES
FOR INITIAL TESTS

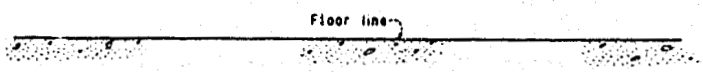



B. HEIGHT OF BAFFLES
FOR MAXIMUM SURGING




C. HEIGHT OF BAFFLES
TO MAKE SURGING TOO SMALL TO MEASURE

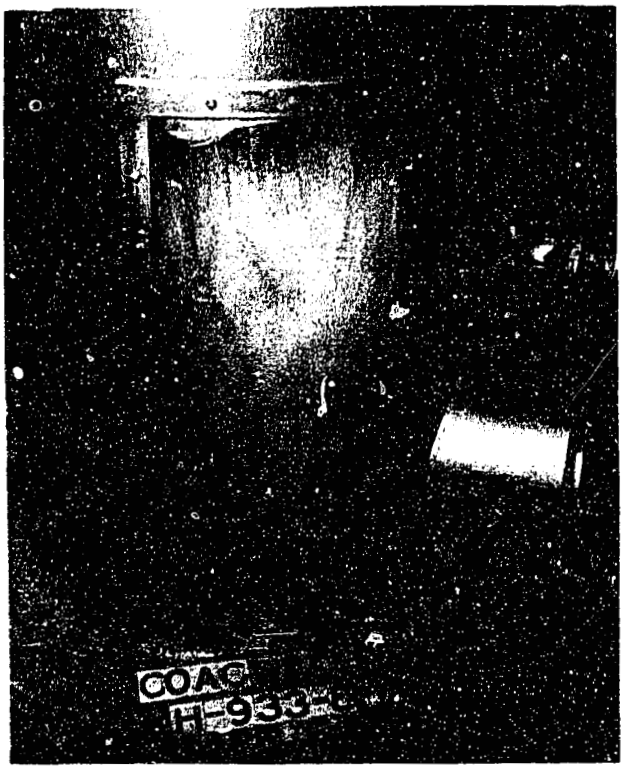
The dimensions given are elevations measured from a reference point on the floor.



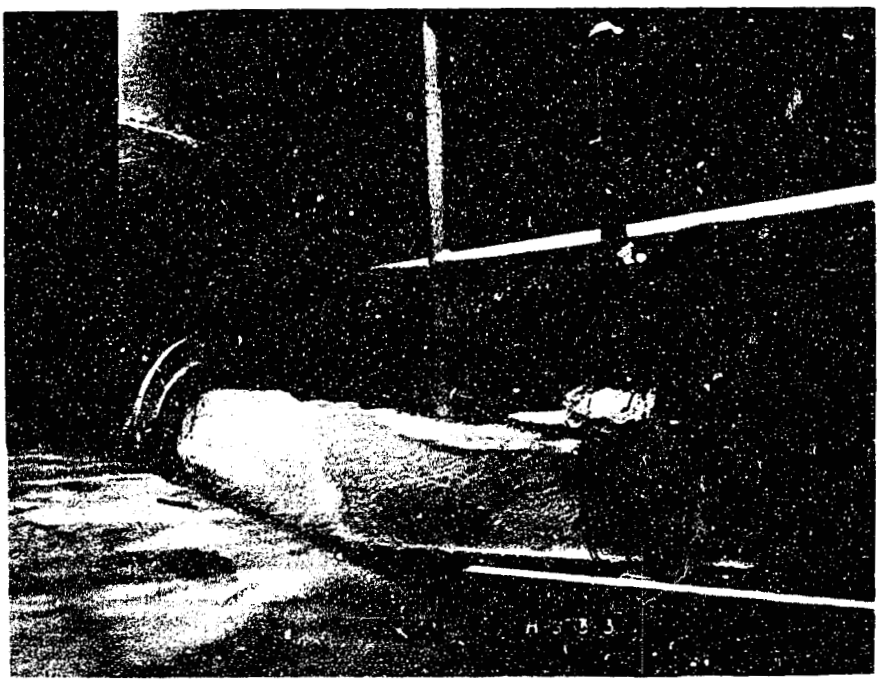

**SURGING - COACHELLA IRRIGATION DISTRIBUTION SYSTEM**

**BAFFLE ELEVATIONS FOR THE INITIAL TESTS AND FOR MAXIMUM AND MINIMUM SURGING**

**LABORATORY MODEL**



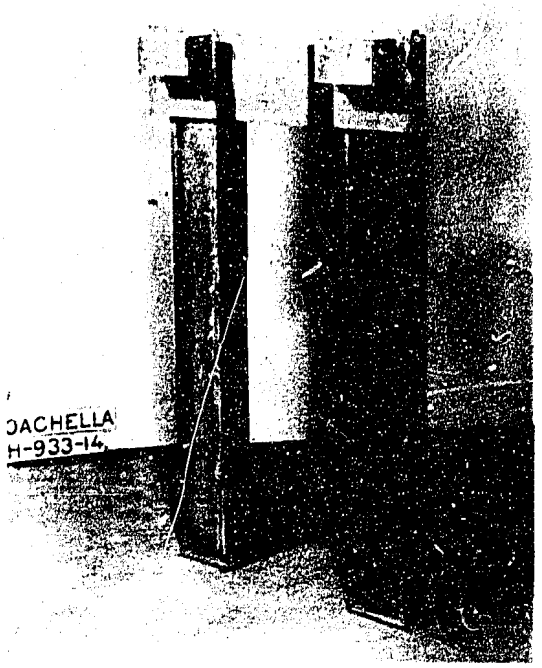
(A) Large quantities of air entrained by the water falling over the baffle. Q = 0.37 cfs.



(B) Entrained air bubbles entering the outlet pipe where they rise to join together as a large bubble. Q = 0.37 cfs. The pipe line vent is shown closed with modeling clay.

SURGING - COACHELLA IRRIGATION DISTRIBUTION SYSTEM

Air Entrained in the Downstream Section of the Stand and Carried Into the Outlet Pipe of the Laboratory Model



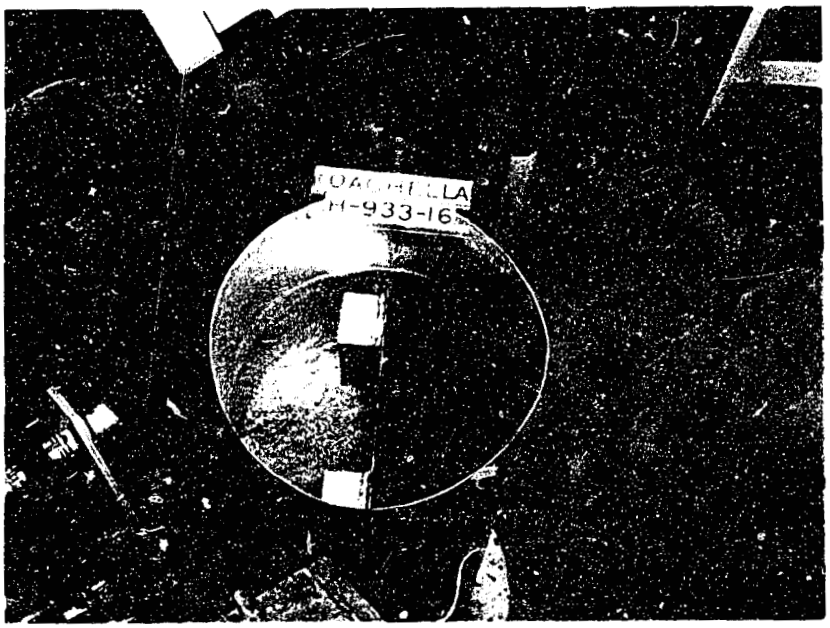

(A) Upstream view of siphons with hoods.

(B) Upstream and downstream views of siphons with hoods removed. Outlets are at different elevations to create opposing swirls.

SURGING - COACHELLA IRRIGATION DISTRIBUTION SYSTEM

**Siphons Through the Baffles**
**Laboratory Model**

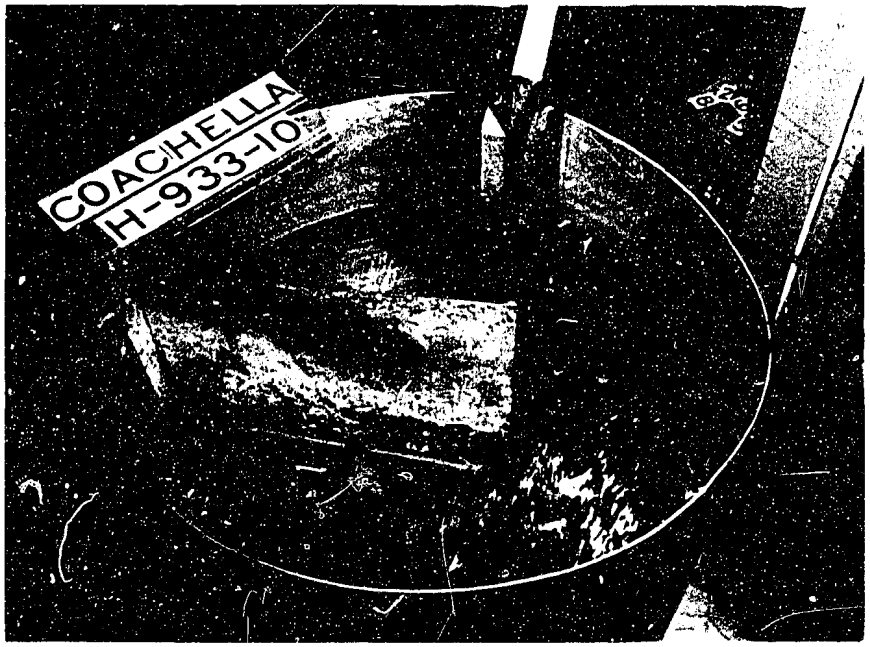
(A) Siphons with hoods.




(B) Siphons with hoods on upstream face removed.

SURGING - COACHELLA IRRIGATION DISTRIBUTION SYSTEM

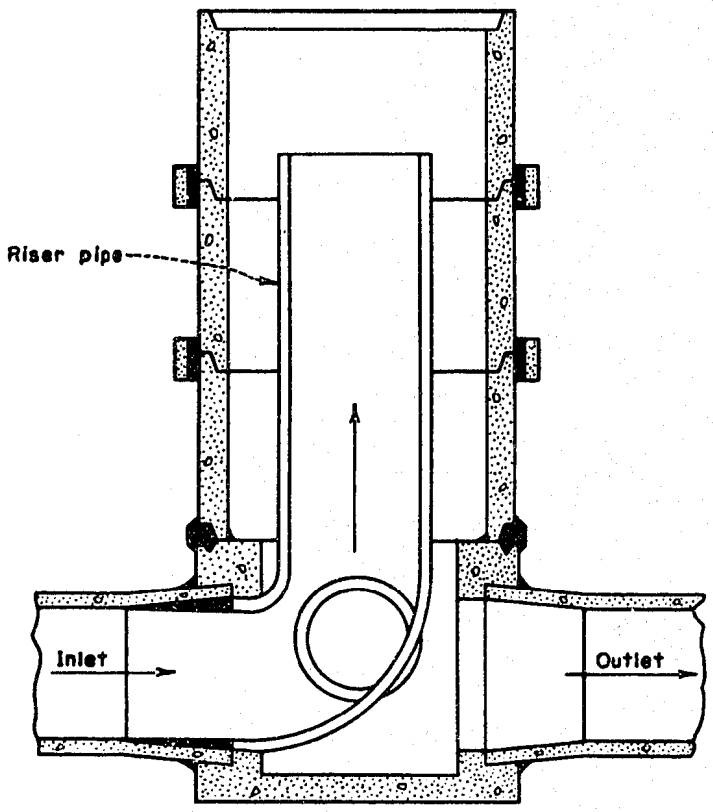
Baffle Siphons Installed in the Pipe Stands
(Stand 2 is in the center with Stand 3 at the left)
Laboratory Model



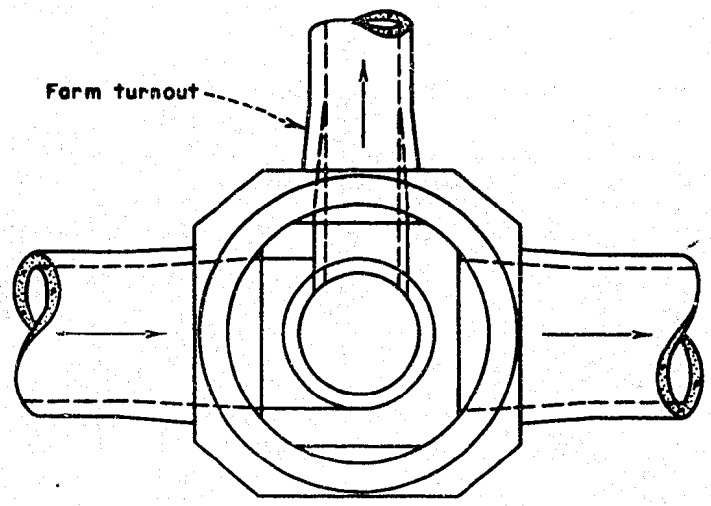

Stand 2

SURGING - COACHELLA IRRIGATION DISTRIBUTION SYSTEM

Partitions in Upstream Side of the Stand to Reduce
the Flow Area and Increase Friction
Laboratory Model




SECTION




PLAN

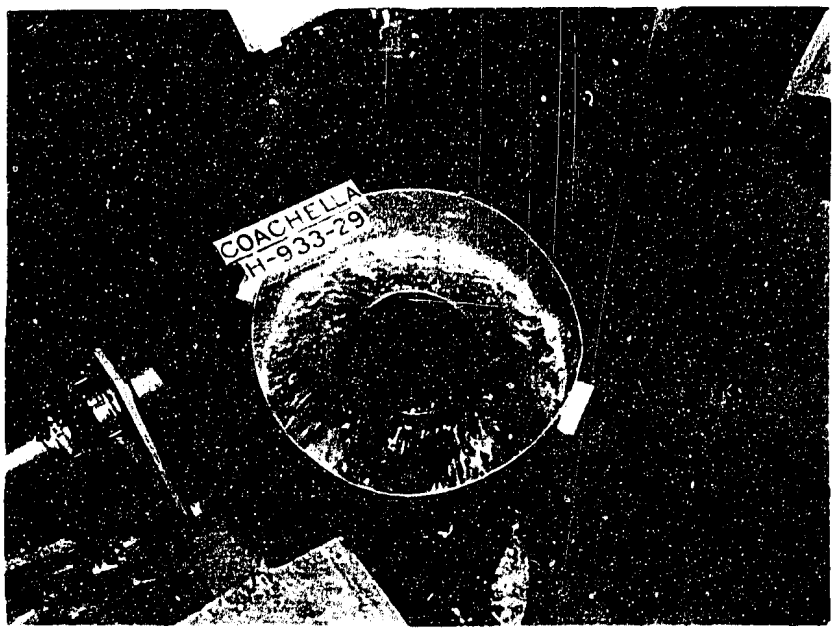
SURGING – COACHELLA IRRIGATION DISTRIBUTION SYSTEM

PIPE STAND WITH AN INLET RISER PIPE

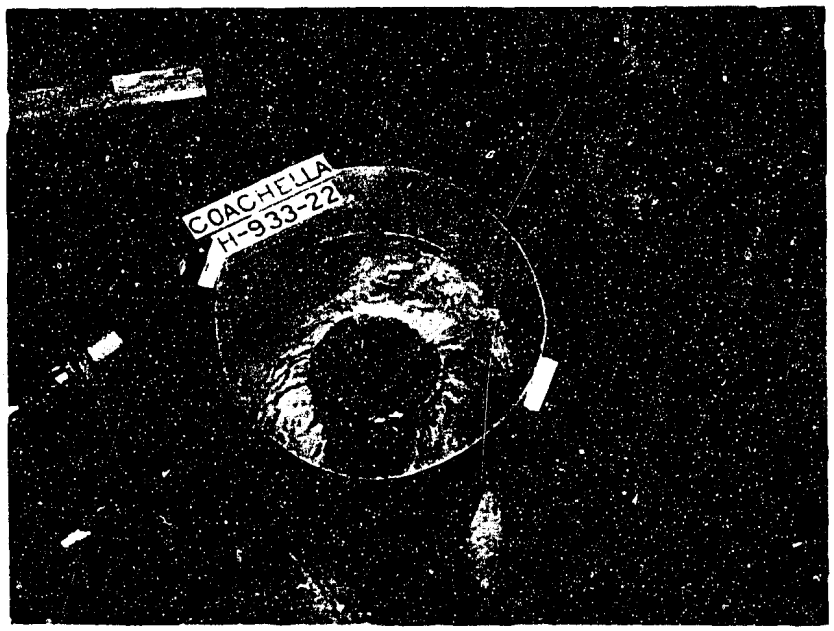
FIELD INSTALLATION

FIGURE 16
REPORT HYD. 324

4-14



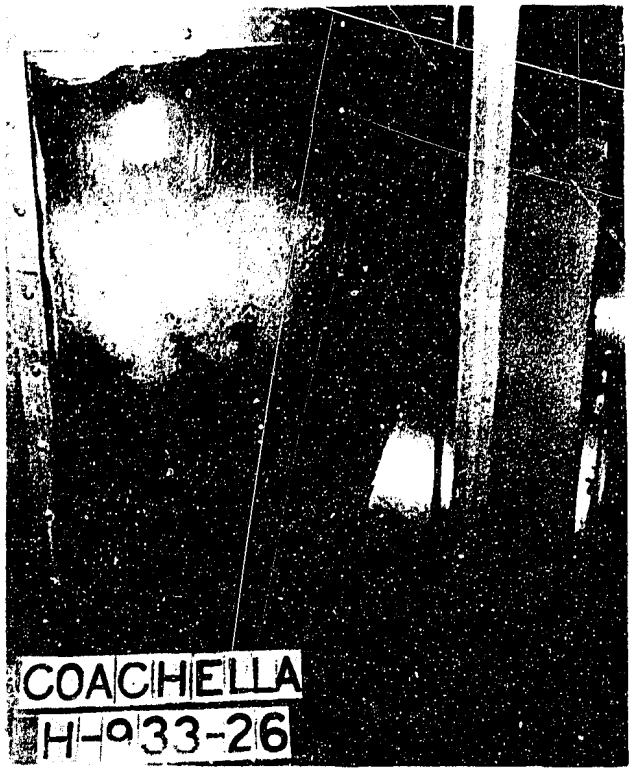

(A) Level inlet riser pipe. Q = 0.37 cfs.




(B) Notched inlet riser pipe. Q = 0.37 cfs.

SURGING - COACHELLA IRRIGATION DISTRIBUTION SYSTEM

Operation of Pipe Stands with Inlet Riser Pipes
Laboratory Model

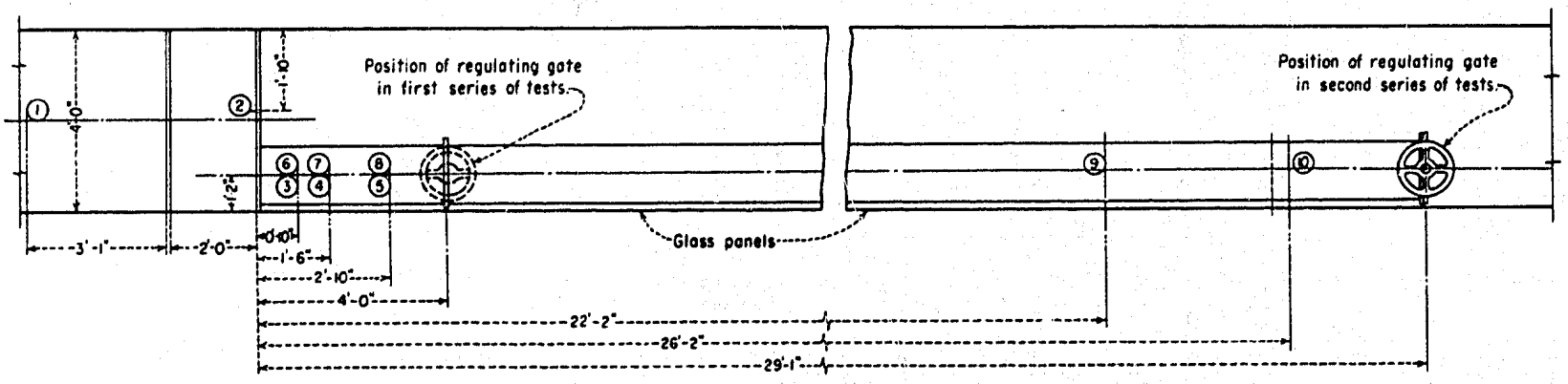


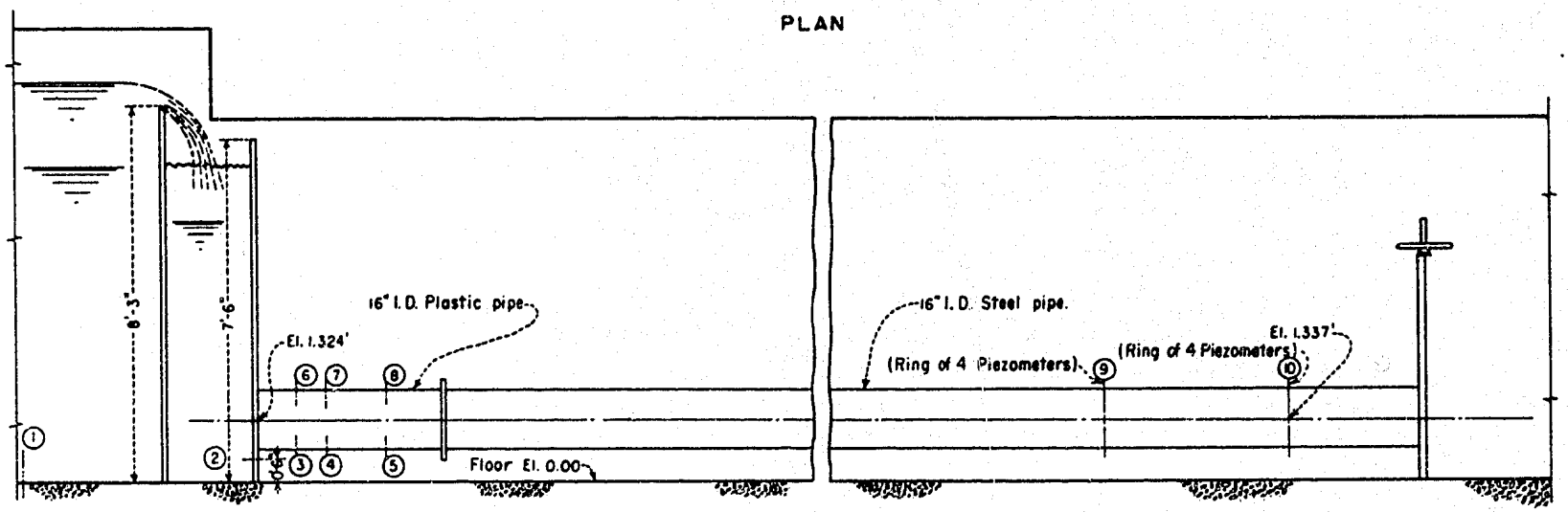

(A) Level inlet riser pipe. Q = 0.37 cfs.

(B) Notched inlet riser pipe. Q = 0.37 cfs.

**SURGING - COACHELLA IRRIGATION DISTRIBUTION SYSTEM**

**Reduced Air Entrainment in Pipe Stand Pool with Inlet Riser Pipe**
**Laboratory Model**




NOTE: (1) indicates piezometer No. 1, etc.

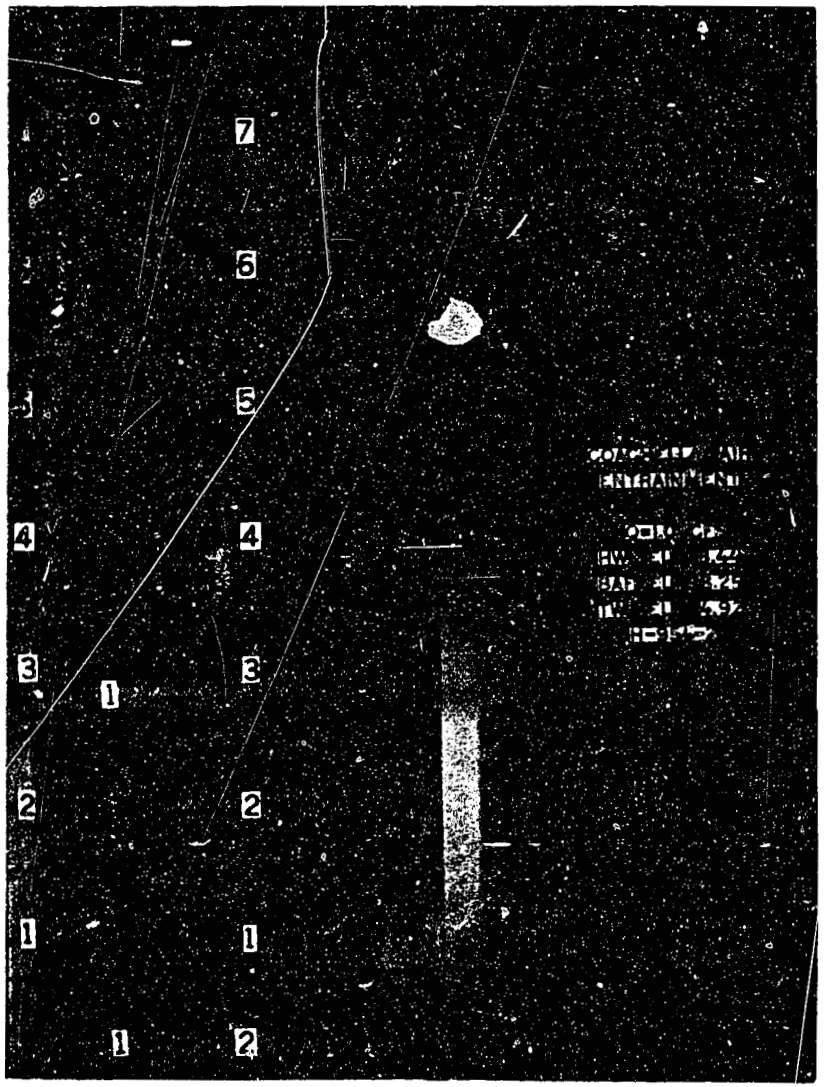
## SURGING — COACHELLA IRRIGATION DISTRIBUTION SYSTEM

### AIR ENTRAINMENT TEST FACILITIES

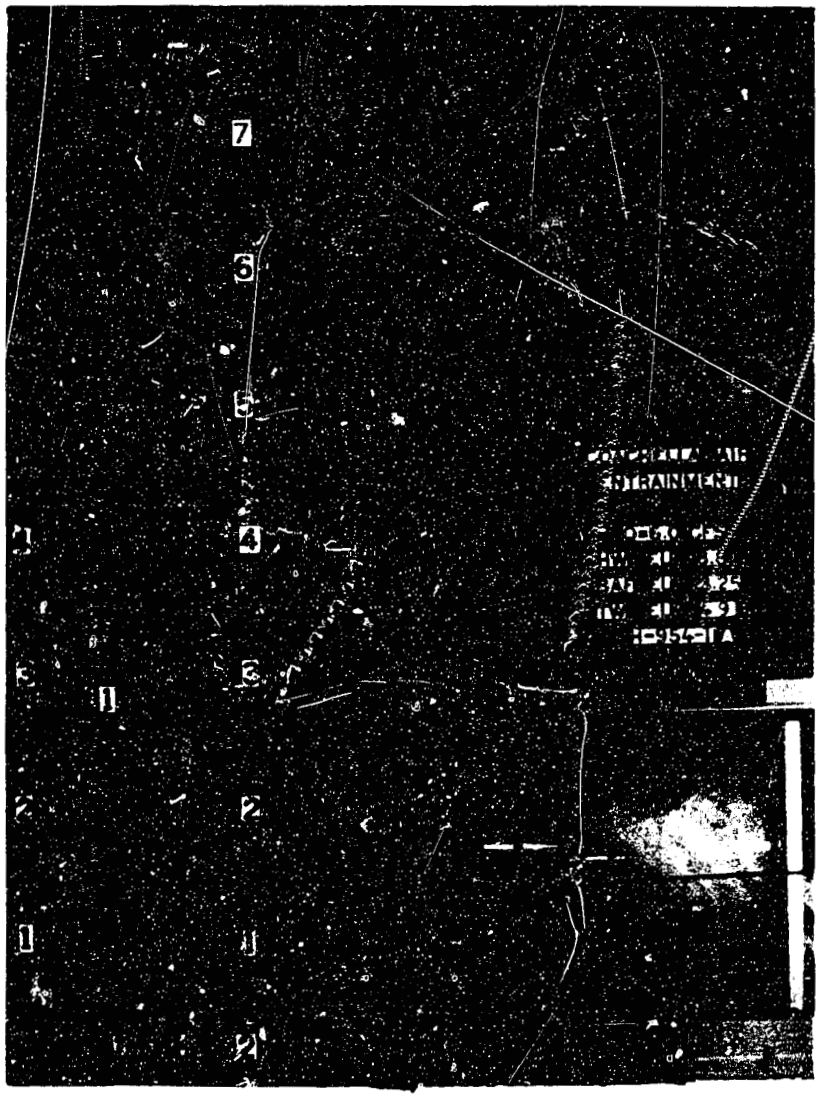
### LABORATORY MODEL

FIGURE 19
REPORT NYD. 324

414



(A) Flow = 1 cfs.

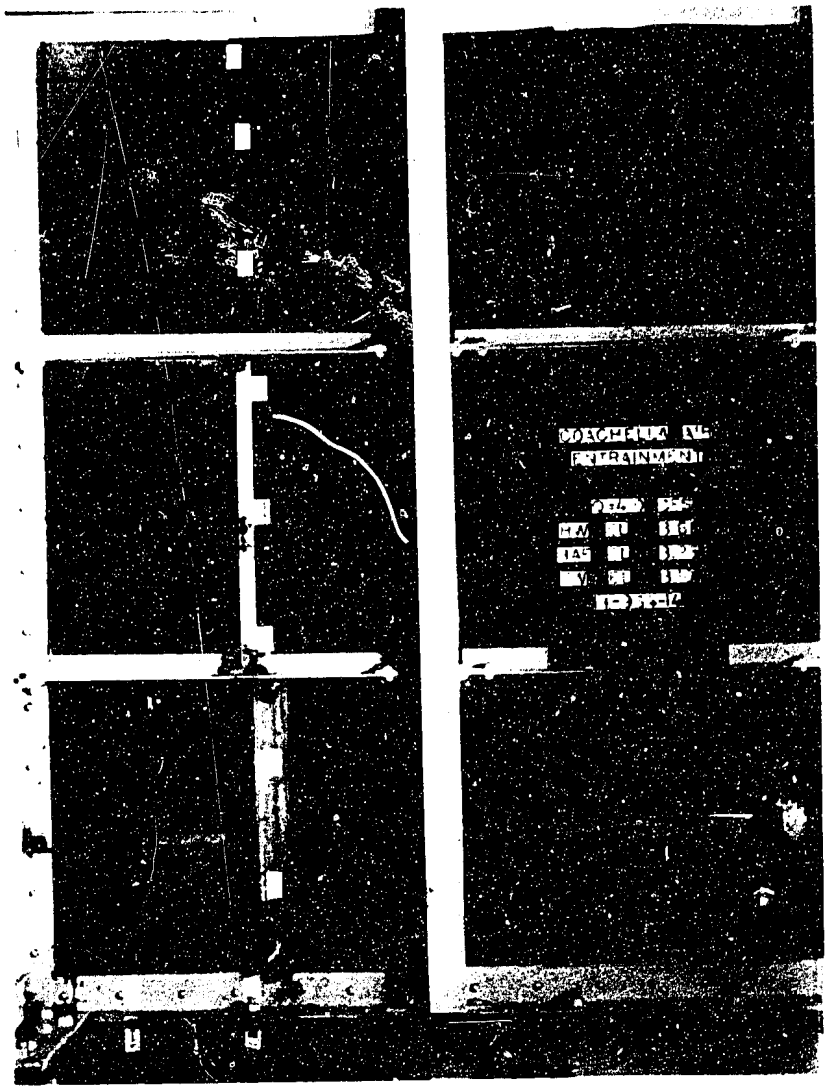


(B) Flow = 6 cfs.

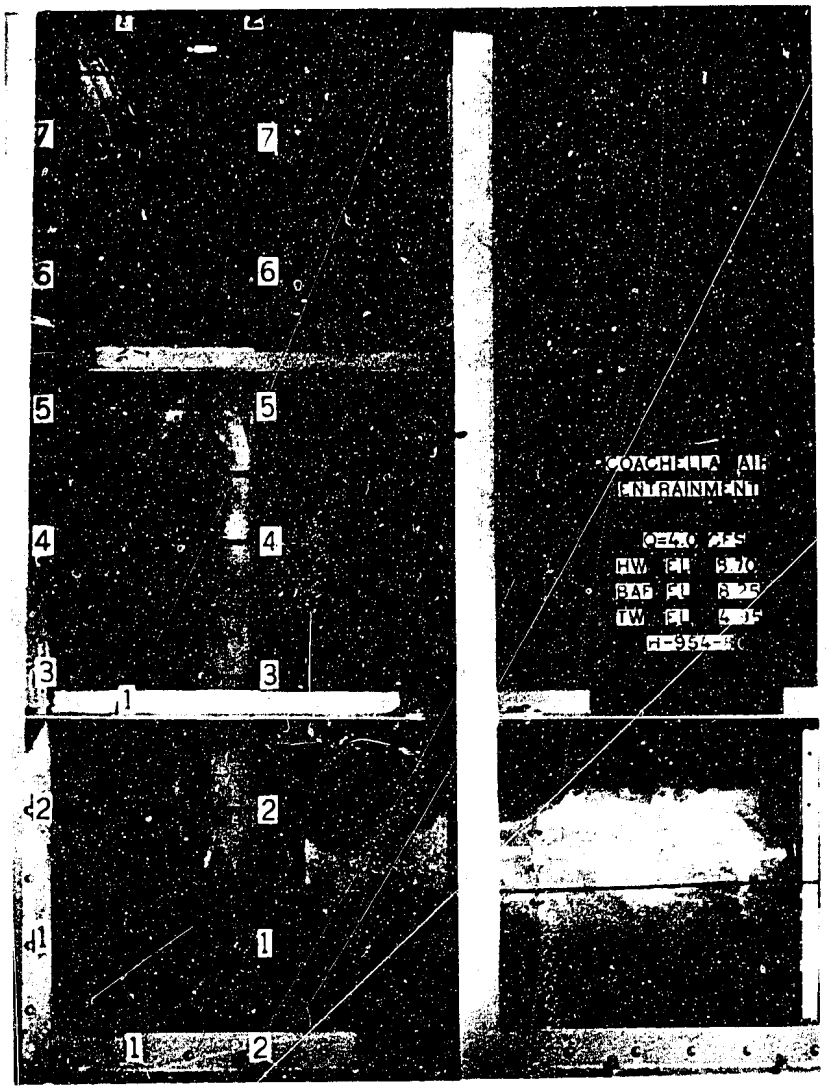
SURGING - COACHELLA IRRIGATION DISTRIBUTION SYSTEM

Increase in Air Entrainment with Increased Flow
Laboratory Model

Figure 20
Report Hyd. 324



(A) Height of fall, 0.15 feet. Q = 4.0 cfs.

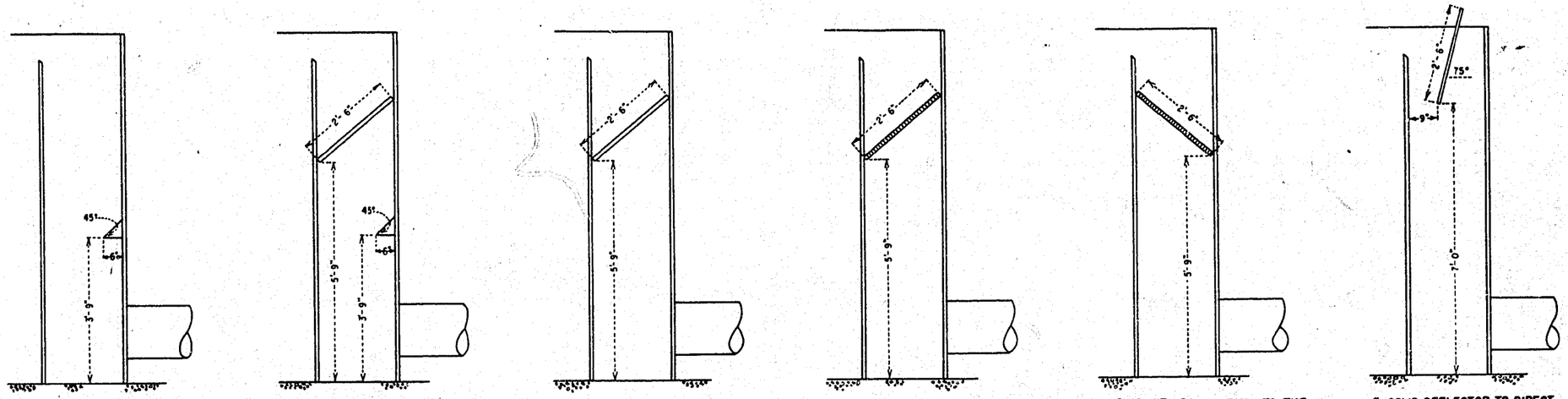



(B) Height of fall, 3.25 feet. Q = 4.0 cfs.

SURGING - COACHELLA IRRIGATION DISTRIBUTION SYSTEM

Increase in Air Entrainment with Increase in Height of Water Fall.
Laboratory Model

Figure 21
Report Hyd. 324




A. 45° DEFLECTOR ON DOWNSTREAM WALL

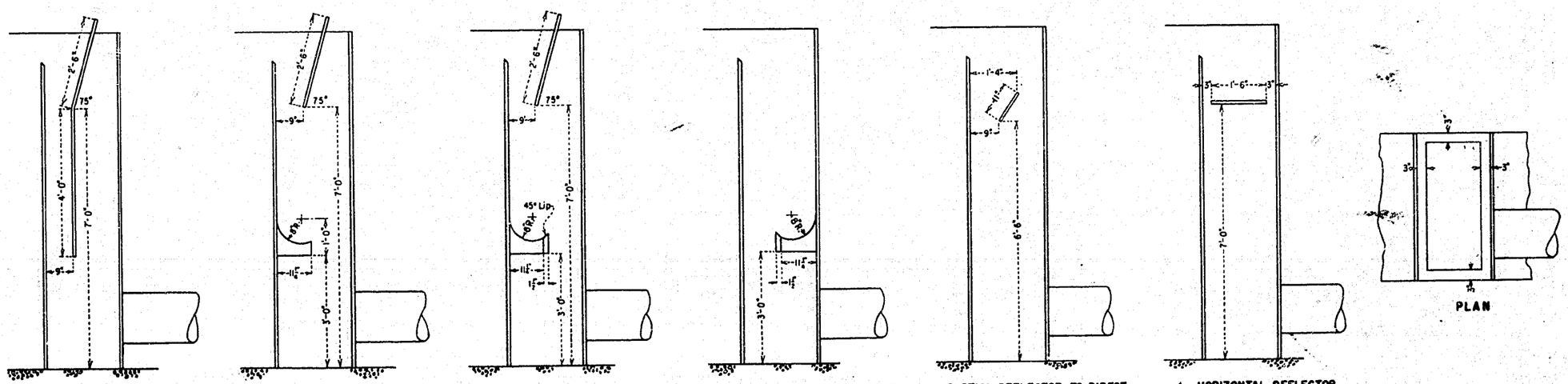
B. GRATINGS WITH BARS PARALLEL TO PIPE AND WITH 45° DEFLECTOR ON DOWNSTREAM WALL

C. GRATING WITH BARS PARALELL TO THE PIPE

D. GRATING WITH BARS NORMAL TO THE PIPE

E. GRATING WITH BARS NORMAL TO THE PIPE WITH OPENINGS DIRECTED UPSTREAM

F. SOLID DEFLECTOR TO DIRECT THE FLOW UPSTREAM




G. SOLID DEFLECTOR EXTENDED DOWN INTO THE POOL

H. SOLID DEFLECTOR WITH A SKI-JUMP DEFLECTOR ON THE UPSTREAM WALL

I. SOLID DEFLECTOR WITH AN EXTENDED SKI-JUMP DEFLECTOR

J. EXTENDED SKI-JUMP DEFLECTOR ON THE DOWNSTREAM WALL

K. PARTIAL DEFLECTOR TO DIRECT LOW FLOWS UPSTREAM

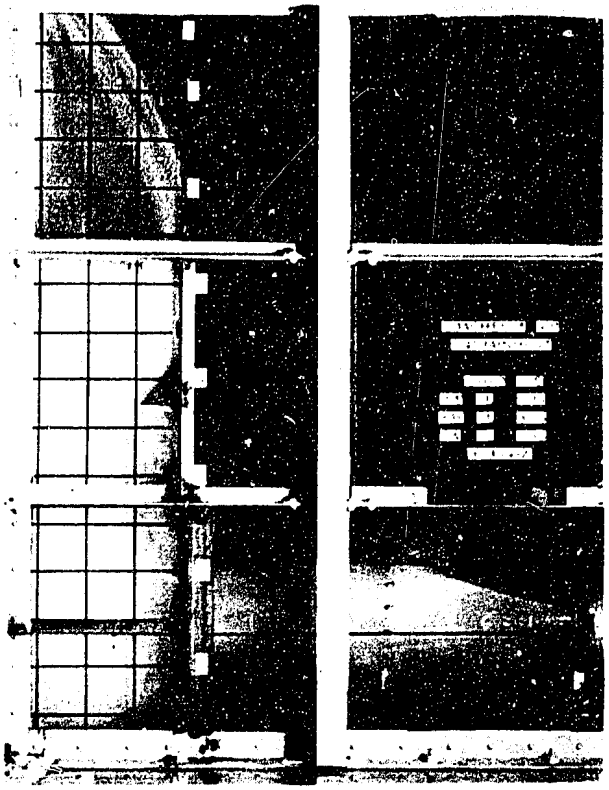
L. HORIZONTAL DEFLECTOR

PLAN

**SURGING - COACHELLA IRRIGATION DISTRIBUTION SYSTEM**

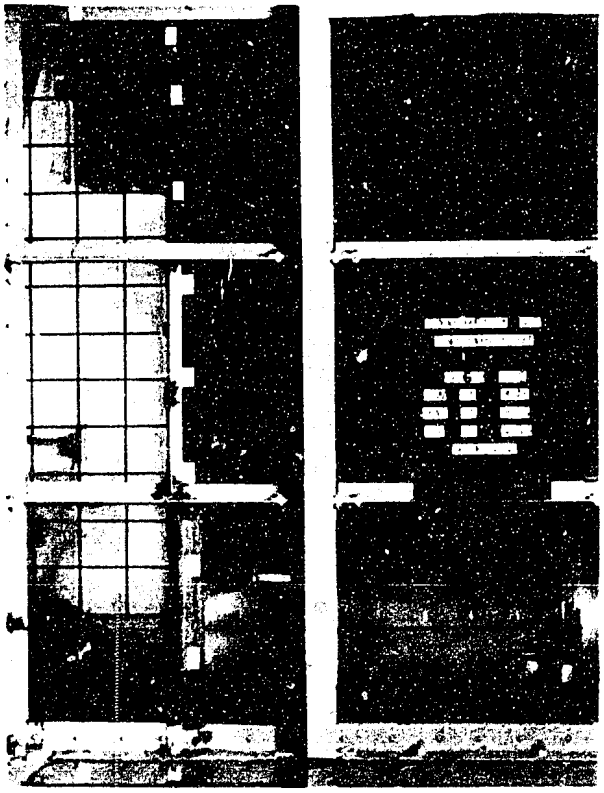
**DEFLECTORS AND GRATINGS USED IN ATTEMPTS TO REDUCE AIR ENTRAINMENT**

**LABORATORY AIR-ENTRAINMENT MODEL**

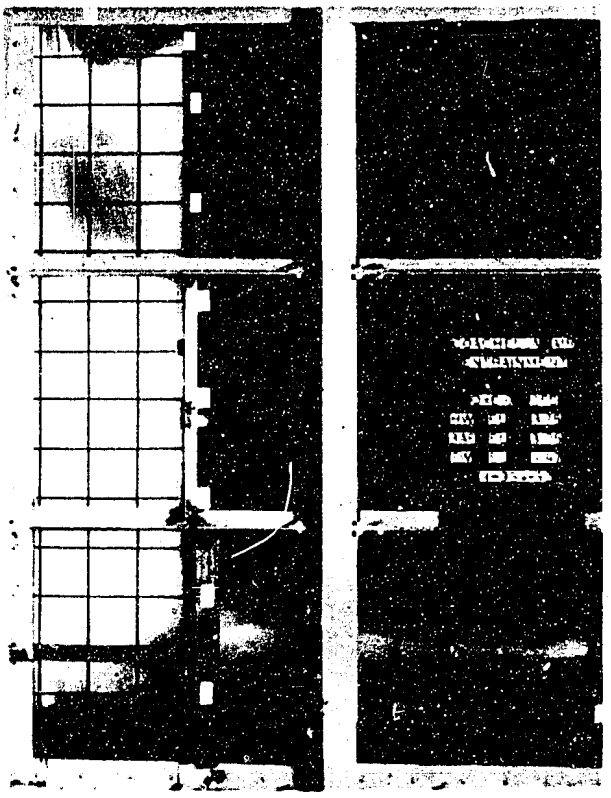


(A) 45° Deflector

(B) Grating



(C) Deflector and extended ski-jump



(D) Horizontal deflector

SURGING - COACHELLA IRRIGATION DISTRIBUTION SYSTEM

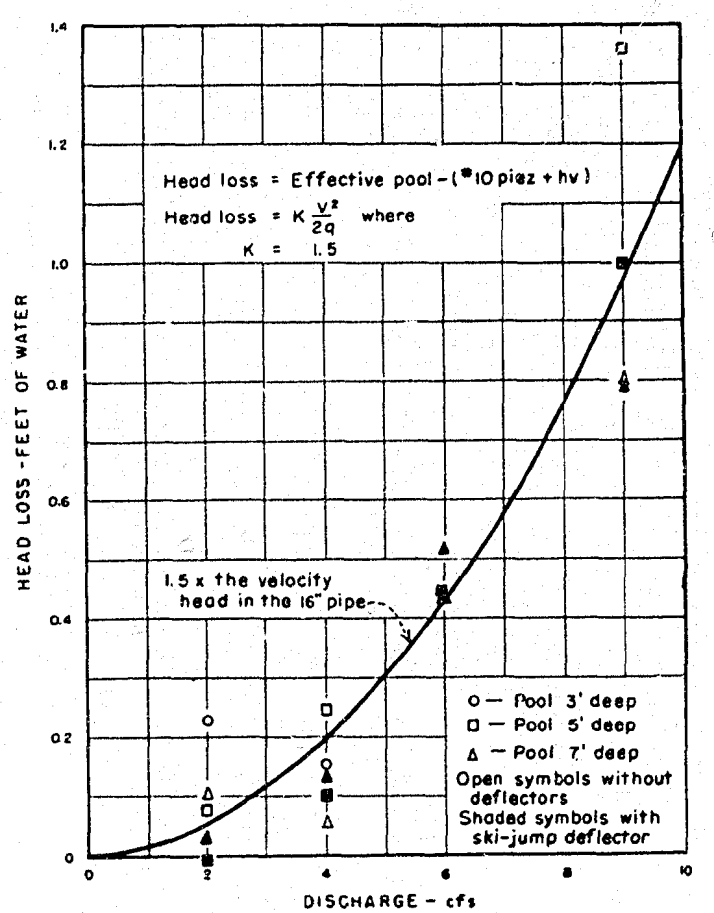
Ineffectiveness of Deflectors and Gratings in Reducing the Air Entrainment

| Q | (EFF. POOL) | PIEZOMETERS | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 2 | 3.06 | 2.83 | 2.80 | 2.96 | 1.05 | 1.05 | 1.05 | 2.75 | 2.90 |
| | 4.85 | 4.81 | 4.81 | 4.81 | 3.06 | 3.06 | 3.06 | 4.79 | 4.71 |
| | 6.94 | 6.89 | 6.89 | 6.89 | 4.98 | 5.20 | 5.65 | 6.78 | 6.85 |
| 4 | 2.72 | 2.21 | 2.33 | 2.19 | 0.89 | 0.90 | 0.94 | 2.36 | 2.34 |
| | 4.71 | 4.19 | 4.28 | 4.14 | 2.65 | 2.55 | 2.75 | 4.34 | 4.35 |
| | 7.09 | 6.89 | 6.94 | 6.93 | 4.46 | 4.46 | 4.46 | 6.91 | 6.92 |
| 6 | 4.83 | 3.93 | 3.63 | 3.73 | 1.73 | 2.07 | 2.10 | | 3.18 |
| | 6.96 | 6.27 | 6.33 | 6.31 | 5.50 | 5.35 | 4.40 | 6.20 | 6.11 |
| 9 | 4.91 | 2.70 | 1.85 | 2.01 | 1.60 | 1.10 | 1.51 | 2.81 | 3.01 |
| | 7.14 | 5.86 | 5.89 | 5.84 | 2.55 | 2.80 | 2.99 | 5.69 | 5.71 |

A. PIEZOMETRIC PRESSURES WITHOUT DEFLECTORS

| Q | (EFF. POOL) | PIEZOMETERS | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 2 | 4.75 | 4.70 | 4.70 | 4.70 | | 1.72 | | 4.73 | 4.73 |
| | 7.20 | 7.16 | 7.15 | 7.15 | | 2.29 | | 7.14 | 7.13 |
| 4 | 4.55 | 4.32 | 4.33 | 4.33 | | 1.57 | | 4.32 | 4.32 |
| | 6.86 | 6.50 | 6.64 | 6.63 | | 2.09 | | 6.60 | 6.59 |
| 6 | 4.04 | 3.20 | 3.39 | 3.41 | | 1.30 | | 3.32 | 3.29 |
| | 6.84 | 5.98 | 6.20 | 6.15 | | | | 6.04 | 6.02 |
| 9 | 4.21 | 1.88 | 2.67 | 2.45 | | 0.89 | | 2.57 | 2.56 |
| | 6.44 | 4.42 | 5.13 | 5.05 | | 1.74 | | 5.00 | 4.91 |

B. PIEZOMETRIC PRESSURES WITH SKI-JUMP DEFLECTOR ON THE DOWNSTREAM WALL




C. HEAD LOSS FROM THE POOL TO A POINT 19.5 DIAMETERS DOWNSTREAM IN THE PIPE LINE (PIEZ. 10)

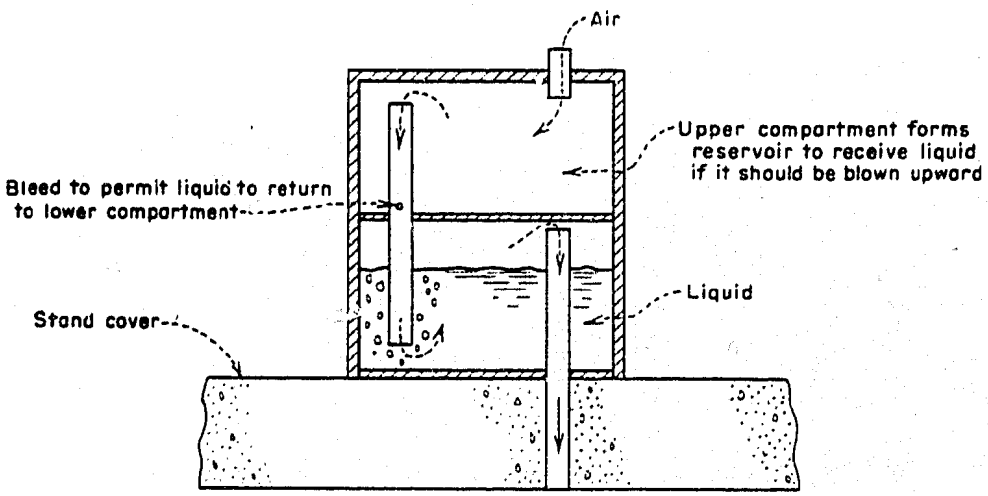
## SURGING — COACHELLA IRRIGATION DISTRIBUTION SYSTEM

PIEZOMETRIC PRESSURES IN THE PIPE LINE AND HEAD LOSS FROM THE DOWNSTREAM POOL TO THE PIPE

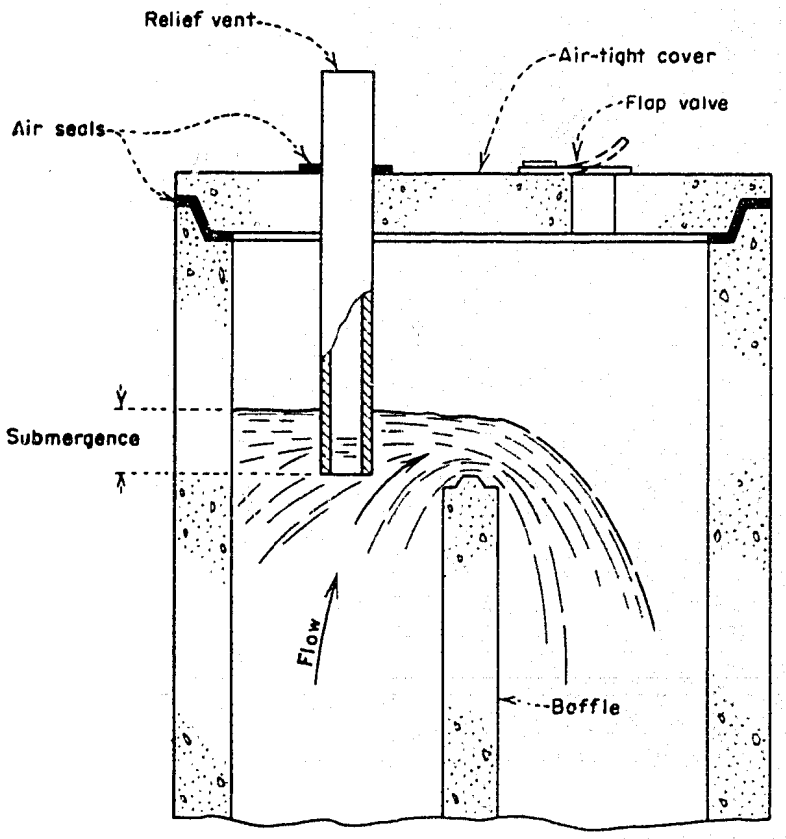
LABORATORY AIR ENTRAINMENT TESTS

FIGURE 24
REPORT HYD. 324

414



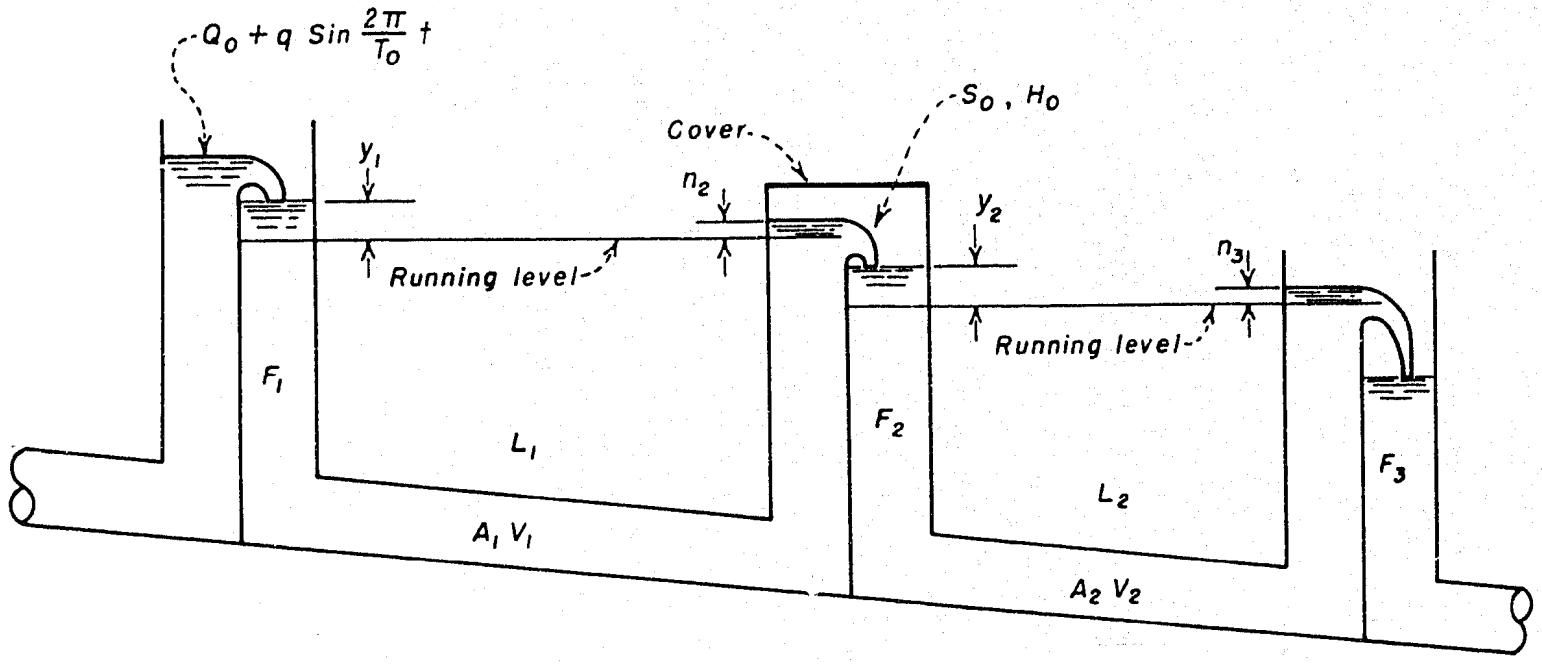

A. FIELD-DESIGNED RELIEF VENT




B. PIPE STAND COVER WITH LABORATORY RELIEF VENT AND FLAP VALVE

SURGING — COACHELLA IRRIGATION DISTRIBUTION SYSTEM

PIPE STAND COVER TO SUPPRESS SURGING

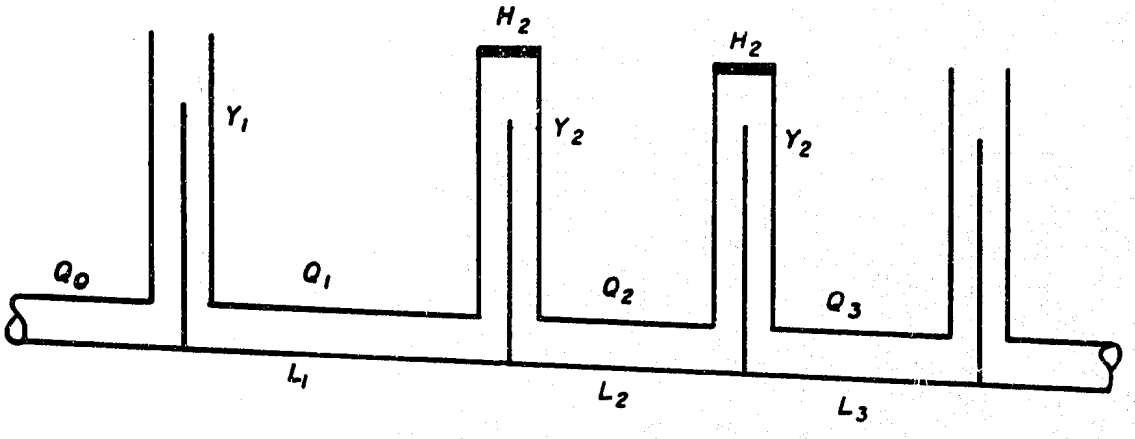



SURGING - COACHELLA IRRIGATION DISTRIBUTION SYSTEM
SKETCH OF TWO PIPE REACHES HAVING A COMMON COVERED STAND

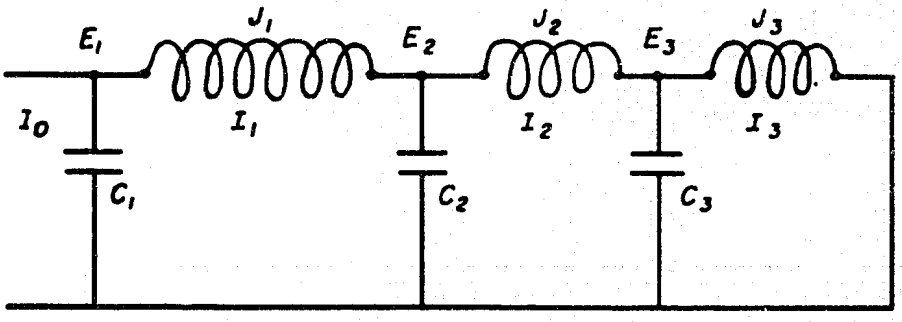
FIGURE 26
REPORT HYD 324

414

FIGURE 27
REPORT HYD. 324



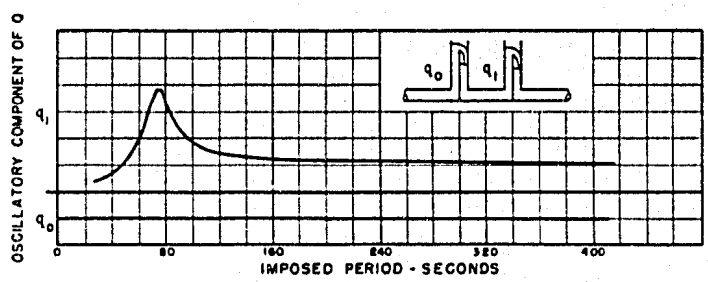

A. HYDRAULIC SYSTEM OF THREE PIPE REACHES WITH TWO ADJACENT STANDS COVERED



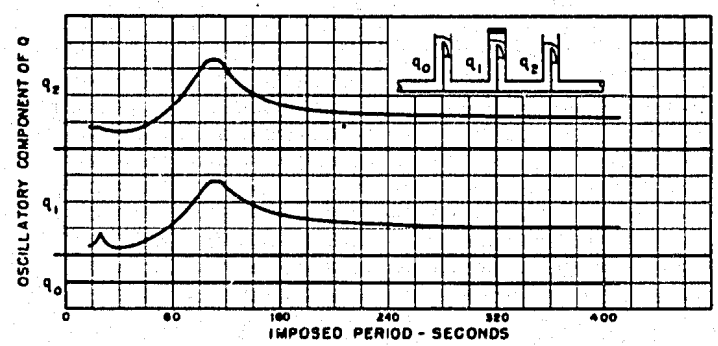

B. ANALOG CIRCUIT FOR THREE PIPE REACHES WITH TWO ADJACENT STANDS COVERED

SURGING - COACHELLA IRRIGATION DISTRIBUTION SYSTEM

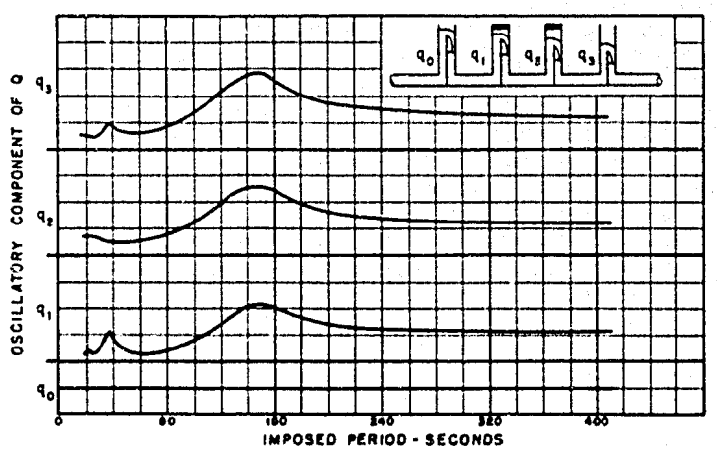
COMPARISON BETWEEN HYDRAULIC SYSTEM AND ELECTRIC ANALOG CIRCUIT



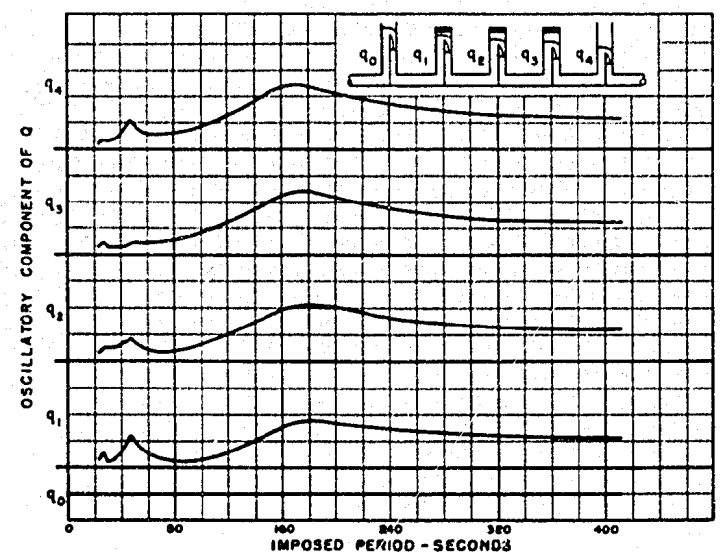

A. NO STANDS COVERED




B. ONE STAND COVERED




C. TWO STANDS COVERED




D. THREE STANDS COVERED

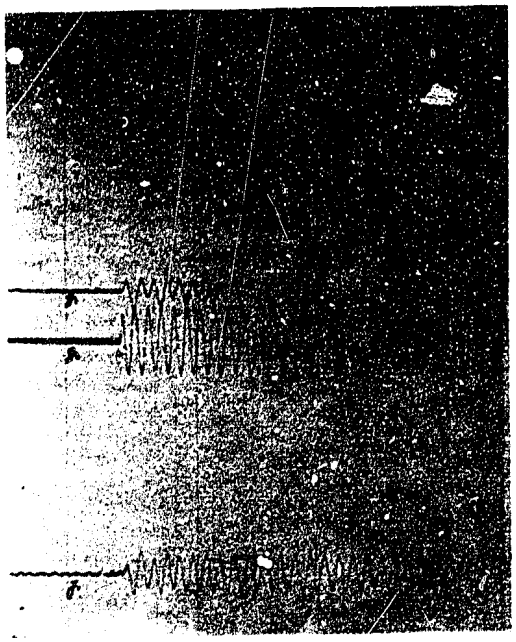
Note:- $q_0$, $q_1$, --- represent the oscillatory components of discharge which, when superimposed on the mean flow, $Q_0$, produce the instantaneous total flow, Q.

## SURGING – COACHELLA IRRIGATION DISTRIBUTION SYSTEM

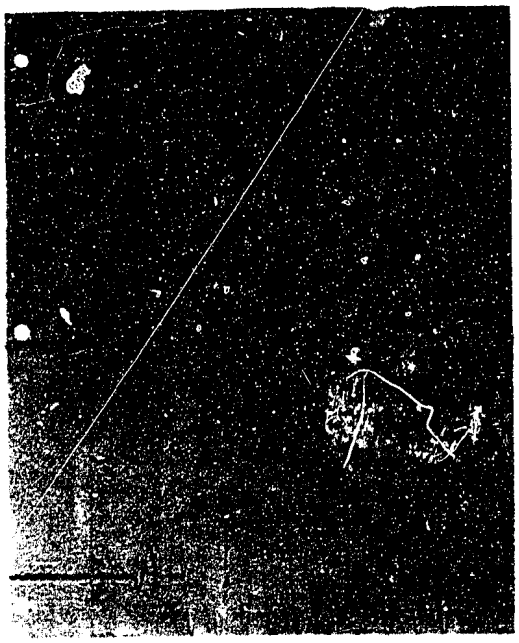
### RELATION OF RESONANCE FOR VARIOUS PIPE LINE SYSTEMS TO THE IMPOSED OSCILLATION PERIOD

DATA FROM ELECTRIC ANALOG REPRESENTING PROTOTYPE SYSTEMS

FIGURE 28
REPORT HYD. 324

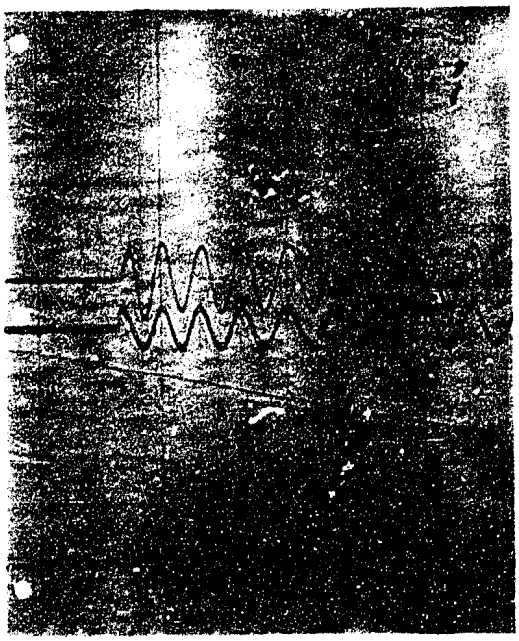


A. PERIOD – 33.2 SECONDS



B. PERIOD – 66.4 SECONDS

C. PERIOD – 73.8 SECONDS

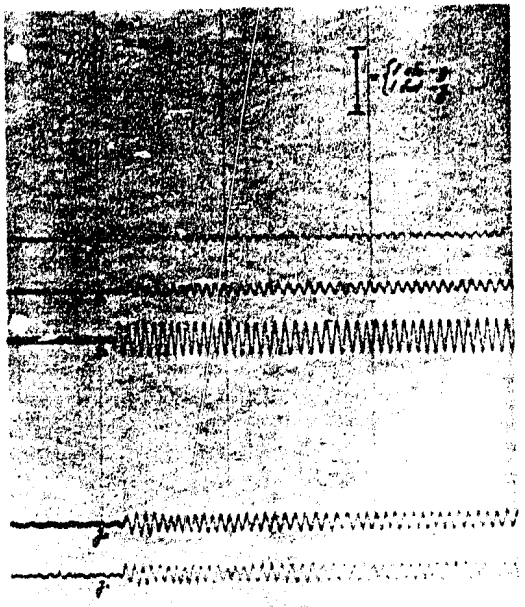


D. PERIOD – 111.0 SECONDS

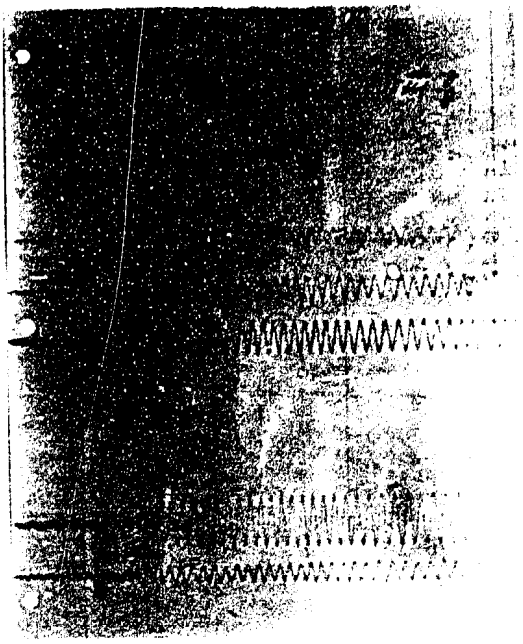
**SURGING – COACHELLA IRRIGATION DISTRIBUTION SYSTEM**

THE ACTION WITHIN THE PIPE SYSTEM WHEN OSCILLATING FLOW WAS STARTED

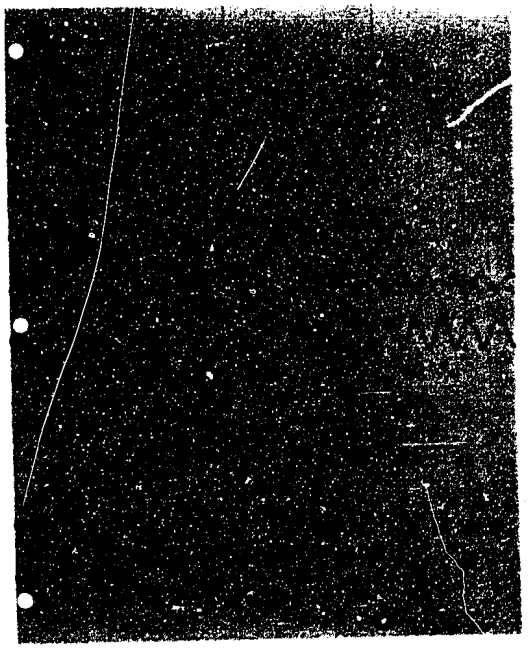
NO STANDS COVERED



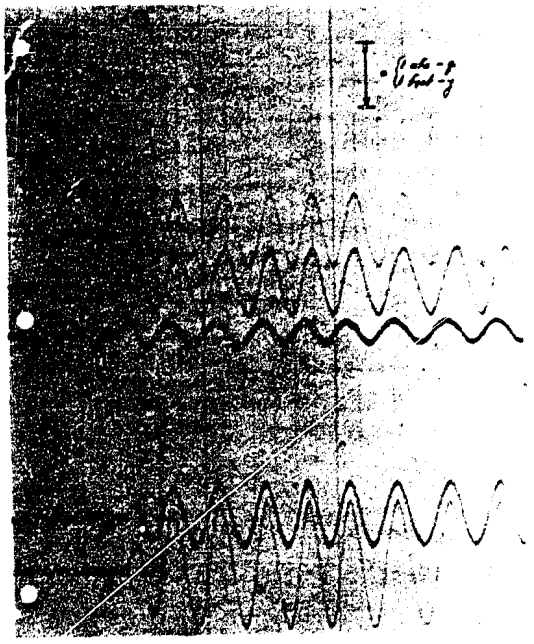
A. PERIOD – 22.2 SECONDS



B. PERIOD – 26.6 SECONDS



C. PERIOD – 66.4 SECONDS



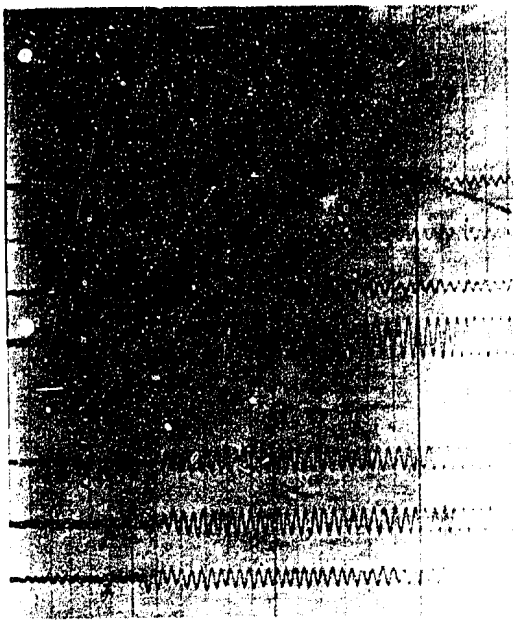
D. PERIOD – 111.0 SECONDS

**SURGING – COACHELLA IRRIGATION DISTRIBUTION SYSTEM**

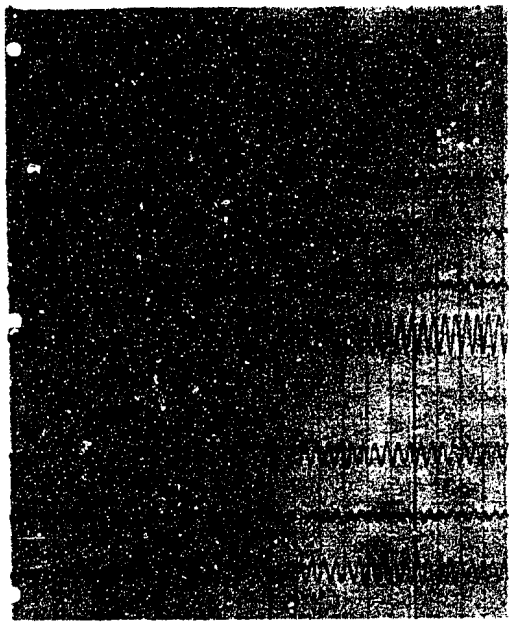
THE ACTION WITHIN THE PIPE SYSTEM WHEN OSCILLATING FLOW WAS STARTED

STAND 1 COVERED

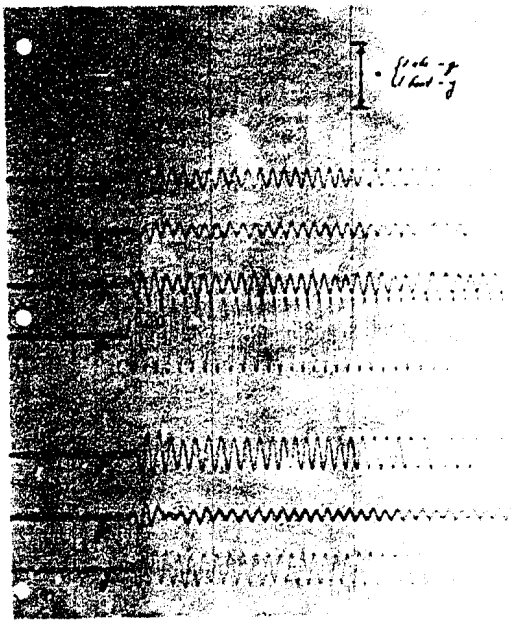
A. PERIOD – 16.5 SECONDS



B. PERIOD – 22.2 SECONDS



C. PERIOD – 26.6 SECONDS

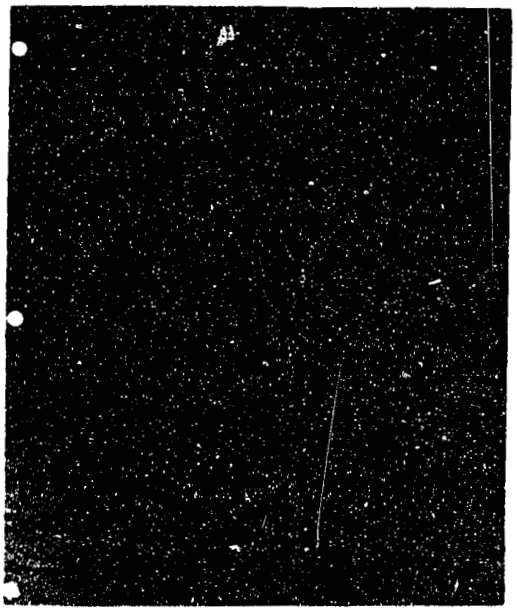


D. PERIOD – 27.7 SECONDS

**SURGING – COACHELLA IRRIGATION DISTRIBUTION SYSTEM**

THE ACTION WITHIN THE PIPE SYSTEM WHEN OSCILLATING FLOW WAS STARTED

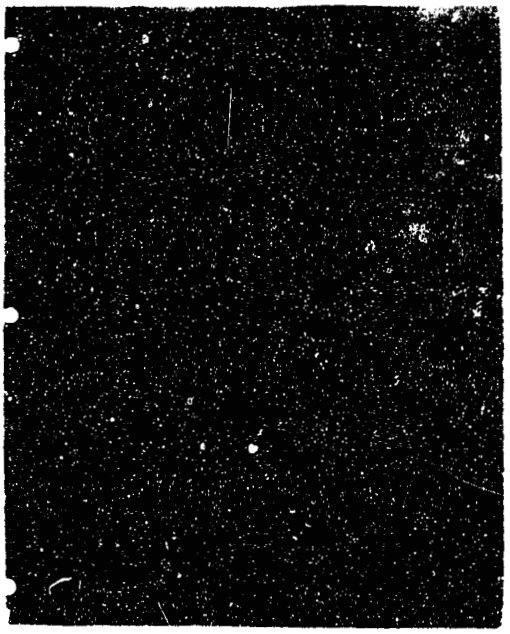
STANDS 1 AND 2 COVERED



A. PERIOD – 36.9 SECONDS

B. PERIOD – 66.4 SECONDS

C. PERIOD – 111.0 SECONDS



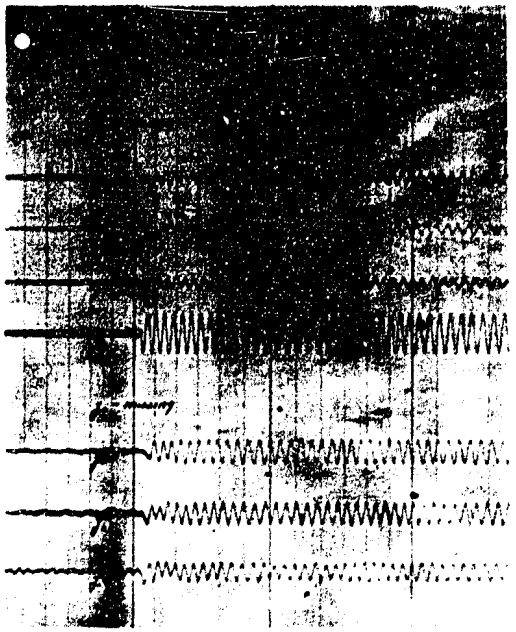
D. PERIOD – 144.0 SECONDS

**SURGING – COACHELLA IRRIGATION DISTRIBUTION SYSTEM**

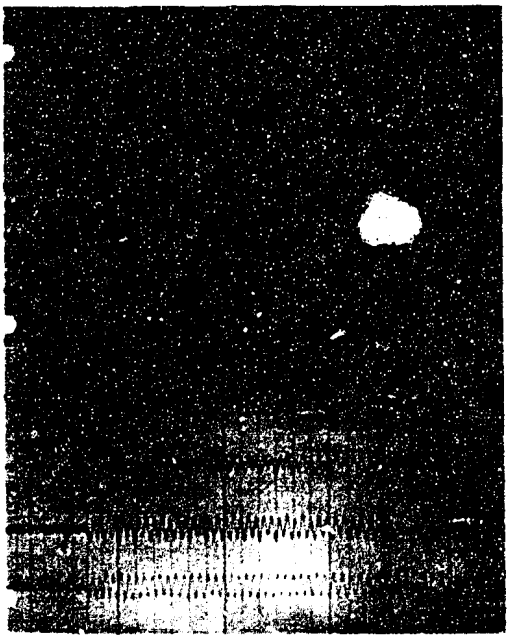
THE ACTION WITHIN THE PIPE SYSTEM WHEN OSCILLATING FLOW WAS STARTED

STANDS 1 AND 2 COVERED

A. PERIOD – 18.5 SECONDS



B. PERIOD – 22.9 SECONDS



C. PERIOD – 24.6 SECONDS

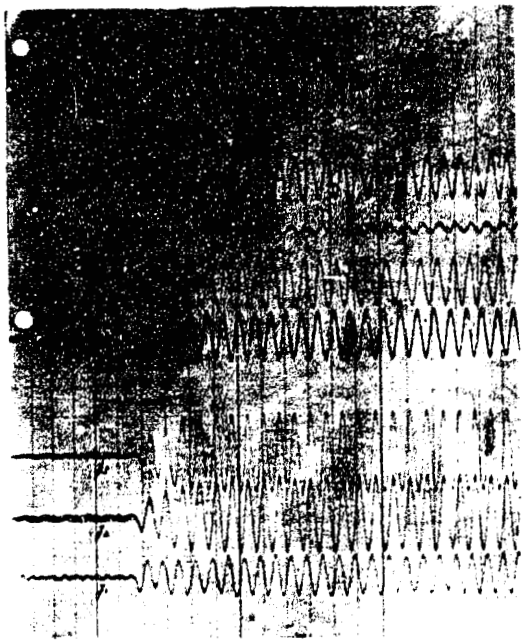
D. PERIOD – 27.7 SECONDS

**SURGING – COACHELLA IRRIGATION DISTRIBUTION SYSTEM**

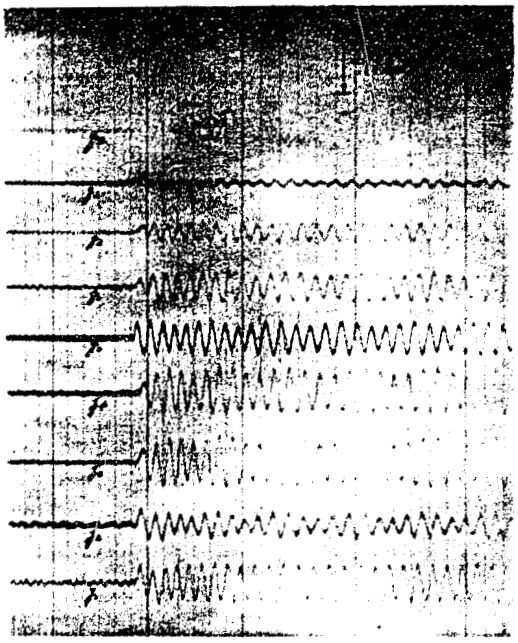
THE ACTION WITHIN THE PIPE SYSTEM WHEN OSCILLATING FLOW WAS STARTED

STANDS 1, 2, AND 3 COVERED

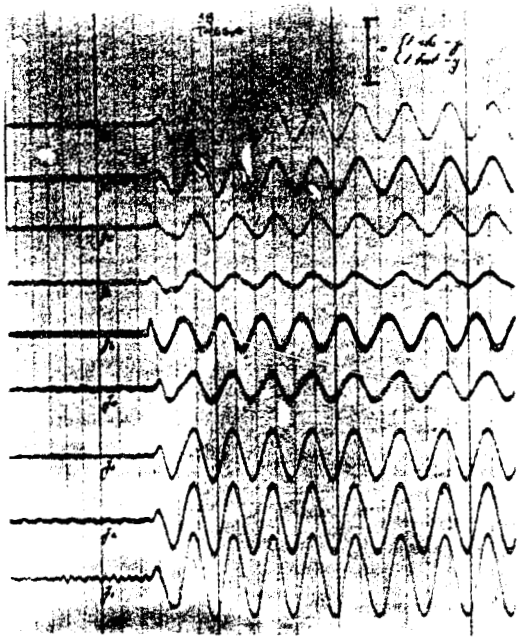
A. PERIOD – 33.2 SECONDS



B. PERIOD – 36.9 SECONDS



C. PERIOD – 43.7 SECONDS

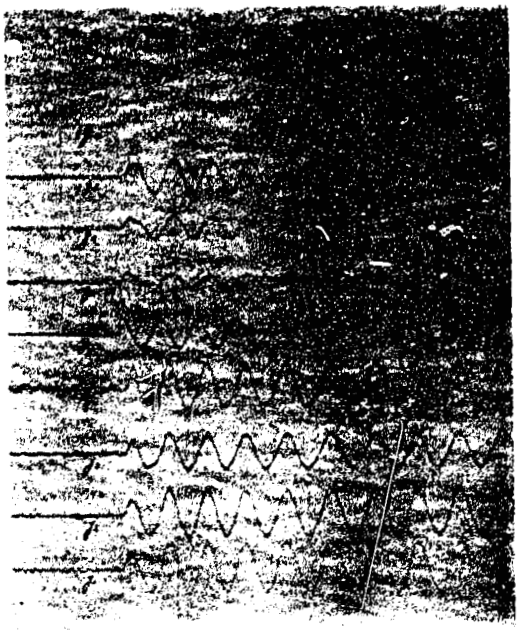


D. PERIOD – 66.4 SECONDS

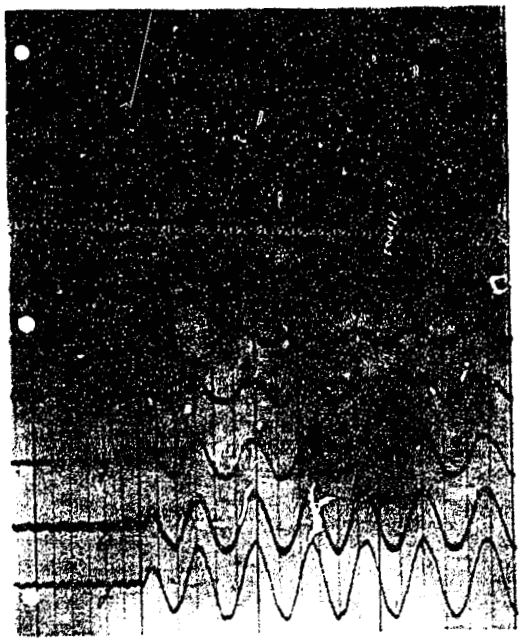
**SURGING – COACHELLA IRRIGATION DISTRIBUTION SYSTEM**

THE ACTION WITHIN THE PIPE SYSTEM WHEN OSCILLATING FLOW WAS STARTED

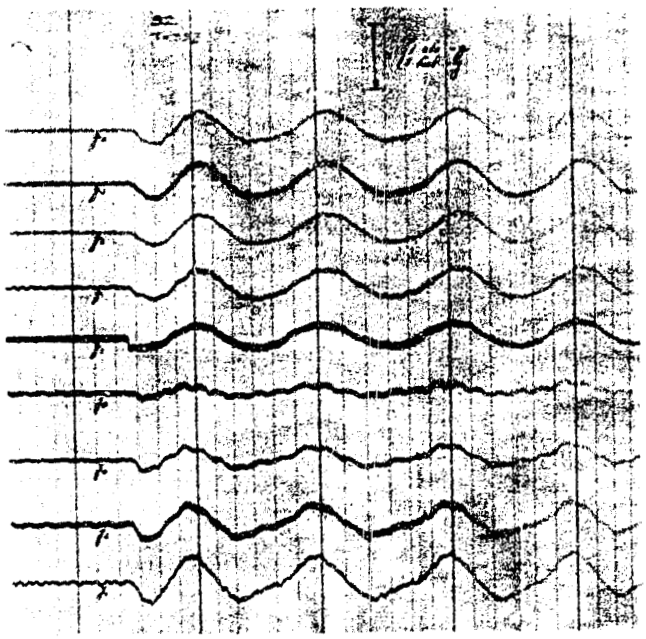
STANDS 1, 2, AND 3 COVERED



A. PERIOD – 111.0 SECONDS



B. PERIOD – 144.0 SECONDS

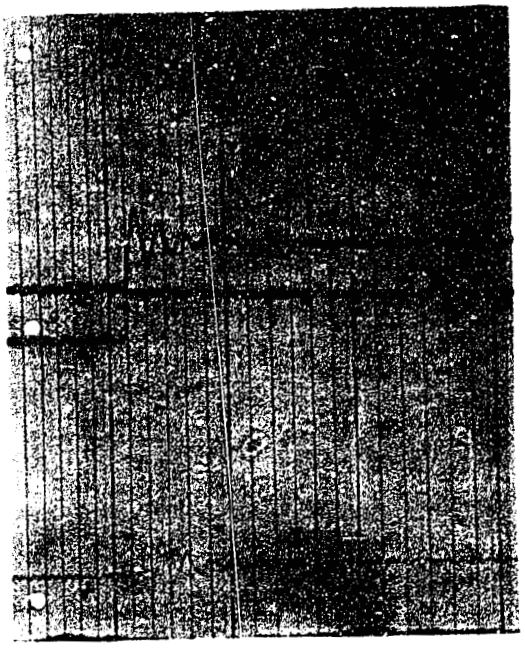


C. PERIOD – 332.0 SECONDS

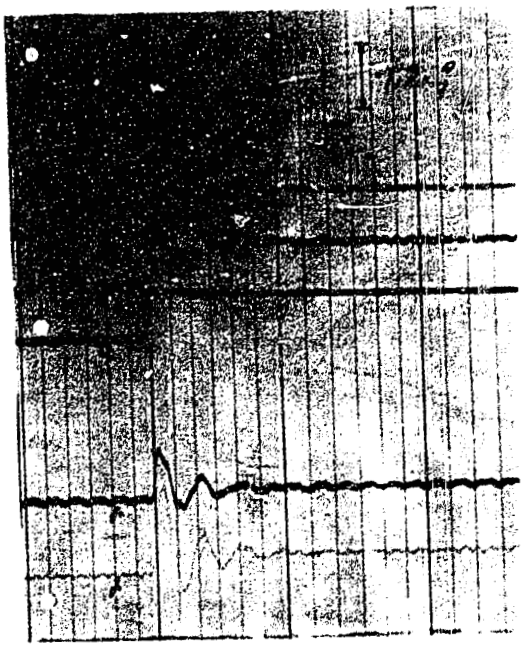
**SURGING – COACHELLA IRRIGATION DISTRIBUTION SYSTEM**

THE ACTION WITHIN THE PIPE SYSTEM WHEN OSCILLATING FLOW WAS STARTED

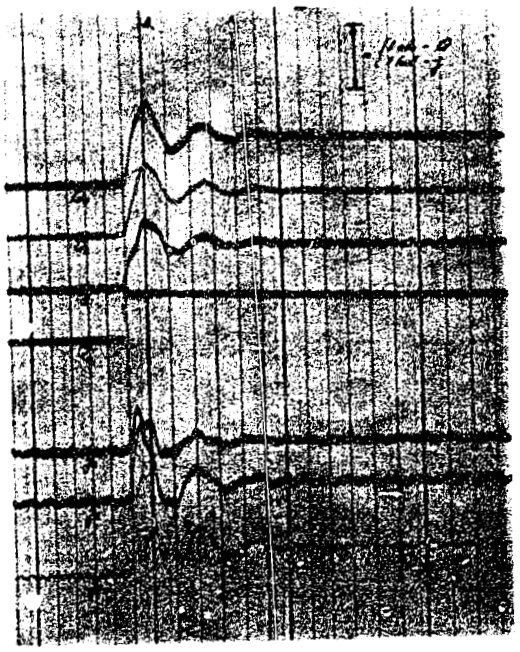
STANDS 1, 2, AND 3 COVERED



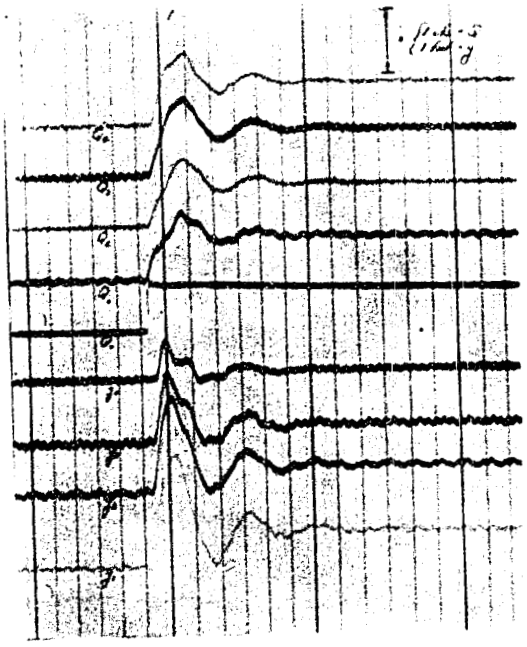
A. NO STANDS COVERED



B. STAND I COVERED



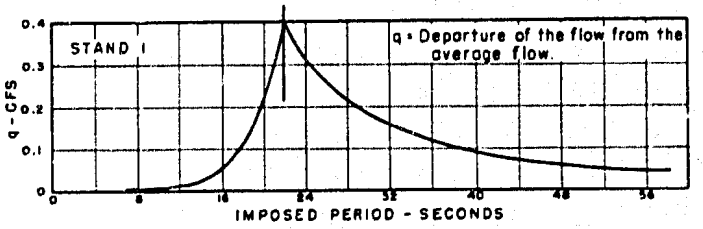
C. STANDS I AND 2 COVERED



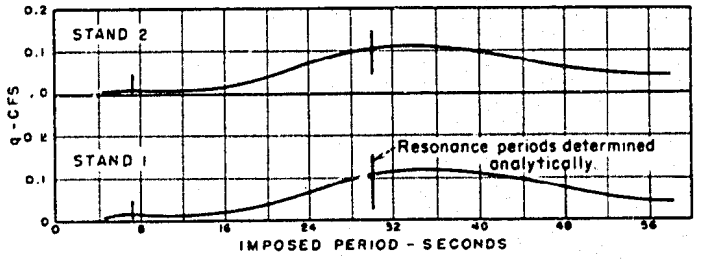
D. STANDS 1, 2, AND 3 COVERED

**SURGING – COACHELLA IRRIGATION DISTRIBUTION SYSTEM**

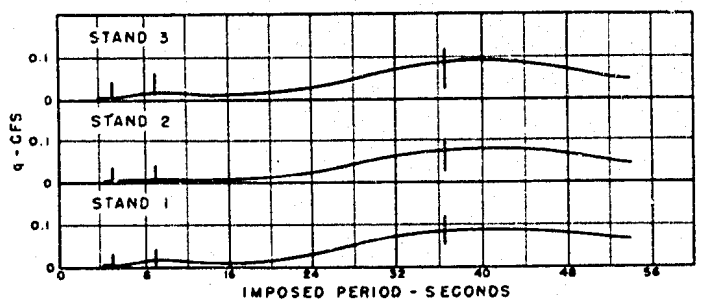
THE ACTION WITHIN THE PIPE SYSTEM WHEN THE FLOW WAS SUDDENLY INCREASED




A. NO STANDS COVERED

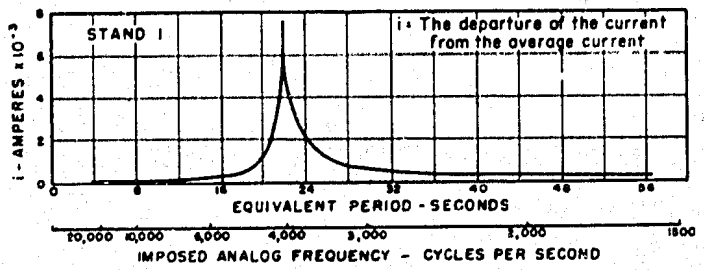



B. STAND I COVERED

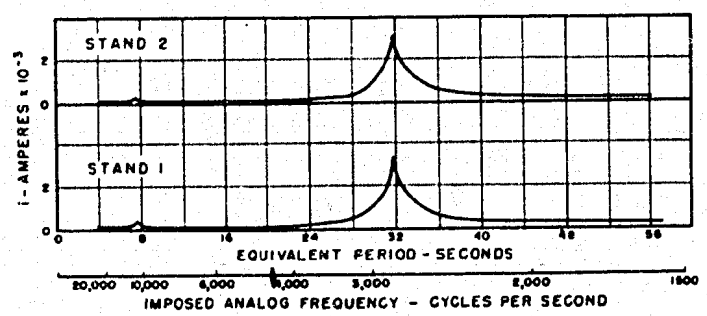



C. STANDS I & 2 COVERED

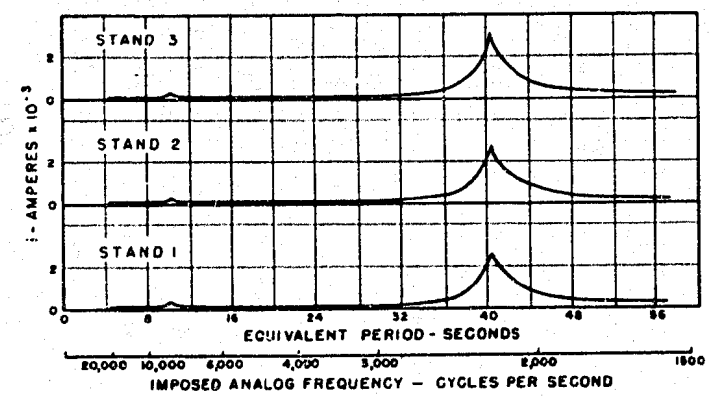
HYDRAULIC MODEL STUDIES




D. NO STANDS COVERED




E. STAND I COVERED




F. STANDS I & 2 COVERED

ELECTRIC ANALOG STUDIES

**SURGING - COACHELLA IRRIGATION DISTRIBUTION SYSTEM**

**RELATION OF RESONANCE TO IMPOSED PERIOD**

**AS DETERMINED BY ANALYTICAL, ELECTRIC ANALOG, AND HYDRAULIC MODEL TESTS**

FIGURE 37
REPORT HYD. 324

414